ONE

Discovering the Ocean

OF FISH AND SHIPS AND PEOPLE

Lobster, scallop, and tuna are among the more expensive items on the seafood menu, and for good reasons. We like to eat these things, and there are many of us, and not so many of them any more. In fact, with regard to fish suitable for fine dining, there are now roughly 10 times fewer in the sea than only a few decades ago.[1] Many other animals of the sea once or recently heavily exploited are similarly diminished, including, for example, sea turtles and large whales. Jellyfish, however, remain in sufficient abundance (fig. 1.1). Their nutritional value, in relation to weight, is low. Nevertheless, they are already finding their way into seafood restaurants, thus confirming a long-term trend away from catching highly prized predators such as tuna and swordfish, toward netting plankton-eaters and invertebrates.[2]

For millennia, the relationship between people and the sea has been determined largely by human fondness for seafood. Fishermen had the most intimate knowledge of winds and currents and of the changes that come with the seasons. Also, of course, they knew where to go to find fish and crabs and oysters. Their prey was found in view of the land. Later on, with bigger vessels, fishing moved out into the open ocean away from visual contact with the coast. Fishermen discovered new riches: enormous aggregations of cod, schools of herring. In high northern latitudes, whales have long been part of marine hunting cultures. Not so long ago, in the nineteenth century, whaling was an important business in many coastal communities throughout the world. In New England, shore whaling off Nantucket and Long Island made a start around 1690. The business grew into a worldwide enterprise in the early 1800s, centered at New Bedford, where more than 400 whalers were registered at the Custom House in 1857.[3] Yankee whalers knew the sea and the habits of whales.[4] They were the sages of the sea well before oceanography emerged as a branch of the Earth sciences. Their knowledge was

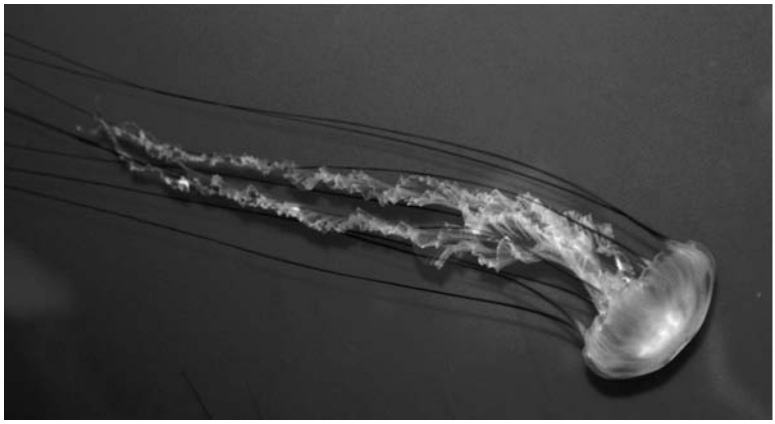

FIGURE 1.1. Pelagic jellyfish include some of the largest and most ancient forms of animal life in the sea.

closely tied to purpose, a link that has largely persisted into modern ocean sciences. The main lesson of the story of whale hunting, often retold, is that the sea's resources are not inexhaustible, and that overexploitation will not engender restraint but will stop only after collapse of the resource or from outside intervention (in this case, the discovery of petroleum).

As we have learned more about the ocean, motivated by the needs of fisheries, navies, and shipping, and also by curiosity, a new planet has entered our awareness, one where the ocean is the dominating feature of conditions on Earth. Winds from the sea bring the rain that determines where plants and animals on land shall thrive. Their patterns of distribution, in turn, determine the life-style of humans dependent on agriculture.

Awareness that our planet has an enormous ocean, with island continents, starts with the discovery of the World Ocean around AD 1500. Knowledge that the deep ocean is cold and that its salt is the same everywhere are achievements of the nineteenth century. Since then, the science of the sea has expanded rapidly. The general pattern of this expansion, as seen in the large oceanographic institutes around the world, is nicely reflected in the history of Scripps Institution of Oceanography ("Scripps" for short), one of the largest and oldest of the genre. As it happens, Scripps is just over 100 years old: it was founded in 1903.

A BOUNTIFUL SEA?

The lesson learned from whaling—that the ocean's resources are large but limited—has recently emerged again with respect to many other prey items that once yielded millions of tons of food, such as herring and cod (fig. 1.2).

The collapse of these fisheries in the North Atlantic was not entirely unexpected. Warnings were sounded back in the early twentieth century.[5] But optimism prevailed. As recently as 1967, the American fishery scientist W. M. Chapman averred that the total harvest of fish from the ocean each year could be expanded to some 2 billion tons, given the right technology. At the same time, Scripps oceanographer John D. Strickland preferred a much lower number, admitting a maximum of 600 million tons.[6] Both guesses were much too high, exceeding reality by more than a factor of 20 and of 6, respectively. In the decades since, it has become clear that the total catch has stagnated around 100 million tons, despite ever increasing efforts. At the catch of 100 million tons, already, the sea is being fished out. Large fish are becoming rare, and the food web in the sea is changed accordingly.[7]

To become an honorary citizen of Newfoundland (a distinction bestowed by the natives during happy hours to many a visitor over a suitable number of drinks) one must pass several tests, one of which consists of kissing the lips of a dead codfish.[8] There are good

FIGURE 1.2. For centuries, herring and cod have supported major fisheries of the North Atlantic.

reasons for demanding that any citizen of Newfoundland, real or honorary, should demonstrate allegiance to this grim-faced denizen of the sea. The settling of the coast of Newfoundland by Europeans, and indeed of all the shores north of Cape Cod, owes a great debt to the rich cod fisheries of the Grand Banks off Newfoundland, and to those along much of the coast of Atlantic Canada and New England.[9]

The Atlantic cod *(Gadus morhua)*, until very recently the King of the Grand Banks, is a member of the gadoid fishes, an extremely important group of predators obtaining much of their food at the bottom of the sea, in fertile regions. The cod is commonly caught at weights up to 25 pounds or so but is able to grow to a size of 6 feet and 200 pounds.[10] Other gadoids are the haddock, the pout, the poor cod, the coalfish or saithe, the pollock (the British "Pollack"), the whiting, and the silver cod. The various species of the genus *Gadus* differ in color and markings and appearance of the lateral line, and the presence or absence of a barbel (the appendage on the lower jaw that is the hallmark of the cod).

Fishing for cod off New England was part of the negotiations between the new nation of the United States of America and the King of England, following the revolution. At the insistence of John Adams, the United States was granted fishing rights on the Grand Banks by England and permission to land in Nova Scotia and Labrador to salt-dry the catch. Georges Bank is largely in international waters (even today, notwithstanding the expanded economic zone). It is an extension of the continental shelf, out to some 200 miles off New England, covered with debris piled there by enormous glaciers that once moved out from the Hudson Bay region. The shelf ends at an underwater precipice where cold Arctic waters flowing southward meet the warmer water of the Gulf Stream. The meeting of cold and warm eddies provokes much turbulence and mixing, aided by strong currents interacting with the shallow bottom, and this turbulence moves nutrient-rich deep waters into the sunlit zone at the surface. The rich supply of nutrients and the strong sunlight in spring and early summer start the food chain that supports the fish and crustaceans that cod feed on.[11]

The Atlantic cod ranges throughout the North Atlantic, from the North Sea and around the British Isles and the Bay of Biscay to Iceland and up to northern Norway and into the Barents Sea. An important problem for fishery biologists has been to define the degree to which the stocks in different regions are separate populations. There was a time, in the early 1970s, when Atlantic cod was the second most important species, by weight, in the world's fish catch. Only the Peruvian anchovy yielded a higher tonnage.[12] By 1980, the catch had fallen from more than 3 million tons to just over 2 million, and the cod moved from second to sixth place. The cod's less-exploited cousin, the Alaska pollock, moved from third to first, the Peruvian anchovy fishery having collapsed in 1973. In 1992, Peruvian anchovy (by then recovered) and Alaskan pollock shared first and second place, while cod dropped off the list of the top 10 species. The fisheries of Atlantic Canada and Newfoundland suffered accordingly.[13] Equally important, the entire ecology supporting the bounty of the sea in the North Atlantic has been affected.[14]

A fishery can decline, in principle, for a number of reasons, including changing preferences of the fishermen, overfishing, unfavorable environmental change, or a combination of these. The evidence suggests that the rise of very large industrial fishing vessels with enormous nets and advanced facilities for finding and processing fish is the main reason for the demise of the cod fisheries since the 1970s. Serious fish removal efforts started in 1951, with the 2,600-ton *Fairtry* from Britain. The technology of the *Fairtry* incorporated insights gained during the Antarctic whale fishery, which by then had little future left.[15] For example, an enormous chute at the heck of the ship led up from the water line to the deck, to facilitate the hauling in of large nets, in a manner analogous to hauling up freshly killed whales. Likewise, processing at sea, a technology long used to advantage in harvesting whale products, was now adapted for fish. Other nations soon followed in building large long-distance floating fish factories, equipped with modern acoustic detectors developed during World War II. By the 1970s close to a thousand factory ships were operating at sea, nearly half of them with a homeport in the Soviet Union, with the next largest fleets being from Japan and Spain. Thus, the time-honored activity of harvesting fish was replaced with systematic fish removal on an enormous scale using sophisticated industrial methods.

When discussing the collapse of fisheries, the influence of climate change cannot be neglected. Historical records suggest that climate change had profound effects on the abundance of cod through the centuries. For example, off the Faroe Islands the cod fishery failed in 1625 and 1629, and the cod disappeared entirely for many years after 1675, presumably because of cooling associated with the harshest period within the Little Ice Age. Catches of cod were rather low for the entire time between 1600 and 1850, during the reign of this climatic period, which is known for having brought expanded sea ice around Iceland and abundant violent storms that discouraged sea voyages in the northern North Atlantic.[16] The climate has been warming since, especially in the North Atlantic realm.[17] Such warming has effects on the ecology of the North Atlantic, including recovery of fish stocks.[18] However, both the sense and the magnitude of such effects on the various stocks are quite uncertain. Climate change introduces a wild card into the betting game called "fisheries management."

The strain from the new methods of fish mining on the fisheries in the northwestern Atlantic soon had political consequences. In 1977 Canada proclaimed exclusive use of its coastal waters to 200 nautical miles offshore, following similar action by Iceland. Since then a 200-mile zone of exclusive economic use has been claimed by other nations bordering the sea, greatly expanding a kind of privatization of the ocean, with the coastal nations as owners. While there are positive aspects to taking ownership in terms of managing resources, the effect on ocean sciences has not been beneficial, on the whole. Neither has the potential advantage for rational management played out in a desirable manner. After annexing the coastal ocean, Canada promptly expanded its own factory fishing fleet. The reasons included misconceptions about the ocean's productivity, along with misguided economic considerations. (The prominent Canadian fisheries scientist Daniel Pauly refers to such calculations as the "march of folly."[19]

The second most important food fish of the North Atlantic realm traditionally has been the Atlantic herring; its peak catch (in 1966) exceeded that of the cod (in 1968) by 5 percent, at a tonnage of more than 4 million. The Atlantic herring *(Clupea harengus)* is a plankton-eating fish traveling in schools (like sardine and anchovy). It has a close relative in the Pacific, the Pacific herring *(C. pallasi)*. Another important member of the genus is the sprat (or brisling). Herringlike fishes, including anchovy, sardines, and pilchard, strain the water for small organisms, swimming through clouds of plankton. The fishes in this group (clupeids) use specialized comblike tools in the gill region (called gill rakers) to trap the food before it can exit with the water streaming from the oral cavity through the gills. Their food includes microscopic algae and small zooplankton. Thus, they feed at a lower level in the food chain than do the fishes in the cod family, which as adults prey on other fish. Feeding low on the food chain (that is, on small plankton) is the clue to the enormous abundances of herringlike fishes, and their correspondingly large representation in the global catch.[20] Herring became economically important when ways were found to preserve the fish at sea, using salt.

The herring has long been an important food item in northern Europe; in the Middle Ages, the wealth and power of the Hanseatic League of cities in northern Germany (with outposts in other countries including Norway) was closely tied to the herring trade. All through the nineteenth century and during much of the twentieth, the herring continued to be of great importance in the economies of the fishing nations of northern and western Europe. In their classic book on marine biology, first published in 1928, the British zoologists F. S. Russell and C. M. Yonge wrote:

> No fish in the sea are caught in such great numbers as the herring. One boat may catch over 100,000 fish a day and the total catch on such a day for Yarmouth would be 30,000,000. The great fishery gives employment to an army of workers on land, chief among which are the Scottish fisher girls. . . . They work all day cleaning and gutting the herring harvest with razor-sharp knives wielded in their dexterous hands. . . . The value of herring landed in England alone in the year 1924 was about four and a half million pounds.[21] The total value of the herring fisheries of all the nations of Northern and Western Europe was nearly ten million pounds, or a little under a quarter of the value of the whole sea fisheries.[22]

Herring occurs in great aggregations, which greatly facilitates its capture by purse-seining.[23] Thus, the evolution of schooling, which emerged in response to predation (much as the flocking in birds), is proving to be ruinous with the appearance of a predator training his sights on the entire school.[24] In recent decades the herring fishery in the North Atlantic has lost its preeminent position as one of the great fisheries in the world. In the early 1990s it was still among the top species in the total yield, but with distinctly lower tonnage than during the peak years. It has since deteriorated further.

Effective management action is economically painful. It is easier to move elsewhere after collapse of the resource—as long as an elsewhere is available. When "elsewhere" offers no solution, management issues become serious. In the case at hand, the uncertainties regarding the effects from year-to-year changes in food supply and in the mortality of juveniles led to endless and inconclusive discussions about the advisability of restricting fishing efforts. The fisheries biologist R. Bailey and the marine ecologist J. Steele[25] commented:

> Rather than considering the restriction of fishing effort, much of the scientific discussion at this time hinged on the need for controls on industrial fisheries for juvenile herring and on fishing for herring on the spawning grounds. . . . Evidence on changes in recruitment [of juvenile fish to the stock of adults] was equivocal. There was some indication of a decrease in year class strength for the North Sea as a whole, but it was uncertain whether this was simply part of the natural variability in recruitment or related to the egg production of the stock.[26]

Thus the problem: small stocks can produce sufficient eggs to make sufficient juveniles to allow the stock to replenish, provided the survival of juveniles is good. So, why restrict fishing on the stock? Nothing can be done about the survival of juveniles. In the case of predatory fish such as cod, recruitment may actually benefit from removal of adults, because the adults eat the juveniles. Such arguments are difficult to refute, especially when dynamics of stocks and of interactions between stocks are poorly understood.

Not surprisingly, therefore, the assessments concerning sustainable fisheries vary considerably, even among expert scientists. As a result, advice to regulatory agencies regarding the behavior of fish stocks is bound to be somewhat tentative. The outcome is that fisheries science cannot release the regulators from responsibility for their decisions by giving them hard facts with which to pound the table when pressed by special interests (that is, by the fish removal industry). Thus, the regulators quickly discover that doing little or nothing that would impede whatever exploitation is going on commends itself as the least painful strategy for action. Too often, this strategy results in setting "limits" near or even above the actual catch that is economically feasible.

There are many lessons to be learned from the collapse of cod and herring fisheries in the North Atlantic. Mainly, the failure to regulate access to common resources results in unsustainable removal. In moving from local fisheries to industrial clear-fishing, harvesting turns into looting. As a result of untrammeled exploitation, the resource vanishes, to the detriment of those most in need of it. Since gain and loss accrue to different players, there is no inherent control mechanism on the process of overexploitation. It seems futile, therefore, to put much hope on voluntary restraint.

A NEW PLANET

Every generation of environmental scientists—practitioners of meteorology, oceanography, geochemistry, ecology—gets to study a new planet, not only in concept but in reality as well.

The way we humans view our home planet has been changing from century to century, and lately from decade to decade. In the early Middle Ages, the planet was a disk in people's minds, and if one sailed to the edge of it, one was liable to fall off. Monsters occupied the depths of the sea, and they could emerge without warning to wreck a ship and swallow the people. On the whole, the sea was a dangerous place, well beyond human control and understanding. A semblance of control could be achieved by the outstanding seamanship of a competent captain, and by the crew doing nothing that might invite bad luck.

With the arrival first of steamships and then of motor vessels, the balance shifted, and the ocean was no longer dangerous. Perceptions changed fundamentally. Unlike for sailing ships, there is no problem in moving against even strong winds and currents when employing a diesel engine packing the power of thousands of horses. Also, a 100-ton monster whale poses no danger to a vessel that is more than 10 times heavier. On the contrary, in the nineteenth century, steam vessels began to endanger the survival of creatures in the sea that had lived there for millions of years.

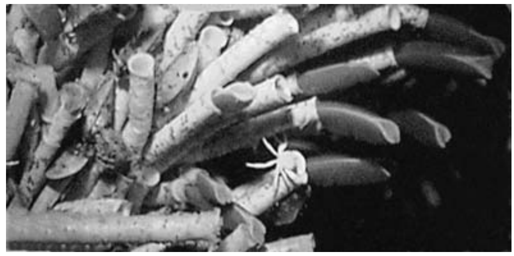

FIGURE 1.3. Gutless tube worms processing sulfurous emissions from a hot vent, with the help of symbiotic bacteria living within their bodies. Also a small crab.

The new habit, started in the eighteenth century, of systematically describing everything in the sea and labeling each organism with a latinized name, soon resulted in a growing list of species populating the sea. A growing list of species, naturally, changes the ocean in concept: each species discovered adds a new dimension to an already complex system. But extinction, whether global or regional, objectively changes the system, and ecological extinction is now commonplace.[27] What is being studied today never existed before, and the same will be true a few decades from now.

In addition, there is much about our ocean planet that has existed for millions of years, is of fundamental interest, and yet has escaped discovery until very recently. Once discovered, such previously hidden features become part of a new conception of the planet, as well.

The presence of strange and wonderful organisms along hot vents in certain places of the deep-sea floor is a case in point. It is a discovery that is well known and rightly celebrated (fig. 1.3). The discovery was made from a small fragile-looking submarine diving at great depth, and this has bestowed to it a flavor of romantic adventure. Diving in *Alvin,* the scientific minisub operated by Woods Hole Oceanographic Institution, in places where hot basalt makes new seafloor, scientists found hot springs and a host of animals surrounding them. The hot vent fauna includes giant clams, gutless tubeworms, eyeless shrimp, and bacteria processing

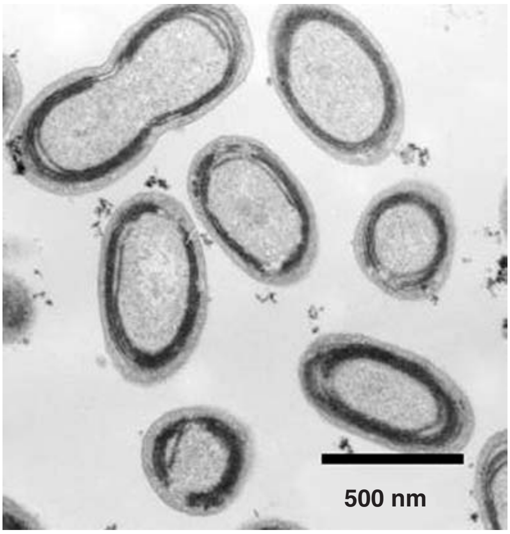

FIGURE 1.4. The smallest and the most abundant: cyanobacteria of the genus *Prochlorococcus*.

sulfur. A new type of ecology was born on that day in 1979, when these strange gardens were first seen. These communities represent an ecosystem that is built not on organisms deriving their energy from the Sun, but on bacterial activity associated with the chemical interactions between hot basalt and seawater.[28]

It is perhaps not so surprising that we should find something new and exciting in places where no one has looked before. But equally noteworthy and surely more marvelous are the instances where fundamental discoveries are made in places where everyone looked intently for nearly a century, while missing vital ingredients of the system. A striking illustration of such a major gap in knowledge, now filled, is the former obscurity of micron-sized photosynthesizing bacteria in the sea.[29] Millions are present in every liter of seawater (fig. 1.4). But the prominence of *Prochlorococcus* as the single most abundant light-consuming creature of the ocean has been discovered only quite recently. Along with the discovery that iron is a limiting nutrient whose rarity impedes production of diatoms and other light-using microbes over large areas of the sea,[30] such new insights demand rethinking of much that was taken as established textbook wisdom.

Lately, much of what we are learning about the ecosystems of the sea is tied to human impact.[31] Large-scale experiments are being performed, unwittingly, through the introduction of invasive species into estuaries and semi-enclosed seas,[32] and through overfishing and coastal pollution. In the meantime, physicists, geologists, and chemists are expanding our horizons using sophisticated instruments developed after World War II and more recently, including satellites, drilling vessels, and automatic analyzers. Modern computing makes it possible to process the enormous amounts of data that are generated with automated devices, and also to simulate complex physical and biological systems and their interactions.

These various developments certainly warrant introducing the notion of a "new planet." But the notion arises especially forcefully in the context of the "great geophysical experiment"[33] that is being performed on the home planet. It is the large-scale release of greenhouse gases to the atmosphere, which physically changes the planet from one decade to the next. As the permafrost melts around the Arctic and the sea ice retreats, a new and unfamiliar planet emerges, for people and for polar bears.[34] In the warmer regions of the global ocean, as well, many changes are afoot that have been ascribed to various types of human impact. One of these is the deterioration of coral reefs in the Caribbean and also elsewhere. To recognize such changes and develop the appropriate policy is a major challenge that calls not just for more science but also for whole-scale mobilization of public awareness.[35]

There was a time, in the 1950s and 1960s, when being a student at Scripps Institution of Oceanography included the opportunity to collect dinner from just outside the breakers, including lobster, abalone, and big territorial fish in the kelp forests. Today, finding any of these within the hour would be quite unlikely, and taking them would be against the law. Things have changed—today's students discover a different ocean. Compared with the ocean of half a century ago, many large vertebrate and invertebrate species are ecologically extinct, that is, they no longer play a role in the ecosystems of the sea. Scripps ecologist Paul Dayton refers to "ghost species," whose erstwhile existence provides explanations for the ecology of a residual community of organisms, in the kelp forests offshore of Scripps and elsewhere along the coast of California.[36] The entire ocean, as it were, is now full of such ghosts, from the once whale-rich seas around the Antarctic and Spitsbergen to the traditional fishing grounds off Newfoundland, and to the Caribbean Sea that once teemed with turtles. To understand the functioning of present ecosystems, we must take into account the response of each system to the removal of key players within it.

Sharks and turtles are well on the way to the realm of ghosts in many regions of former abundance. Both sharks and marine turtles have been part of the ocean's scenery and ecology for hundreds of millions of years—sharks since before the Devonian (see the appendix 4 for a geologic time scale). Marine turtles are offspring from terrestrial reptiles that evolved during the Devonian.[37] The turtles have seen the great marine saurians come and go—ichthyosaurs, plesiosaurs, and mosasaurs. They survived where others failed, and accommodated themselves to the rise of the marine mammals in the last 40 million years. But turtles and sharks are now witnessing the arrival of a new planet with new rules for survival set by the reigning superpredator: humans. The rules are changing faster than ever before. Traditional rates of adaptation cannot cope with such rapid change.

Scripps oceanographer Jeremy Jackson, who was diving on Caribbean reefs some 40 years ago, recalls the exquisite richness of these ecosystems. Even the best-preserved reefs, according to Jackson, have been greatly impacted by human activities including overfishing and pollution. Most strikingly, the large species of branching coral that dominated shallow reefs for at least half a million years have declined dramatically since the 1980s.[38] Thus, there is now no way to explore the natural ecosystem functioning of Caribbean reefs. What can be discovered is the additional human impact on an already impacted system that is rapidly changing.

The overexploitation of the oceans has its origin in the doctrine of the "freedom of the seas," which emerged with the discovery of the World Ocean and its use for trade and fishing.[39] This freedom has been considerably curtailed since, especially by the 200-mile extensions of jurisdiction by coastal nations in the 1970s and 1980s. Yet most of the open ocean remains in the state of an unregulated commons. The late Garrett Hardin, University of California economist and biologist, argued that the exploitation of an unregulated commons by entirely rational parties inevitably leads to collapse of the resource.[40]

Hardin's prediction is well supported by the recent collapse of cod and herring fisheries. An additional dynamic, beyond the "tragedy of the commons" paradigm of Hardin, is the "march of folly" process emphasized by Daniel Pauly of the University of British Columbia. Pauly suggests that ruinous policies pursued by government agencies ensured a subsidy-driven destruction of successive fisheries, with considerable impact on all marine ecosystems.

Marine biologists are not the only ocean scientists who are discovering a new ocean every decade and, indeed, every year. All oceanographers do. The ocean itself—its surface temperature, its currents, the winds driving its waves—is changing all the time. Much of this change is natural, but a substantial portion, not known in detail, is now man-made.[41] Humans have become a major player among the forces of nature on the face of the planet. This fact was not an issue in the first half of the twentieth century but started to emerge in the 1950s and 1960s, mainly among geochemists.[42]

Exciting discoveries have been made over the last several decades regarding various types of oscillations within the climate of the sea. These affect the global distribution patterns of warm and cold water at the surface of the sea, and the delivery of nutrients to surface waters from waters below. The El Niño phenomenon, the Pacific Decadal Oscillation, and the North

Atlantic Oscillation are prime examples of substantial variations in the workings of wind and weather and currents, in various parts of the ocean, and have implications for droughts and floods on adjacent continents.[43]

Just as we discover these patterns, they are already being modified in poorly understood ways by the effects of global warming. In fact, it is conceptually difficult to separate natural variation from human-induced climate change. This difficulty will not go away with additional research. The reason is that the range of natural variation—poorly known in the first place—cannot emerge from studying recent climate variation, because natural variation is no longer the only player in climate change. The implication for marine biology is that the ocean's variability generates ecologic variability, which masks the human impact. Under these conditions, the benefits of management are difficult to assess.

Whenever the benefits of management actions are hard to recognize, there is no ready defense against those who favor business as usual, claiming that the economic costs of regulating the commons are excessive. This is why Hardin's theoretical treatment of the problem is so important. On a global scale, similarly, lack of proof of benefit of restraint may be anticipated in the context of the climate change conundrum. That is why computation of possible and probable changes in the behavior of ocean and atmosphere for different scenarios has become a crucial tool in climate research. The skills needed to produce relevant models have been growing exponentially, based on a rapid expansion of computing power, of raw observational data, and of the understanding of the physics of climate. Unfortunately, the knowledge needed to appreciate the nature of the results of computations is not readily imparted or acquired.[44]

Despite all the expansion of the knowledge bases in recent years, when measured against the complexities of today's rapid global change, our understanding of planetary physics and biology is still woefully inadequate, and this is true also for the economics and the politics of the environment. Our lack of knowledge is especially vexing in regard to the ongoing change in the ocean, the most massive part of the climate system, and the largest habitat for life, hosting the most ancient life-forms. Nevertheless, we must attempt to gain a sense of the nature of the sea and its role in the ongoing changes. If we ignore the ocean, we cannot be good stewards of the Earth.

DISCOVERY OF THE WORLD OCEAN

The Greek tradition, which is the cradle of modern science, held a view of the world dominated by enormous landmasses (Eurasia and Africa) surrounding a smallish sea, the appropriately named Mediterranean. This view changed dramatically 500 years ago with the discovery of the Atlantic, Indian, and Pacific oceans, discoveries that made islands out of continents.[45]

In the western tradition, the single most important step in discovering the World Ocean was the daring expedition into the unknown by three modest-size vessels, the *Santa Maria*, the *Niña*, and the *Pinta*, which set out from Spain to discover a westward passage to India, 500 years ago. When the Genoese explorer and adventurer Christopher Columbus[46] made landfall in the Bahamas on that fateful October day in 1492, he fell on his knees to kiss the ground and give thanks to God. He had good reason. For quite some days many of his men had been ready to throw him overboard, to end the horrifying voyage into the uncharted void. In the nick of time, the cannon had gone off on the *Pinta*, announcing the sighting of land. "What will we get to see?" Columbus wrote into his logbook. "Marble bridges? Golden-roofed temples? Spice gardens? People like us, or some strange race of giants? Did we reach an island or Japan itself?"

Spice gardens, of course, would have been better than even pure gold. What they found were harmless natives, "mighty forests," a clear brook, and "enormous unknown fruits"—but no signs of wealth. Columbus named the island that saved him from mutiny San Salvador, made contact with the friendly "Indians," claimed their land for the Spanish Crown, and promptly started looking for Japan.

One might argue whether Columbus had in fact discovered America on that day. There is, however, little question that he and his disgruntled crew manning the *Santa Maria*, the *Niña*, and the *Pinta* had discovered the Atlantic, crossing it where it is widest, and where the trade winds are most favorable for the task. As far as discovering America, we might, along with many historians, give priority to Leif Ericsson, who made landfalls on Baffin Island (in AD 1001), on Labrador, and on Newfoundland (Vinland). However, Leif's exploits did not result in maps or useful reports for later explorers. His voyage traversed the Atlantic where it is narrowest.

What Columbus did by crossing the Atlantic Ocean at its widest, not once but repeatedly, was to bring that body of water to the attention of the western world. Entirely new possibilities for trade routes opened, and other explorers soon followed Columbus's lead. One of these was Amerigo Vespucci (1451–1512), a Florentine merchant who sailed in the service of Spain and of Portugal. He explored the South American coast and realized that this was not Asia, but a "new world." By 1507 his name was used to refer to the New World. Its inhabitants, however, remained "Indians," and the islands first seen by Columbus the "West Indies"—that is, the Indies found by sailing west.

Columbus thought he had crossed the World Ocean, having reached islands he deemed close to India and Japan. But the awesome truth became known a few years later (in 1520) when Ferdinand Magellan (ca.1480–1521) rounded Patagonia through the straits that now carry his name, and crossed the ocean that Balboa had seen from the shores of Panama—an ocean more immense by far than the Atlantic. A new hemisphere—one covered by water—had to be added to the globe. Mediterranean-centered geography was finally scrapped. Within three decades, Columbus's landfall in the Bahamas, Vasco da Gama's voyage into the Indian Ocean around the tip of Africa,[47] and especially Magellan's crossing of the Pacific had transformed the world.[48] "Planet Earth," it turned out, really is "Planet Ocean." Today, this insight is commonplace. As our satellites view the Earth from a position above the Pacific, we see almost nothing but water.

Right into the eighteenth century, the Mediterranean view of the world, that land encircles the sea, informed excursions into the unknown. Thus, cartographers extended Ptolemy's hypothetical southern continent all the way across the southern Pacific.[49] This enormous Terra Australis finally evaporated when the great navigator and explorer Captain James Cook (1728–1779) tried to find it. During three major expeditions (1768–1771, 1772–1775, and 1776–1780), he established the boundaries of the Pacific, mapped the coast of Australia, and put a great number of islands on the map, including Hawaii and New Caledonia. A series of southward forays took him and his crew into the furious and icy storms of the regions around Antarctica, and even beyond the polar circle. Within one decade of intense exploration, Cook sailed the Terra Australis off the world map and put the Southern Ocean in its place. (He did leave room for Antarctica.)

In the process of discovering the Southern Ocean, Cook noted mammal life of a density never seen before. Soon after, large-scale slaughter by sealers and whalers would considerably reduce that abundance. Such is the fate of explorers; they set in motion events far beyond their vision and intent.

After charting the western coast of North America, James Cook had, essentially, completed the world map. He had, moreover, done so in a style that sets him sharply apart from most previous explorers, seekers of riches who hazarded their ships and crews and had no regard whatsoever for the people they came in contact with. Cook's foremost concern was the safety and health of his men, and he came in peace wherever he made landfall. His sad awareness of the changes he was bringing to native peoples of the islands he discovered and revisited ("we introduce among them wants and perhaps diseases which they never before knew") illustrates his compassionate humanity.[50]

Nevertheless, Cook served king and country. His voyages set the stage for the remarkable global expansion of British sea power, which culminated in the British Empire spanning the globe. The careful and comprehensive mapping of seaways and shores on a global scale was a high priority from the very beginning. Having fewer ships and cannons than the Spanish, the Portuguese, the Dutch, and even the French, England trusted to superior seamanship, and better science. Precision chronometry (to determine longitude) and scurvy-fighting foodstuffs (lemons, sauerkraut) have been part of the naval toolkit ever since Cook. The chronometry, combined with astronomical tables, provided for precise positioning. The tables were the responsibility of the Astronomer Royal in Greenwich, near London. He has long been relieved of that duty: the officer on the bridge now uses satellite positioning and does not need his advice.[51]

Only the polar regions remained poorly known into the nineteenth century. The many efforts of earlier explorers to find a northeast or a northwest passage from the Atlantic to the Pacific (to avoid Spanish and Portuguese galleons interdicting trade) were unsuccessful. Eventually it became clear that to realize any passage in the north, one had to sail into the Arctic Ocean, along a narrow ice-free zone in summer. Most arctic summers were short in the period between 1600 and 1850 AD, and winters severe. The period is referred to as the Little Ice Age and is the coldest on record for the last 8,000 years.

The last great ocean basin to be discovered was the Arctic Ocean. In June of 1883, Nansen left Norway in the *Fram*, built with the support of the Norwegian parliament and many individuals, including the King of Norway.[52] The vessel was built to withstand the crushing pressure from pack ice, her hull specially strengthened and shaped. Nansen had studied the ice drift and concluded that it moved from off Siberia across the pole to between Greenland and Spitsbergen (today's Fram Strait). He sailed the *Fram* to eastern Siberia and let her be frozen in (by 27 September). She stayed that way for the next 35 months. Slowly she drifted toward the pole. However, when it became clear she would miss the pole by some considerable distance, Nansen and his companion F. Hjalmar Johansen set out to reach the pole by sled. They had to turn back 268 miles from the pole. They wintered in a stone hut on the coast of Franz Josef Land, in the Barents Sea. A British exploring expedition picked them up and returned them to Norway. The *Fram* arrived late in summer in 1896, one week after Nansen. The drift of the *Fram* established the Arctic Ocean as a deep-sea basin centered on the North Pole. With this feat, the map of the World Ocean was complete.

EARLY OCEANOGRAPHY AND THE *CHALLENGER* EXPEDITION

The history of oceanography is conveniently divided into "early" and "modern" by the British *Challenger* Expedition (1872–1876). The distinction was appropriate till into the 1960s. Today's postmodern period is characterized by massive data collection using satellites and automated observing platforms (some floating, others swimming), by precision measurement of highly diluted trace substances in the sea, by the application of molecular methods to marine biology, and by ubiquitous and massive computing power. The reason to look at the results of the *Challenger* Expedition today is not so much for the data it still provides, but for the fact that this famous world-circling voyage established many of the basic concepts about the ocean: its overall depth, its generally frigid temperature below a thin warm surface layer, its almost invariant salinity, the abundance of organisms in surface waters and at depth, and the nature of the bottom sediments.

It is interesting to speculate why the largest expedition of the nineteenth century, the U.S. Exploring Expedition (1838–1842) is not credited with laying the foundations for modern oceanography. The Exploring Expedition involved six ships and 346 men, sent to the Pacific by the U.S. Navy. Unfortunately, the commander of the expedition, Lieutenant Charles Wilkes, was not suited as a leader of a collaborative scientific venture, a fact of which he was unaware.[53] More importantly, the tasks of the "Ex. Ex.," as it was commonly referred to, were focused on charting islands and the shores of Antarctica (Wilkes Land), rather than on exploring the deep ocean. Thus, by consensus, the founding feat of modern oceanography is the circumnavigation by the British vessel HMS *Challenger*.

Of course, ocean sciences existed well before that, largely for the benefit of navigation. Benjamin Franklin (1706–1790) published the first map of the Gulf Stream (in 1769), in an effort to help speed ships between England and America. Commander Matthew Fontaine Maury (1806–1873) expanded this task to a global scale. He was the first genuine armchair oceanographer engaged in data processing. Information from the logbook entries from merchant and whaling ships and from navy vessels served him to make charts of winds and currents. These charts delighted the navigators of the time, and his book *Physical Geography of the Sea*, first published in 1855, sold well for decades, in many editions. Maury's legacy lives on in the maps of currents found in every ocean textbook. Such maps offer a pattern of prevalent conditions; whether one finds a current running where it is shown, on any given day, is another matter.

In the nineteenth century, marine biological research was greatly advanced by the British naturalist Edward Forbes (1815–1854), who established that bottom-living organisms tend to prefer their own depth zones. Hence, as one descends deeper into the water along a slope, one would collect different types of animals. Noting that the number of animals in dredges decreased rapidly with depth, and extrapolating to depths with little or no information, Forbes proposed an "azoic zone" in the deepest parts of the ocean, where, he thought, high pressure and low temperature were hostile to life. One of the tasks of the *Challenger* Expedition was to test this idea. Forbes's depth zone scheme proved invaluable. But his notion about a lifeless abyss turned out to be wrong. Ironically, he is more often cited for his one wrong idea than for his many good ones, a fate he shares with the distinguished French naturalist Jean-Baptiste Lamarck (1744–1829), who proposed evolution before Darwin did but failed in defining the mechanism.

Another pre-*Challenger* scientist whose work remains very influential is Christian Gottfried Ehrenberg (1795–1876), professor of medicine in Berlin. He observed that many of the marine limestone layers on land are composed of the remains of microscopic organisms. To find such organisms in the present ocean, he filtered seawater through fine gauze. He established that most of the life in the ocean is of microscopic size—a fact that now dominates our understanding of the productivity of the sea. His work apparently greatly influenced John Murray (1841–1914), the young naturalist of the *Challenger* Expedition, who subsequently pursued plankton studies with outstanding success.

In the years before the C*hallenger* set out on her circumnavigation, pressing new questions had arisen after the publication of Charles Darwin's book *The Origin of Species* (1859). Debate now focused on the evolution of life, which gave meaning to taxonomy and biogeography in ways not appreciated earlier. Darwin's theory of natural selection established biology as a field ranking intellectually with the established sciences of physics and chemistry and beyond, as it impacted the search for meaning in human existence.

The *Challenger* Expedition was the first sent out to satisfy curiosity about the ocean, rather than pursuing economic or military needs.[54] The expedition was carefully planned and prepared by highly motivated scientists and was funded for postcruise studies, for sample handling, and for publication. It was to establish a firm basis for accepting or rejecting many of the tentative ideas put forward previously in the early days of ocean study. Its sampling protocol provided a template for subsequent major expeditions. One important focus was a systematic survey of deep-living organisms in the sea. Would there be an azoic zone as proposed by Forbes? Would there be "living fossils," that is, creatures hitherto only known from their remains in ancient rocks? Darwin's influence was palpable.

The HMS *Challenger* was a substantial vessel, a three-masted sailing corvette with steam engines, a 2,300-ton displacement, and a length of 200 feet; it had been built in 1858. The ship, with a complement of about 240 men, was at sea for 41 months, sailing almost 69,000 nautical miles—the equivalent of three times around the world. During these more than three years, its crew was measuring temperatures, taking water samples and bottom samples, and building up an enormous collection of the organisms of the open ocean. After the *Challenger* returned, scientists were occupied for years working up the samples and publishing the results, in 50 thick volumes. These were edited by John Murray and published from 1885 to 1895. Many of them are still regularly used and referred to in the scientific literature.

The work on the *Challenger* was hard and tedious. There were no cranes, as on today's vessels, to do the lifting of equipment. Every depth determination necessitated letting out a hemp rope and bringing it back by a man-powered winch. Lowering a dredge to capture animals or rocks from the seafloor took hours. The work came to be called "drudging" by the crew, though the dredge was retrieved by a donkey engine. But even the toiling sailors took interest in the samples coming on deck, it is reported, at least in the early phase of the expedition.

At every temperature station the great difference between surface and bottom water was confirmed. Measurements showed that chilly temperatures dominate the water column: only the uppermost layer of the ocean is warm (fig. 1.5). William Benjamin Carpenter (1813–1885), one of the organizers of the expedition, had suggested that the entire ocean might prove to be filled with frigid waters from polar areas. He was right. (It is said that the first application of the new insight about a cold ocean was the cooling of wine bottles by suspending them below the ship on sufficiently long lines. Discoveries have applications!)

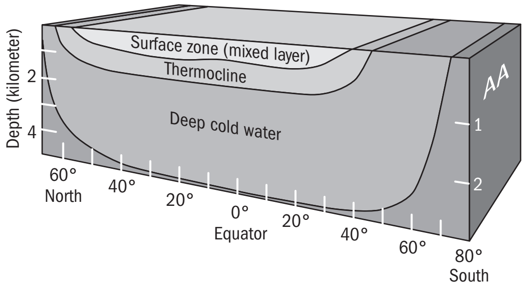

FIGURE 1.5. The ocean is filled with cold water. A thin warm layer covers it, except in high latitudes. Cold and warm water are separated by a transition zone, the "thermocline."

Patterns of seafloor topography started to emerge from the depth soundings. Away from the continents and islands, the ocean was consistently very deep, around 4,000 meters, with a common range between 3,000 meters and 5,500 meters. Interestingly, relatively shallow depths seemed to be typical for the central Atlantic. Eventually, when plotting all soundings and considering a slight difference in temperature of abyssal waters in the eastern and western Atlantic, it was realized that the central Atlantic region rises above the general depth. A deep trough exists on either side of the rise, so that there are two basins in the Atlantic, rather than one. The first step toward the discovery of the Mid-Atlantic Ridge had been taken.

The sounding lead at the end of the wire was constructed so as to retain some of the bottom mud it struck. The majority of samples consisted of the familiar vanilla-colored ooze, found in the North Atlantic by earlier expeditions. The ooze is full of the tiny shells of single-celled animals called foraminifers (fig. 1.6). Their remains were well known from the Cretaceous chalk deposits on the shores of southern England. It was thought by scientists of the time that these organisms had populated the seafloor and left their shells in the bottom sediment upon death. Could the deep-sea floor be teeming with life? Well, in fact the teeming is of a modest sort: there is not much food available in the vast deserts of the abyss. John Murray solved the puzzle. He showed, using a net for sampling surface waters, that the shells came

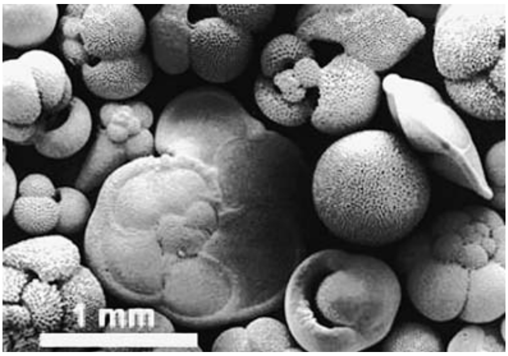

FIGURE 1.6. Foraminiferal shells extracted from deep-sea sediments. The size is that of sand grains. The shells within the sediment are a means by which the ocean remembers its history.

from the foraminifers in the surface waters of the ocean, where they live together with the rest of the plankton. Murray explained that the shells of the foraminifers fall to the seafloor after death of the animal within.[55] Many decades later, the shells became the chief means by which to reconstruct the history of the ocean.

Soundings from very great depths brought samples not of light gray foraminifer ooze, but of red clay, an extremely fine soil deposit with a dark reddish brown color. Where did that come from? Wind-blown dust? Fine suspended matter brought by rivers? Weathering of volcanic ashes? The scientists had a great time guessing and arguing. They could not see the particles making up the red clay, which are too small for study by a standard microscope. X-ray analysis (which allows study of clay minerals) was to come 60 years later. In fact, it turns out that all of the sources considered by the scientists at the time do contribute to red clay in different proportions, depending upon the region studied. The reddish color is owing to the presence of iron oxide, testimony to the abundance of oxygen in a cold ocean.

Within the very first months of the *Challenger* Expedition, the dredge brought up organic structures that biologist Rudolf von Willemoes-Suhm (1847–1875) (who died later in the voyage) identified as tube-building worms. The depth was almost 3,000 fathoms—well over 5,000 meters. Living creatures from the abyss! After some more such hauls Forbes's concept of an azoic zone was finished. Right there, before the very eyes of the crew (who wondered, one suspects, why the scientists became so excited about some worms) the azoic zone attained the unenviable status of one of the curious notions in the junkyard of science (fig. 1.7).

The scientists of the *Challenger* also discovered one of the deepest places in the Atlantic: the Puerto Rico Trench, and one of the deepest places in the Pacific: the Challenger Deep in the Mariana Trench, near Guam. (Serendipity works, on occasion, even at sea.) In each case, thermometers fractured at the end of the line, as pressures kept mounting to enormous values. What could possibly be the origin of these great chasms? The time for this question had not yet come. Not in their most speculative moods did the thought occur to these explorers that here the seafloor might move downward and disappear into the interior of the Earth.

The *Challenger* Expedition still ranks as the most successful venture of its kind. Acclaim was great for the returning scientists, albeit not precisely unanimous. In this case, however, any "taxpayer's concern" was unjustified. In connection with working up the *Challenger* materials, John Murray came across some phosphatic samples from Christmas Island (in the Line Islands of the central Pacific). Subsequently, the Crown annexed the phosphate-bearing island, and Murray obtained a concession to work the deposits. The taxes from this venture made up for the expedition costs. Also, the income allowed Murray to finance much additional oceanographic research on his own. (Murray's achievement remains inspiring but unfortunately unique.)

The rich harvest in terms of marine biology showed that the organisms everywhere in the sea are thoroughly modern. The scientists studying the material gathered by the *Challenger* could not know that the deep ocean used to be warm through much of geologic time and turned cold only beginning 40 million years ago. Thus, there is every reason that the deep-sea fauna should be geologically young. But these discoveries came a century later.

FIGURE 1.7. Creatures (sea cucumber, octopod) brought up by the dredge on the *Challenger*, showing there is life at great depth.

POST-*CHALLENGER* EXPEDITIONS

The glorious example of the *Challenger* Expedition soon invited replication and follow-up. Among the most important of these were Nansen's *Fram* Expedition (1893–1896), referred to earlier, and a number of expeditions directed by Albert I, Prince of Monaco, focused on marine biology. Many followed in the first half of the twentieth century, for example, the German *Meteor* Expedition (1925–1927), a series of British expeditions to Antarctica (*Discovery* I and II, 1924–1934), the Swedish *Albatross* Expedition (1947–1948), and the Danish *Galathea* Expedition (1950–1952). Scripps joined the spirit of the time by launching the MidPac Expedition to the Mid-Pacific Mountains (1950) and the Capricorn Expedition (1952–1953) to the western Pacific.

Through the *Fram* Expedition, Nansen discovered that the Arctic is a deep, wide ocean rather than a shallow sea studded with islands. Also, the two-layer structure of this ocean, with a brackish layer on top of normal seawater filling the basin, was firmly established. The expeditions of Albert I, near the end of the nineteenth century, documented the rich diversity of sea creatures within the North Atlantic, with some emphasis on the poorly known fauna below the sunlit zone.

The *Meteor* Expedition (1925–1927) was the first thoroughly modern oceanographic expedition, laid out in a grid pattern. It systematically surveyed the Atlantic Ocean in three dimensions, collecting information on physical and chemical properties, plankton and bottom life, seafloor morphology, and sedimentation. The German government financed this expedition at a time of severe economic depression. Possibly, the supersalesmanship of the physical chemist Fritz Haber played a role. (Haber was famous for showing how to make money from air, by generating nitrogen fertilizer.) He proposed that there is a lot of gold in the ocean, which was exactly what the treasury needed during the aftermath of World War I.[56]

For 27 months the *Meteor* crisscrossed the Atlantic between latitude 15° N and the ice limit to the south (64° S), logging a distance of 125,000 kilometers, about the same as the HMS *Challenger* did. A newly developed method, quasi-continuous echo-sounding, showed that the Mid-Atlantic Rise discovered by the *Challenger* is a rugged mountain system, easily exceeding the Alps in size (see chapter 11).

The measurements of temperature and salinity at depth (by Nansen Bottle) showed a complicated layered structure of the water. Closest to the bottom there is extremely cold water, coming from the Antarctic; then there is a layer of rather more saline water, not quite so cold, which comes from sources around Greenland. Other layers, from less-frigid source regions, follow upward, and finally there is a top layer of warm tropical or subtropical waters.

Measurements of the most important dissolved gases—oxygen and carbon dioxide—showed that the ocean breathes like a living organism. Oxygen enters the system at high latitudes, with sinking cold water. It is then used up by decay and respiration at depth, resulting in production of carbon dioxide. In the process, nitrate and phosphate are released to the water, from the decaying organic matter. The discoveries regarding the marine carbon cycle and the associated nutrient cycles contributed to the understanding of the productivity patterns of the sea. The central subtropical regions were recognized as deserts bearing mainly minute organisms ill suited to feed fish. Coastal oceans, in contrast, showed high nutrient contents in surface waters, supporting diatoms, the "grass of the sea." Where such "grass" is abundant, grazers can thrive and feed the larger predators including seabirds and mammals.

At the time of the *Meteor* Expedition, the British started a series of cruises into Antarctic waters (1924–1934), with *Discovery* I and *Discovery* II, to investigate physical oceanography and marine biology, largely in the context of whaling, which had become an important industry. The expeditions established the high seasonal productivity of the waters of the Antarctic and worked out the food chain of the giant baleen whales (which is based on diatoms and krill), as well as patterns of migration. These expeditions also determined the structure of the circumpolar ocean, which turned out to be highly complex. Stripped to the essentials, we may think of the Southern Ocean as a ring of water, poorly stratified, running from west to east around the Antarctic and mixing vertically right to the bottom. This ring serves as a mixing station for the waters of the World Ocean and, thereby, governs the rate of deep circulation. Different types of water enter it, and a more or less uniform mixture leaves it, at various places and depths. This mixing process keeps the deepwater masses of the several ocean basins at close to average values with regard to temperature and salinity.

The Swedish *Albatross* Expedition (1947–1948) and the Danish *Galathea* Expedition (1950–1952) were the last significant voyages of the traditional globe-encircling type. The *Albatross* logged 70,000 kilometers in 15 months. Its chief contribution was a large number of long sediment cores from the tropical zones of all ocean basins, including the Red Sea and the Mediterranean. The analysis of these cores showed clearly that the last 500,000 years were characterized by a regular succession of ice ages separated by warm periods. Our own time, for the last 10,000 years, is in one of those warm intervals.

The chief contribution of the *Galathea* Expedition was to provide the first survey toward establishing the global distribution of plankton productivity. The biologist E. Steemann Nielsen did the work, using a novel method he had invented, based on radiocarbon. He collected, in a glass container, a sample of the microscopic algae in the plankton. He then added a solution of radioactive bicarbonate. As the organisms grew, while exposed to light, they would take up some of the radioactive carbon and become radioactive themselves. By measuring their radioactivity, Nielsen could determine their rate of growth. He found that this rate varies greatly between different regions of the ocean, with upwelling areas having the highest rates, and warm tropical waters having the lowest, excepting the regions of equatorial upwelling.

Large expeditions provided for quantum steps in the progress of oceanographic science in the first half of the twentieth century—but they are not the whole story. Many institutions throughout the world carried out regional researches that provided valuable information about currents, tides, seasonal changes in productivity, and the distribution and natural history of marine organisms. In the 1930s, there were two sizeable ocean-research centers in the United States, Scripps Institution of Oceanography, in La Jolla (San Diego, California), and Woods Hole Oceanographic Institute, in Massachusetts. Woods Hole, established in 1930, owned the 142-foot ketch *Atlantis,* which explored the Gulf Stream, among other things, discovering the nature of this largest of currents in the Atlantic.

Scripps had a smaller vessel, the 64-foot fishing vessel *Scripps.* Unfortunately, it burned at the dock in November 1936, shortly after the meteorologist and oceanographer Harald U. Sverdrup arrived from Norway to lead the institution. Within a year, Scripps was mobile again, thanks to a generous gift by Robert P. Scripps, who donated a 100-foot auxiliary schooner, which was renamed *E. W. Scripps* in honor of his father.[57] While the *Atlantic* studied the Gulf Stream, the Caribbean, and the Gulf of Mexico, the *E. W. Scripps* worked the California Current, the California Borderland, and the Gulf of California.[58]

Some of the ventures of the *E. W. Scripps* may serve as an example of the type of regional work in progress at the time in many parts of the world. The first long-distance expedition mounted at Scripps was to the Gulf of California, for two months in 1939. The primary objective was to study the currents and water structure of the Gulf and the relationships with the adjoining Pacific Ocean. Water samples and bottom samples were taken at more than 50 stations. A grid of 2,500 soundings showed unexpected ridges, basins, and troughs in the southern part of the Gulf. Surface samples demonstrated that the well-known intermittent red color of this region's water (which invited the label of "Vermilion Sea") is due to certain types of plankton. The waters were rich in organisms as a result of upwelling.

Sediments retrieved from below upwelling areas smelled of hydrogen sulfide. It turned out that the high supply of organic matter to the seafloor overwhelms the oxygen supply, stripping the bottom water of oxygen and making it anaerobic. At that point, bacterial decay proceeds by using oxygen from sulfate to burn the carbon of the organic matter. One result of tearing the sulfate apart is the production of poisonous hydrogen sulfide. The finely laminated shale in marine deposits of hundreds of millions of years of geologic history now had a simple explanation: accumulation in anaerobic conditions, with hydrogen sulfide keeping out burrowing organisms. The mother rocks for petroleum typically consist of such shale.

Scripps geologist Roger R. Revelle was especially interested in these processes and obtained funds from the Geological Society of America to carry out additional work in the area, in a cruise lasting 78 days in the late fall of 1940, on the same ship. The geologist Francis P. Shepard joined him on that cruise, continuing his studies on submarine canyons (which he had begun along the California coast), and bringing along his graduate students Robert S. Dietz and Kenneth O. Emery. The proceedings for this cruise were published after the war (in 1950).[59]

The work by individual institutions—as opposed to national expeditions—became ever more important as a result of World War II. The emphasis shifted from large-scale exploration to systematic surveying, from mapping of distributions to studying processes. Oceanographers were sought out for their expertise, and oceanography became a profession. When German submarines threatened the support lines of the Allies across the Atlantic, the government was forced to develop means to combat this threat. The physics of the ocean suddenly became a prime topic of study, notably the physics of sound transmission.

Waves, and especially the breaking of waves along shores, proved to be important in planning the landing of assault troops. The success of the invasions of Sicily and Normandy by the Allies owed much to the wave forecasts by professional oceanographers back in California. Right after the war, the atomic tests on Bikini Atoll were monitored (at some risk) by a large contingent of oceanographers. Effects of explosions on waves and on the regional ecology, and the dispersion of radioactive materials were the subjects of study.

Following this period of military engagement, the U.S. Navy remembered how useful the ocean sciences had been and remained in partnership with the oceanographic institutions, supporting their work. Several new institutions were established. The war also had brought a quantum jump in instrumentation, especially electronics. Thus, in the 1950s, sophisticated survey equipment came into use, such as seismic profiler systems that send sound to below the seafloor and record the echoes, and towed magnetometers that detect the slightest change in the strength of the magnetic field. The measurements made with such instruments led to a major revolution in the Earth sciences in the 1960s. Deep-sea drilling and satellite oceanography provide additional examples of the continuing advances in technology that now shape the course of the ocean sciences.

Concern about the economics of fisheries and, more recently, about pollution, as well as a strong and growing interest in weather and climate prediction, have contributed to the rapid expansion of oceanographic facilities in the last several decades. These concerns motivate many of the large interinstitutional and international projects that are at the hub of oceanographic activities today. In fact, the problems arising in the context of global warming require integration not just across institutes and nations, but across disciplines, notably climatology, biogeochemistry, atmospheric chemistry, bacteriology, all aspects of ecology, and geologic history. Oceanography, along with the other Earth sciences, is converging toward Earth system science. It may seem like a long voyage, but it took only a little over a century, from the spotty measurements of the *Challenger* to the satellite surveys of today.

SCRIPPS: EVOLUTION OF A MARINE RESEARCH CENTER

The history of Scripps Institution of Oceanography nicely reflects the general major trends in oceanographic research in the past 100 years. Research proceeded from marine biological work concerned with the study of nearshore organisms, to worldwide operations investigating the geophysics of the seafloor and the life-support systems of the planet.

Scripps Institution of Oceanography is located some 10 miles north of the Navy harbor of San Diego, where its research vessels are berthed when in port. The campus enjoys a pleasant setting just north of the palm-studded seashore village of La Jolla. Scripps vies with Woods Hole Oceanographic Institution for the status of most distinguished oceanic research center in the world. Its research, like that of its sister institute on the East Coast, is directed mainly toward the deep sea and global problems, without, however, neglecting the coastal ocean and the seashore. Scripps is part of the University of California at San Diego, one of the top research universities in the nation, founded in the early 1960s.

Researchers and students at Scripps (more than a thousand scientists) investigate a broad sweep of problems in the ocean sciences and ocean engineering, as well as in Earth sciences and atmospheric sciences. Scripps's world-renowned library holds an enormous store of knowledge about the ocean and the planet in general. Much of the more recently acquired knowledge is too vast to be printed: it is stored electronically for downloading into the computers of specialists using the data.

The institution started as a marine biology station for summer fieldwork, with the modest goal of making a biological survey of the coast of California. More ambitious goals soon involved the California Current, the Gulf of California, and finally the entire Pacific basin, the Indian Ocean, and the World Ocean. Today, ocean studies are but one part of global studies on Earth systems, which include the seas, the air, the land, and the great ice fields at the poles. These days, Scripps scientists (and their colleagues at similar institutions) are members of national and international projects involving deep-sea circulation, ocean-air interaction, satellite-based measurements of gravity and productivity, as well as all aspects of the carbon cycle on Earth.

More than a century ago, in 1903, Berkeley's zoology professor William Emerson Ritter (1856–1944) established the Marine Biological Association of San Diego, with the help of newspaper magnate E. W. Scripps and his sister Ellen Browning Scripps, and physicians Fred and Charlotte Baker, as well as other prominent citizens of San Diego.[60] Ritter, eager to start exploring the sea within the constraints of available resources, put forward a vision to make a biological survey of the Pacific Ocean adjacent to the coast of California.

The investigation of the coastal zone and its organisms, of course, had been the first step in ocean exploration for a number of similar stations on the shores of Europe. E. W. Scripps found cheap land for the necessary facilities north of La Jolla, about an hour's walk from the village. By 1910 the marine terrace north of La Jolla bore a two-story concrete laboratory, and a graded road provided access. Ellen Browning Scripps (1836–1932) promised a generous endowment.[61] When the University of California accepted the property in 1912, the regents acknowledged the primary donors to the laboratory with the name "Scripps Institution for Biological Research.[62]

By then, in the San Diego region, Ritter and his colleagues had collected 862 species of marine organisms and described 328 of them as new. Aware of the vastness of the ocean and the modest means of his fledgling institution, Ritter wrote wistfully about the infinite complexity of cause and law in the sea. Ritter was a great admirer of Darwin and diligently pursued the implications of adaptation through evolution, emphasizing the importance of habitat and environment in attempting to understand organisms.[63] His specific research interests centered on tunicates and acorn worms. Ritter took evolution to be the great unifying theory for all manifestations of life, including human behavior. It is perhaps not by chance that Ritter's favorite objects of study, the acorn worms, are among the most primitive of humankind's own phylum, the chordates.[64]

The distinguished paleontologist Thomas Wayland Vaughan (1870–1952) succeeded Ritter as director of Scripps, in 1924. Vaughan pushed to have Scripps take a major role in the scientific exploration of the Pacific Ocean, partly by urging scientists to hitch rides on ships of federal agencies. In 1925, Vaughan purchased a 64-foot fishing boat and named it *Scripps*. She was a small vessel to face so large an ocean but was very useful for coastal work.[65]

In 1936, Harald Ulrik Sverdrup (1888–1957), who was to become the most prominent ocean scientist of his generation, became the third director of Scripps. He carried the institution through the war years and beyond until 1948. Sverdrup's unique background in meteorology and oceanography enabled him to tackle large-scale problems, and in several disciplines. His many years of experience in the Arctic had taught him how to make measurements in the most difficult of circumstances. As a Norwegian, naturally, he was very familiar with fishing and fisheries. His tenure at Scripps set the institution on a new course of integration of physics and biology, and on thinking big. Sverdrup had a low opinion of the research vessel acquired by Vaughan; he wanted a boat that could venture farther out to sea. As noted above, he soon obtained the 104-foot *E. W. Scripps* and thus could lead exploration well offshore.[66]

When, in 1938, the U.S. Bureau of Fisheries proposed a project to explore the spawning activity of the sardine, Sverdrup readily accepted the challenge. The Pacific sardine is a smallish herringlike fish less than 12 inches long, with a glittering dark green to blue back and an iridescent silvery belly. It travels in large schools not far from shore. The sardine fishery had expanded considerably in previous decades and was producing fishmeal and fertilizer at a profitable rate. In the 1936/37 fishing season 726,000 tons of sardines were hauled into California harbors. It was the most productive season on record, about one-quarter of the U.S. tonnage of fish landings. Some fisheries scientists were concerned that overfishing might soon drive down sardine abundances.[67] This was the situation that called for research on sardine reproduction patterns, and systematic studies of the California Current system were initiated accordingly.

From 1938 to mid-1941, Scripps scientists monitored the Current, repeatedly occupying a grid of 40 stations in a regular fashion. A full integration of physical, chemical, and biological studies was now accomplished—the very task that Sverdrup had set himself on arriving at Scripps. Sverdrup soon longed to go back to Norway, as did his wife Gudrun. However, the invasion of Norway by German troops in 1940 closed this option, and the Sverdrups stayed on for the remainder of the war, and three more years after that.

Sverdrup's masterful opus, *The Oceans,* coauthored with the biologist Martin W. Johnson and the chemist Richard H. Fleming, was completed during the war.[68] It was started in 1938, and it was the first book to offer a comprehensive view of Pacific oceanography. It aided the U.S. Navy in the war effort and was restricted in its distribution, initially. The hefty volume (more than 1,000 pages) defined the field of oceanography for the following decades, till about 1970, before the arrival of satellites, deep-ocean drilling, data processing, and ecosystem modeling. It is still useful, after more than half a century. When oceanography became a popular subject of instruction at the college level, in the 1970s, many courses (and textbooks written for these courses) owed their contents and their organization to that book. Most oceanographers keep a copy of it handy.[69]

Thus, the transition from marine biology and fisheries science to oceanography was accomplished. After the war, the navy took a strong interest in all aspects of oceanography, giving massive support to the expansion of all sorts of ocean research, with special emphasis in those areas related to its mission. In addition, the survey of the California Current resumed, under the auspices of the state, initiating the longest-running detailed documentation of the history of any such large region in the world, with most interesting results.

Led by Roger Randall Revelle (1909–1991), Scripps's fifth director (from 1950 to 1964), Scripps participated fully in the navy-funded postwar expansion, with several ocean-going vessels, contributing significantly to the new global view of the ocean emerging in the postwar years. Marine geology, the stepchild in prewar oceanography, benefited enormously and ended up creating a major revolution in its mother science, as a result of intense global exploration of the seafloor in the 1950s and 1960s. The years that followed are marked by the growth of climate sciences, and of all fields connected to human impact on the ocean's life-support systems—physical, chemical, and biological.

NOTES AND REFERENCES

1. P. Ward, R. A. Myers, 2005, *Shifts in open-ocean fish communities coinciding with the commencement of commercial fishing.* Ecology 86, 835–847; B. Worm, M. Sandow, A. Oschlies, H. K. Lotze, R. A. Myers, 2005, *Global pattern of predator diversity in the open oceans.* Science 309, 1365–1369.

2. The trend has a name: fishing down marine food webs. D. Pauly, V. Christensen, J. Dalsgaard, R. Froese, F. Torres, 1998, *Fishing down marine food webs.* Science 279 (5352), 860–663.

3. *Encyclopaedia Britannica,* 1974, *Macropaedia* 19, Whaling.

4. J. R. Spears, 1908, *The Story of the New England Whalers.* Macmillan, New York, 418 pp.; C. W. Ashley, 1942, *The Yankee Whaler.* Halcyon House, Garden City, N.Y., 156 pp.; J. T. Jenkins, 1921, *A History of the Whale Fisheries.* Whitherby, London, 336 pp.; E. K. Chatterton, 1926, *Whales and Whaling.* William Farguer Payson, New York, 248 pp.; P. Budker, 1959, *Whales and Whaling.* Macmillan, New York, 182 pp. For a lively account of the whale hunt in the nineteenth century, see H. Melville, 1851, *Moby-Dick.* Harper and Brothers, New York; and N. Philbrick, 2000, *In the Heart of the Sea: The Tragedy of the Whaleship Essex.* Penguin Putnam, New York, 302 pp. An early example of the modern scientific approach to the natural history of whales is provided by K. S. Norris (ed.), 1966, *Whales, Dolphins, and Porpoises.* University of California Press, Berkeley, 789 pp. A scholarly and poetic description of life in the sea from the point of view of a sperm whale is presented by V. B. Scheffer, 1969, *The Year of the Whale.* Charles Scribner's Sons, New York.

5. E. S. Russell, 1942, *The Overfishing Problem.* Cambridge University Press, London, 130 pp.

6. Quoted in V. B. Scheffer, *The Year of the Whale,* p. 125.

7. D. Pauly, J. Maclean, 2003, *In a Perfect Ocean: The State of Fisheries and Ecosystems in the North Atlantic Ocean.* Island Press, Washington, D.C., 175 pp.

8. Another is to pronounce *Newfoundland* correctly, with the stress on the last syllable.

9. At the very end of the fifteenth century, John Cabot (born Giovanni Caboto, of Venice) found the Grand Banks, sailing from England to Newfoundland (or thereabouts). After Cabot, the English no longer had to fish off Iceland and argue with the powerful Hanseatic League, a trust of cities centered in northern Germany that had the annoying

habit of laying claim to good fishing grounds everywhere in the eastern North Atlantic. Cabot discovered the fishing grounds for England, but apparently Basque fishermen had been working the area, and this is how Cabot learned about fishing with weighted baskets (*fide* Fagan, 2000, p. 77). In any case, the Basques had been selling salt cod for years, but they chose not to tell anyone where they fished (Kurlansky, 1997, p. 29). Brian Fagan, 2000, *The Little Ice Age*. Basic Books, New York, 246 pp.; Mark Kurlansky, 1997, *Cod, A Biography of the Fish That Changed the World*. Penguin Books, New York, 294 pp.

10. The first effect of heavy fishing pressure is to decrease the typical size of adult fish. For example, concerning the smallish Atlantic cod from kelp forests in the coastal Gulf of Maine, we know from the leftover cod bones in Indian middens that the typical length in pre-European times was around 3 feet or more. In contrast, for the last 50 years or so a 1-foot-long fish is a perfectly respectable catch. J. B. C. Jackson, M. X. Kirby, W. H. Berger, K. A. Bjorndal, L. W. Botsford, B. J. Bourque, R. Bradbury, R. Cooke, J. Erlandson, J. A. Estes, T. P. Hughes, S. Kidwell, C. B. Lange, H. S. Lenihan, J. M. Pandolfi, C. H. Peterson, R. S. Steneck, M. J. Tegner, R. R. Warner, 2001, *Historical overfishing and the recent collapse of coastal ecosystems*. Science 293, 629–638.

11. The word *fish* is used both for singular and plural in common English. The context prescribes when to use *fishes*. Fishermen catch fish, while scientists study fishes.

12. Food and Agriculture Organization statistics, summarized in P. Weber, 1994, *Fish, Jobs, and the Marine Environment*. Worldwatch Institute, Washington, D.C., 76 pp.

13. M. Kurlansky, 1997, *Cod*. Penguin Books, New York, 294 pp.

14. D. Pauly, J. MacLean, *In a Perfect Ocean*.

15. C. S. Woodard, 2000, *Ocean's End: Travels through Endangered Seas*. Basic Books, New York, 300 pp.

16. B. Fagan, *The Little Ice Age*.

17. P. D. Jones, K. R. Briffa, T. P. Barnett, S. F. B. Tett, 1998, *High-resolution palaeoclimatic records for the last millennium: Interpretation, integration and comparison with general circulation model control-run temperatures*. The Holocene 8, 455–471.

18. N. C. Stenseth, A. Mysterud, G. Ottersen, J. W. Hurrell, K.-S. Chan, M. Lima, 2002, *Ecological effects of climate fluctuations*. Science 297, 1292–1296. K. T. Frank, R. I. Perry, K. F. Drinkwater, 1990, *The predicted response of northwest Atlantic invertebrate and fish stocks to CO_2-induced climate change*. Transactions of the American Fisheries Society 119, 353–365.

19. D. Pauly, 2003, presentation at the Scripps Symposium for Marine Biodiversity, November 2003.

20. It is the same on land: rabbit and deer feed low on the food chain and are correspondingly more abundant than foxes, wolves, and mountain lions.

21. Assuming Keynesian inflation, this is between $100 and $200 million in today's money.

22. F. S. Russell, C. M. Yonge, 1936, *The Seas: Our Knowledge of Life in the Sea and How It Is Gained*. Frederick Warne, London, 379 pp. F. S. Russell was a leading figure in marine biology in the first half of the twentieth century, and the director of the Plymouth Laboratory of the Marine Biological Association, the world-renowned center for sea research in Scotland. C. M. Yonge was a distinguished British marine zoologist and ecologist.

23. Purse-seining is a fishing method whereby the vessel sets a long and deep ribbon of net around a school of fish, encircling the prey. When the circle is complete, the bottom is pulled shut by shortening the string at the lower limit of the net, as when closing a purse.

24. Fish aggregate in schools, presumably to avoid or confuse natural predators. They have no defense against purse-seining because this type of attack is not part of their evolutionary history.

25. John Steele was director of Woods Hole Oceanographic Institution from 1977 to 1989.

26. R. Bailey, J. Steele, North Sea Herring Fluctuations: in M. H. Glantz, L. E. Feingold (eds.), 1990, *Climate Variability, Climate Change and Fisheries Project*. National Center for Atmospheric Research, Boulder, Colo., pp. 213–220.

27. *Ecologic extinction* describes the loss of an important role of a given species in structuring regional ecologic systems. For example, many of the great baleen whales are ecologically extinct. So are groupers in the kelp offshore of Scripps. In contrast, the great auk (a flightless bird of the northern North Atlantic) is terminally extinct, from overexploitation. Of course, it is ecologically extinct as well.

28. The initial discovery of the hot vents was by geologists and geochemists wondering about the interaction of seawater with hot basalt. They wanted to know why seawater has the chemistry it does. Biologists soon took over with a more spectacular story. See C. L. van Dover, 2000, *The Ecology of Deep-Sea Hydrothermal Vents*. Princeton University Press, Princeton, N.J., 424 pp.

29. T. Platt, W. K. W. Li (eds.), 1986, *Photosynthetic picoplankton*. Canadian Bulletin of Fisheries and Aquatic Sciences 214, 1–583; S. W. Chisholm, R. J. Olson, E. R. Zettler, J. Waterbury, R. Goericke, N. Welschmeyer, 1988, *A novel free-living prochlorophyte*

abundant in the oceanic euphotic zone. Nature 334, 340–343. Much of the carbon fixation in the sea is by the newly discovered chlorophyll-bearing prokaryote *Prochlorococcus:* K. Suzuki, N. Handa, H. Kiyosawa, J. Ishizaka, 1995, *Distribution of the prochlorophyte Prochlorococcus in the central Pacific Ocean as measured by HPLC*. Limnology and Oceanography 40 (5), 983–989.

30. J. H. Martin, S. E. Fitzwater, 1988, *Iron deficiency limits phytoplankton growth in north-east Pacific subarctic*. Nature 331, 341.

31. R. M. May (ed.), 1984, *Exploitation of Marine Communities*. Dahlem Konferenzen, Springer-Verlag, Berlin, 366 pp.

32. A striking example of a large-scale experiment of this sort is the introduction of the ctenophore *Mnemiopsis leidyi* into the Black Sea, from ballast water of cargo ships. The common name for ctenophores is gooseberry jellyfish. They are small and feed on minute plankton. The invasive predator, lacking predators of its own, became extremely abundant. By eating the food for fish larvae, and the fish eggs and larvae too, it destroyed important fisheries in the region. The appearance of another ctenophore, a species of *Beroë* that preys on smaller ctenophores, moved the system toward recovery in the mid-1990s. J. Travis, 1993, *Invader threatens Black, Azov seas*. Science 262, 1366–1367; A. E. Kideys, 2002, *Fall and rise of the Black Sea ecosystem*. Science 297, 1482–1483.

33. The phrase "great geophysical experiment" is ascribed to Roger Randall Revelle (1909–1991), director of Scripps from 1951 to 1964.

34. R. A. Kerr, 2002, *A warmer Arctic means change for all*. Science 297, 1490–1492. The same issue of *Science* has several articles concerning climate change in polar regions. On NASA's Web site *Visible Earth,* there are images relating to the changing Arctic sea ice cover (*30 years of Arctic warming;* last updated 26 Feb 2005). While temperature changes are less drastic in low latitudes, warming here may result in widespread coral bleaching events. C. Wilkinson, 2001, *Status of coral reefs of the world: 2000*. Web site for Global Coral Reef Monitoring Network, Australian Institute of Marine Science.

35. Proposals for policy implications and stewardship are made in Pew Oceans Commission, 2003, *America's Living Oceans: Charting a Course for Sea Change*. Pew Oceans Commission, Arlington, Va. (summary and full report on CD-Rom).

36. P. K. Dayton, M. J. Tegner, P. B. Edwards, K. I. Riser, 1998, *Sliding baselines, ghosts, and reduced expectations in kelp forest communities*. Ecological Applications 8 (2), 309–322.

37. The Devonian period lasted from 410 to 360 million years ago. See the geologic time scale in appendix 4.

38. J. B. C. Jackson et al., *Historical overfishing*.

39. M. Orbach, 2003, presentation at the Scripps Symposium for Marine Biodiversity, November 2003.

40. G. Hardin, 1968, *The tragedy of the commons*. Science 162, 1243–1248.

41. The well-known difficulties in separating natural background variations in climate from human impact based on the release of greenhouse gases from automobiles and power plants has given rise to intense political discussions (sometimes dressed up as scientific debates by special interests, and in the media).

42. *The Encyclopedia of Oceanography,* edited by R. W. Fairbridge (Reinhold, New York, 1966), has no entry for "pollution" but makes reference to human impact in the essay entitled *Carbon dioxide cycle in the sea and atmosphere,* by Taro Takahashi. Takahashi cites works by G. N. Plass (1956) and R. Revelle and H. Suess (1957) and refers to studies by C. D. Keeling, among others. He writes (p. 171): "A change in the CO_2 concentration in the atmosphere could appreciably affect the thermal budget of the surface of the Earth, and might cause a long-term change in the weather and climate due to the greenhouse effect." By the 1970s, Scripps geochemist E. D. Goldberg was treating human input to biogeochemical cycles as one more factor in the cycling of elements on the planet. E. D. Goldberg, 1975, *Marine pollution,* in J. P. Riley, G. Skirrow (eds.), *Chemical Oceanography,* 2nd ed., vol. 3. Academic Press, London, pp. 39–89.

43. J. W. Hurrell, Y. Kushnir, G. Ottersen, M. Visbeck (eds.), 2003, *The North Atlantic Oscillation: Climatic significance and environmental impact*. Geophysical Monograph 134, 1–279; H. F. Diaz, V. Markgraf, 1992, *El Niño: Historical and Paleoclimatic Aspects of the Southern Oscillation*. Cambridge University Press, Cambridge, U.K., 476 pp.

44. The lack of such knowledge is painfully evident in many editorials criticizing the results of climate computations, even in some prominent newspapers.

45. There are indications that Chinese seafarers reached the Americas sometime in the early fifteenth century, well before the period of global European discovery associated with the names of Columbus, Magellan, and da Gama. Gavin Menzies, 2002, *1421, the Year China Discovered America*. HarperCollins, New York, 552 pp.; D. J. Boorstin, 1983, *The Discoverers*. Random House, New York, 745 pp. Clearly, if this is true, Chinese rulers were aware of the World Ocean long before Magellan crossed the Pacific.

46. Cristoforo Colombo (1451–1506), leader of the expedition to the West Indies, discovered the trade

wind route across the Atlantic, about 20° north of the equator.

47. Vasco da Gama (ca. 1460–1524), seafarer, trader, and buccaneer, opened the way from Portugal to India, for the spice trade, sailing around the Cape of Africa, later called the Cape of Good Hope.

48. Ferdinand Magellan (1480?–1521), supported by King Carlos I of Spain, discovered a passage from the Atlantic to the Pacific, through Tierra del Fuego, at 52° S. He sailed across the Pacific to the Philippines, where he was slain by natives.

49. Claudius Ptolemaius (second century AD), Greek astronomer and geographer, described the motions of the Sun, Moon, and planets and created a global map reflecting the limited knowledge of his time.

50. James Cook (1728–1779), captain in the British navy, explored the boundaries of the Pacific and charted the islands within it, including Hawaii (where he was killed by natives). He was one of the great explorers of all of history.

51. The present distinguished holder of the position of Astronomer Royal, Sir Martin Rees thinks deeply about the life history of the universe, past and future. M. Rees, 2001, *Our Cosmic Habitat*. Princeton University Press, Princeton, N.J., 205 pp.

52. Fridtjof Nansen (1861–1930) established that the Arctic Sea is a deep ocean basin. He discovered that ice drifts to the right of the wind, an observation that was crucial in the development of theories linking currents to wind.

53. N. Philbrick, 2003, *Sea of Glory: America's Voyage of Discovery—The U.S. Exploring Expedition, 1838–1842*. Viking, New York, 452 pp.

54. Edmond Halley's 1698 *Paramore* Expedition, sponsored by the Royal Society to take observations of magnetic declination, is sometimes accorded the honor of the first sea journey undertaken for a purely scientific object. It is well to remember that ships were steered by compass, and thus navigation depended on knowledge of declination. In consequence, research on magnetism had immediate use in a military and commercial context.

55. In actuality, most of the shells apparently derive from individuals that disappeared into their offspring, by dividing into hundreds of new cells or gametes and leaving an empty house.

56. There is indeed gold in seawater—there is a bit of everything dissolved in it—but the concentration is very low, and hence it would be very difficult to extract.

57. E. N. Shor, 1978, *Scripps Institution of Oceanography: Probing the Oceans, 1936 to 1976*. Tofua Press, San Diego, 502 pp.

58. There are many outstanding oceanographic institutions with a long history. A survey is in E. M. Borgese (ed.), 1992, *Ocean Frontiers: Explorations by Oceanographers on Five Continents*. Abrams, New York, 288 pp. Scripps Institution of Oceanography is represented with an article by its former director, the late Roger Revelle.

59. C. A. Anderson, J. W. Durham, F. P. Shepard, M. L. Natland, R. R. Revelle, 1950, *1940* E. W. Scripps *Cruise to the Gulf of California*. Memoir 43, Geological Society of America, New York, 398 pp.

60. Edward Willis Scripps (1854–1926), owner of many so-called penny newspapers in the United States , designed to bring news to the general public, was also a yachtsman who sought relaxation at sea. He befriended marine biologist William E. Ritter and helped plan the founding of the Marine Biological Association of San Diego (the forerunner of Scripps Institution of Oceanography) in the early 1900s.

61. Ellen Browning Scripps (1836–1932), a major benefactor in the San Diego area and beyond (hospital, college, science, and other projects), she played a leading role as a sponsor of the newly founded Marine Biological Association of San Diego. E. W. Scripps was her younger half-brother; she had written a column for his newspaper chain for some years before she retired to La Jolla.

62. The early years of the laboratory and its transformation into an ocean-going institution are summarized in H. Raitt, B. Moulton, 1967, *Scripps Institution of Oceanography: First Fifty Years*. Ward Ritchie Press, Los Angeles, 217 pp.

63. D. Day, 2002, *Scripps benefactions: The role of the Scripps family in the founding of the Scripps Institution of Oceanography*, in K. R. Benson, P. F. Rehbock (eds.), *Oceanographic History: The Pacific and Beyond*. University of Washington Press, Seattle, pp. 2–6.

64. Ritter was director from 1903 to 1923. Ritter's holistic approach to biology did not readily provide for testable hypotheses. At least one historian claimed that it did not produce a clear research focus—neither for "regular" marine biology, nor for oceanography. K. R. Benson, 2002, *Marine biology or oceanography: Early American developments in marine science on the West Coast*, in K. R. Benson, P. F. Rehbock (eds.), *Oceanographic History: The Pacific and Beyond*. University of Washington Press, Seattle, p. 301.

65. T. W. Vaughan, the second director of SIO (1924–1936), was a paleontologist and a recognized authority on corals and coral reefs.

66. H. U. Sverdrup, the third director of SIO (1936–1948), was the lead author on the book that defined the scope of oceanography for the three decades that followed.

67. W.L. Scofield, F.N. Clark of the California Department of Fish and Game; *fide* J. Radovich, 1982, *The collapse of the California sardine fishery. What have we learned?* California Cooperative Oceanic Fisheries Investigations Reports 23, 56–78.

68. H.U. Sverdrup, M.W. Johnson, R.H. Fleming, 1942, *The Oceans, Their Physics, Chemistry, and General Biology*. Prentice-Hall, Englewood Cliffs, N.J., 1087 pp.

69. No survey data are available, but a cursory inspection of bookshelves of colleagues at Scripps suggests that this is true at least for gray-haired oceanographers.