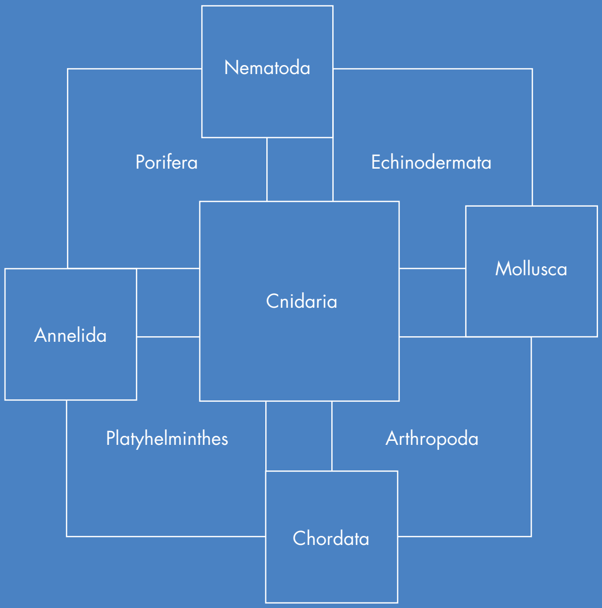
The Unknown Ocean

CENSUS
OF MARINE LIFE

Baseline Report
of the Census of Marine Life
2003



Cover Images

Annelida: Marine polychaete, *Polychaeta sp.* (Serpulidae) Photo: Dieter Fiege
Arthropoda: Coral crab, *Rochina crassa.* Photo: Ian MacDonald
Chordata: Pink salmon, *Oncorhynchus gorbuscha.* Photo: Manu Esteve
Cnidaria: Moon jellyfish, *Aurelia aurita* (Ulmaridae). Photo: Karen Gowlett-Holmes
Echinodermata: Purple sun star, *Solaster endeca.* Photo: Strong/Buzeta
Mollusca: Emperor nautilus, *Nautilus pompilius.* Photo: James B. Woods
Nematoda: Threadworms, *unidentified species.* Photo: Cindy Lee Van Dover
Platyhelminthes: Flatworm, *Pseudoceros ferrugineus.* Photo: L. Newman and A. Flowers
Porifera: Stinker sponge, *Ircinia felix.* Photo: Shirley Pomponi

The Unknown OCEAN

The Baseline Report of the Census of Marine Life Research Program

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with the International Scientific Steering Committee
and Project Leaders of the Census of Marine Life

Consortium for Oceanographic Research and Education

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FOREWORD

Welcome to the Baseline Report of the Census of Marine Life (CoML, www.coml.org), a cooperative international research program. CoML audaciously aims to assess and explain the diversity, distribution, and abundance of life in the oceans. This Baseline Report offers a framework for considering marine life and reports essential elements of today's knowledge and its limits. The report is intended for readers concerned with marine life, including environmental journalists, teachers, and resource and research managers as well as researchers.

Overall, the strategy of CoML is to clarify and make much more accessible what we know, to identify what we do not know and why we do not know it, to learn much more of what is knowable, and also to identify what we may never know or at least not learn for a very long time, well beyond the life of the research program. While audacious, CoML humbly recognizes the formidable limits to knowledge. Good reasons including size and the inaccessibility of the deep explain why no one has before tried the task of CoML.

A census requires dividing the whole of the oceans into parts. The oceans do not divide into easily defined, separate compartments. Waters and animals move. In this Baseline Report, we offer a division of six realms that encompass all life from the surface of the nearshore to the bottom of the deep ocean. We hope the framework of realms and of zones within some of the realms helps readers appreciate the diversity, distribution, and abundance of marine life.

Along with the framework, the baseline offers facts, for example, about numbers of known and unknown species and about the quantity of marine life and how it is broadly distributed. However, the baseline is not a great wet database reporting estimates of the number or tonnage of animals in every species. The program looks forward to developing and sharing more of this kind of information, as well as explanations of why matters are as they are. A companion document, the CoML Research Plan 2003, explains how the new knowledge could be won.

The senior scientist of the CoML, Ronald O'Dor, led the preparation of this Baseline Report. Many CoML scientists assisted him, especially members of the International Scientific Steering Committee and leaders of CoML projects. Their names are listed in the Acknowledgments. Thanks to all and to the government agencies, marine laboratories, universities, natural history museums, and other organizations that are making the census possible.

We have aimed at a level of detail such that many readers might read this entire document with profit, but with less detail and citation than in scientific papers. A bibliography lists sources for the information in the report.

Initiated in the year 2000, CoML intends to publish its formal census in 2010. The 2010 census will surely be "born digital" and much of it will probably appear to users as an on-line dynamic atlas. CoML looks forward to issuing interim reports as research progresses. We hope this Baseline Report usefully orients the many people concerned with marine life, including researchers in the program itself and those who support it. And, we hope the baseline prepares the way for a near future in which vastly superior and more complete information about marine life is readily available to all who would constructively use it.

J. Frederick Grassle,
Chair, International Scientific Steering Committee
Census of Marine Life

SUMMARY

With several species of fish being discovered weekly and countless marine organisms still unknown, assaying reports of trouble in the oceans requires a global Census of Marine Life (CoML). Already, more than 300 scientists from 53 countries are at work in CoML. After three years of organizing and demonstrating the opportunities and feasibility of the global effort with initial explorations, CoML here draws a baseline for exploration to 2010.

Challenges to explorers include the vastness of the oceans stretching far wider than land and their darkness as much as 11 km underwater. The size of marine organisms ranges a hundred million million million fold, from drifting bacteria through shrimplike krill and familiar fish, up to whales that swim as fast as 50 km/hr.

The census divides itself into three tasks. History, like the 400-year record of fish catches assembled for Denmark, tells what lived in the ocean. Exploration, like the submarine discovery of sponge gardens nearly 4 km deep in a gap in the Mid-Atlantic Ridge, tells what lives in the ocean now. Only combining historical trends with what lives now can answer the core question of what will live in the ocean tomorrow.

Technology and difficulty divide the oceans into realms for exploration. In the nearshore zone and on continental shelves and slopes, fish, shellfish, and lobster abound. In the light zone of the ocean's central water, drifting microbes photosynthesize food that miniature shrimp and swimming fish eat. In the dark of central water, jellyfish swarm, and in the sediment snowed from above onto the abyssal plain, microbes and worms prosper. Around active seafloor vents, heat-resistant microbes survive. In polar oceans, algae photosynthesize on the underside of ice. The small, drifting organisms that photosynthesize all the primary food make up almost all the 145,000 million tons of marine biomass. Small animals like krill account for most of the animal mass, while prominent large animals, like fish and whales, constitute only a small crucial percentage. In all oceanic realms, finding and naming species of animals show unflagging progress as well as unknowns yet to resolve. Estimating populations and biomass to distinguish between decline, fluctuation, and shift has only begun.

New technology opens today's unknowable to exploration and enables translation of the unknown to known. Techniques for accessing archives and visualizing the past in dusty records rank as new technology. Sounds from animals serve as signatures, while sounds from sonar reveal shapes in the darkness of the ocean. Sea lions carrying telemetry devices and tankers towing plankton recorders ally themselves with marine scientists. Video cameras photograph unknown giants deep in the sea, and luminescence reveals both the shape of marine organisms and their spectral signatures. The speed and economy of reading genomes – spinoffs from human genome sequencing – make the identification of species by the series of compounds on a gene similar to scanning a barcode in a market.

This report provides a baseline encompassing all the oceanic realms and a prefilter for explorations likely to yield the great surprises about marine life, past and future. Discovery is ahead.

THE UNKNOWN OCEAN: BASELINE REPORT OF THE CENSUS OF MARINE LIFE

Reports of trouble in the oceans accumulate. Some say salmon are declining in the Pacific, and others say the abundance of cod has plummeted in the Atlantic. A 400-year record shows smaller herring catches in Denmark (Figure 1). Paradoxically, other reports say that more fertilizer is washing into the ocean for the phytoplankton that feeds the fish. Deciding whether these are anecdotes and fish tales or the tip of an iceberg of oceanic disaster under way requires a global census of marine life. For marine life, global means exploring across waters extending more than twice the expanse of land. Oceanic exploration has a third dimension of depth, water as deep as 11 km in the Mariana Trench with sediment adding depth below (Figure 2). Global means exploring waters from the coasts of many nations to the high seas. Far beyond salmon, cod, and herring, global means encompassing the myriad forms of life hinted at in the nine pictures on the cover of this report.

To learn what is under way requires more than a global snapshot of today's oceans. Rather, a motion picture is needed to impart the dimension of time. To start the movie, this report attempts to draw baselines for measuring change over time in six ocean realms distinguished by the techniques and difficulties of their exploration. Although a census must finally measure abundance, the report for now focuses on the seemingly simpler, but still formidable exploration of diversity and distribution – how many species live where in the vast, deep oceans.

At the same time the report draws baselines, it looks forward to exploration and analysis. Effort, instruments, and change will eventually select which explorations succeed and which fail. Nevertheless because good sense argues for preselection to improve the odds of successful discovery, the report examines the oceanic realms with the criteria of known, unknown, and unknowable. It assays the dimensions of the oceans and visualizes three large tasks that a census of marine life must accomplish to appraise change in the oceans dependably. After examining the known, unknown, and unknowable in the six ocean realms, it inventories the technology that can transform unknown to known.

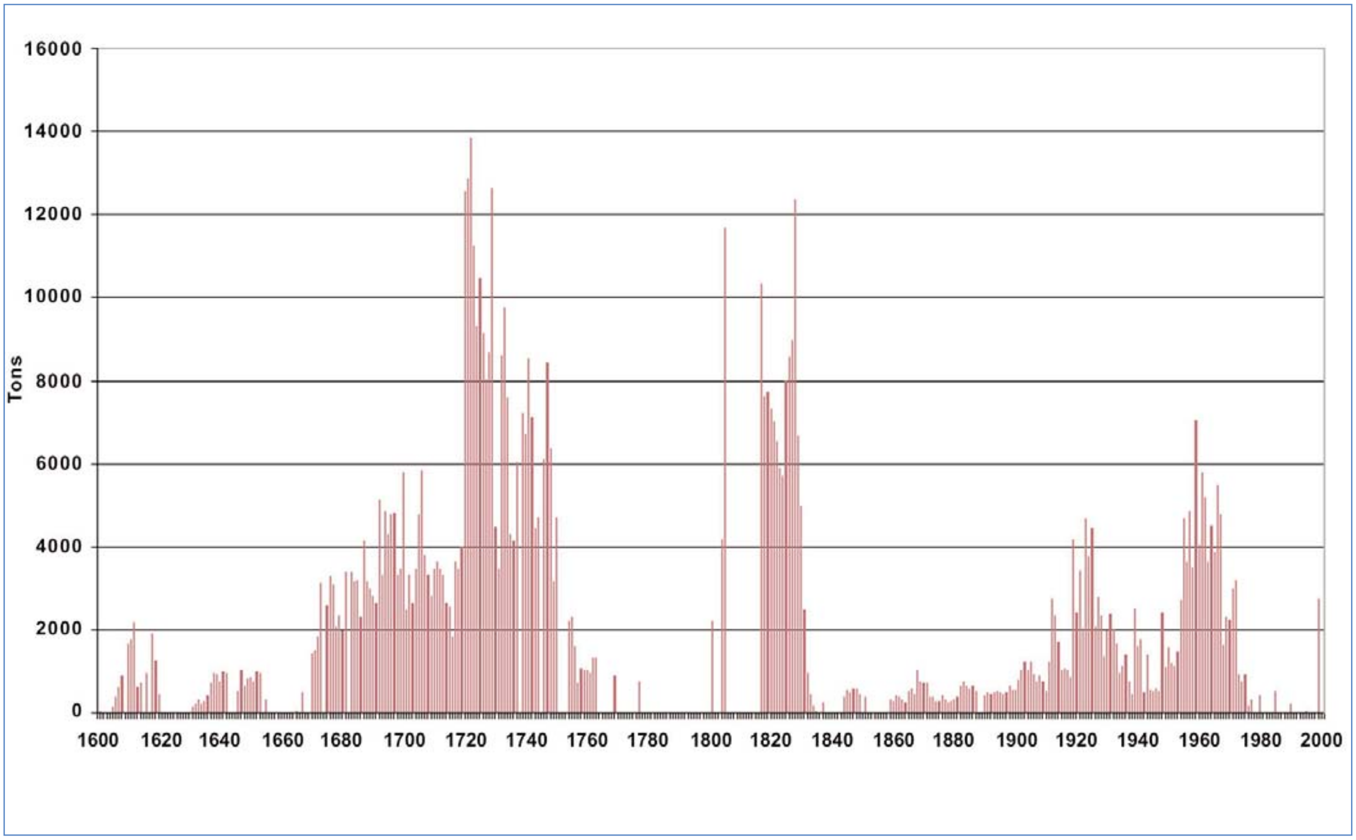


Figure 1. Herring catches in Denmark for 400 years reconstructed from historical records. Historical records help distinguish fluctuations from trends. Also, they can extend trends backward from the baseline of the present, giving a head start to detection of future trends. Source: Poulsen 2002

I. SEPARATING THE KNOWN, UNKNOWN, AND UNKNOWABLE

Explorers pondering where the best prospects for discovery lie use logic to preselect paths with the highest probability of success. Nature will make the final selection between open avenues and blind alleys, but distinguishing among known, unknown, and unknowable is a basic preselection filter.

The known is easiest to filter out. It includes whales and bacteria already perceived by one of our five senses, sometimes with the help of an instrument like binoculars or a microscope. Stone tablets, libraries, and now the electronic web have accumulated a vast inventory of the known. A standard scientific publication reviews Literature before Materials, Methods, and Results to draw a baseline of the known and to preselect against its reexploration. It also teaches modesty about what is known, how accidental the known may be and how subject to revision. Below, the examinations of realms of the ocean begin with the known.

Filtering unknowable from unknown is hardest. The profit of avoiding fool's errands and focusing instead on the knowable unknown justifies the hard thinking. Nevertheless, the causes of unknowability must be carefully plumbed because too fine a filter might preselect against a great discovery.

Intrinsically, some things are unknowable. An illustration is the impossibility of foreseeing whether an auto will strike you next year. In some systems small initial differences, the flutter of a butterfly's wings, can cause large differences in outcomes and thus make, for example, the weather weeks hence unknowable. Similarly, the number of fish in a bay a decade from now is also intrinsically unknowable. Such intrinsically unknowable things seem safe to filter out.

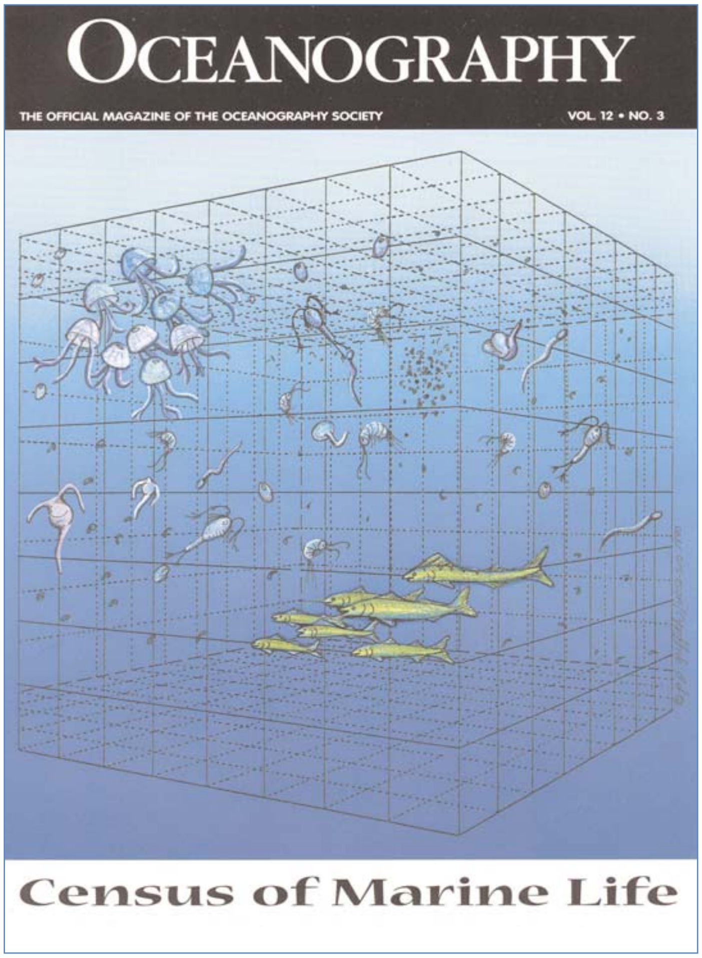


Figure 2. **A schematic representation of some kinds and locales of ocean life.** Because oceans are three-dimensional, their exploration extends not only across water twice as wide as all global land. It also extends through several oceanic realms into water as deep as 11 km in the Mariana Trench with sediment adding depth below. Image courtesy of The Oceanography Society.

Culture, the habits and ethics that curb us, can also render things unknowable. In the 21st century, people can smugly believe they would not recant as Galileo did in the 17th century. Nevertheless, social limits persist, as illustrated by examples of chemists uninterested in exotic chemistry only a score of years ago. Ethics would certainly stop a scientist from censusing fish in a bay by dynamiting and counting floating bodies. How culture renders knowledge unknowable merits a second look before preselection.

Finally some things are unknowable because search is impractical. For example, a sea to be explored is inaccessible, specimens explode when brought to the surface, our senses cannot perceive factors, or cost and tedium overwhelm. Because boundaries of practicality between the unknown and unknowable can be breached, as by submarines and high-throughput analysis, the filter for removing the practically unknowable must be revised frequently and kept up to date. Below, the examinations of realms of the ocean include what is currently unknowable. The explorers preselect the unknown as the region where discovery is most probable.

Analysts of research consider discovery an analog of fishing and warn that big catches eventually exhaust fishing holes. The question, therefore, is whether the fishing hole of the unknown ocean has been fished out.

The rate of finding new species of fish tests whether discovery has been exhausted (Figure 3). Surely we know all the fish! Not at all. For a century, the rate at which scientists have described new species of fish has not slowed. Since 2000, icthyologists have added about 600 species to the catalog of marine fishes. Neither the sciences of collecting new species nor those of validating them have slowed. The fishing hole of unknown large, edible marine organisms is not exhausted.

Further, the analogy of fishing admits the possibility of finding new fishing holes. Beyond the best-known group of marine life, the fish, lies the scarcely imaginable, total diversity of marine life pictured on the cover of this report. Also, new technologies open new fishing holes.

Finally the technology of classification of species, of taxonomy itself, can accelerate. There are currently nearly 500 fish taxonomists who classify and name fish. This is many times the number working on some marine phyla of less commercial importance. Consider a million possible new nematodes, that is, roundworms. Even if nematode taxonomists work ten times as fast as fish experts, thousands of years would pass by the time they named most of the species. Whereas the exchange of letters and drawings among early taxonomists took months to circle the globe, email does this in seconds. Couriers can deliver physical samples overnight. By countering the exponential rise of effort to compare new specimens to old as the number of species increases, improved technology can open opportunities and accelerate discoveries.

Below, the examinations of realms of the ocean conclude with suggestions where the opportunities of the unknown lie, and most important, with actual, recent explorations that demonstrate the fishing holes of fresh knowledge are teeming.

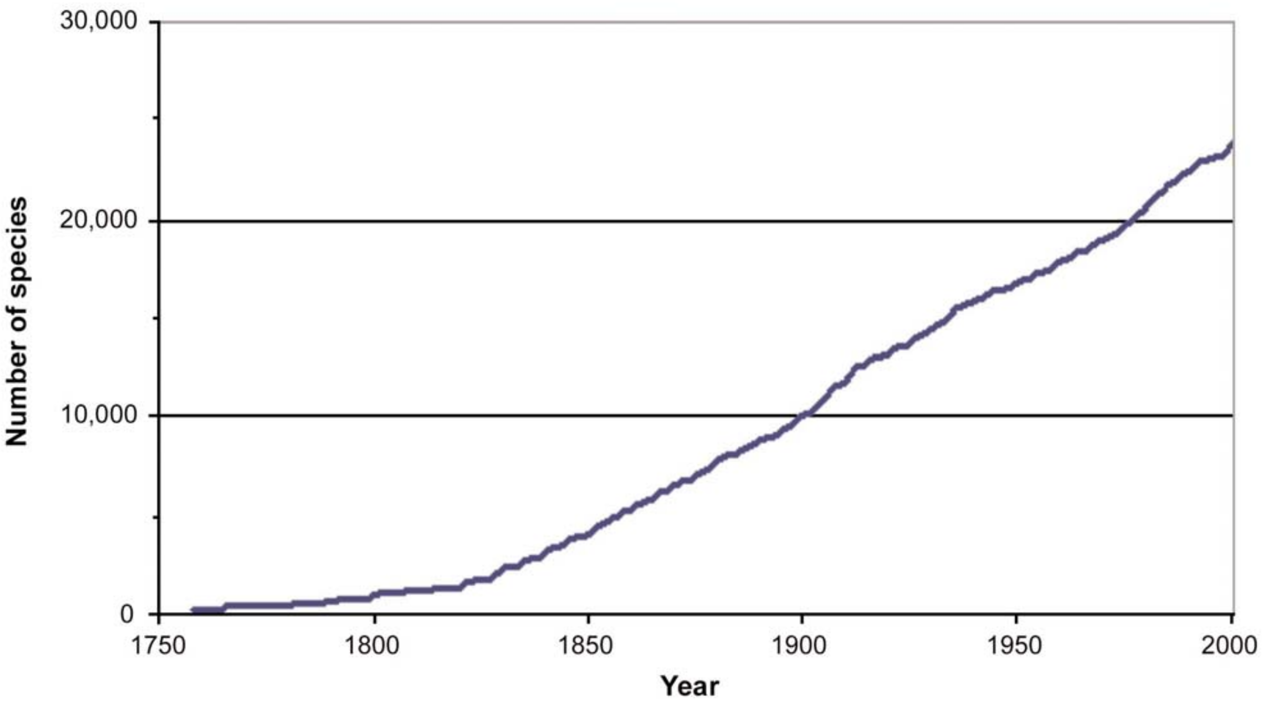


Figure 3. **The number of identified species of fish.** Since the 18th century, biologists have named living things according to the system established by Linnaeus (1707-1778). Thus, the addition of new names charted here equals the rate of discovery of new species. The undiminished rate demonstrates that even after three centuries, the progress of discovery goes on unabated and opportunities abound. Fish experts estimate about 5,000 marine species remain to be discovered and identified. About 15,300 species are so far cataloged. Source: Eschmeyer & Froese 2003

II. THE DIMENSIONS

Size

Size encompasses the three dimensions of length, width, and height, leaving only the fourth dimension of time for later discussion. In the polar view in the inset of Figure 4, the reader can grasp the scale of the length and width of the oceans that cover more than twice as much of our 8,000 km diameter globe as land does. The oceans' average third dimension sinks through some 4 km of water to the abyssal plain and still more into trenches. If the waters of the ocean were poured on global land, they would be 2.8 km deep. A similar depth of sediment accumulated at the bottom of the ocean adds to the volume of oceanic exploration. The size of the ocean presents both awesome challenges for exploration and thrilling opportunities for discovery.

Awesome, too, is the range of marine life (Figure 5). Blue whales weigh some 100 million times as much as the 1-gram, shrimplike krill they eat. The krill in turn weigh about 50 trillion times as much as the blue-green bacteria that convert sunlight and carbon dioxide into food for the krill.

The mass of marine life, so-called biomass, is the sum of these disparate creatures. Humanity does not deplete and may increase the minerals to fertilize marine life, so the biomass feeding the oceans should be steady or increasing unless toxic substances are a factor. The distribution of that scarcely changed biomass along the millionfold range of size and of species, however, can change. Changed distributions, not the sheer biomass, are what fishers and reef-watchers care about. They want big fish and brilliant corals, not more bacteria and krill.

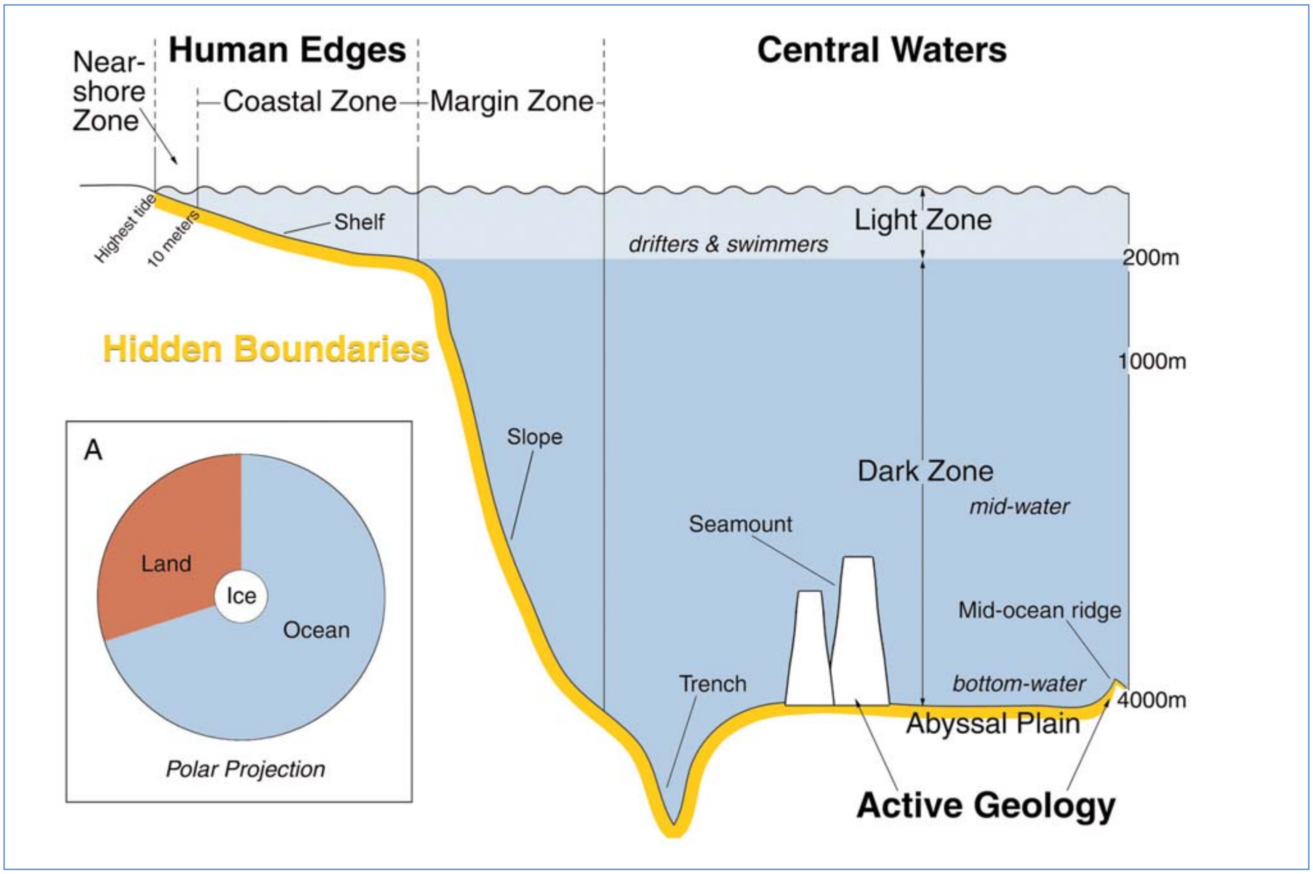


Figure 4. Ocean realms and zones. The baseline reports what lives in oceanic realms today. The realms diagramed in the cross section correspond to the difficulty and technology of their exploration. The nearshore zone nearest people and the coastal where fishers gather constitute the realm of human edges. Unstable continental margins and the sediment of the abyssal plain provide the hidden boundaries of the oceanic bowl. Small drifters like plankton and swimmers like fish inhabit the upper, light zone of the central waters, while another range of creatures inhabit the darkness below 200 m. The realm of active geology includes ghost volcanoes called seamounts rising from the abyssal plain and hot vents in the plain. The ice realm surrounds the poles, and the microscopic realm cuts across all realms. The inset (A) compares the expanse of global water, ice, and land.

Although this report focuses on the exploration of how much diversity and how many species are in the oceans, the distribution of biomass among the species matters greatly (see Food, Growth, and Biomass inset). Consider hypothetical water that produces 100 units of biomass in two species weighing 1 and 10 kg, respectively. Let the biomass of 100 in the water be determined by the supply of nutrients. If the 10 kg species has a population of 9, the smaller will contribute a population of 10 with low biomass. Alternatively if all but one of the larger species were caught, the population of the smaller could rise to 90. In the real ocean where big fish eat little ones with an efficiency of only 10 percent, the population might change even more dramatically. Recent research on the depletion of sharks and other large predators suggests the size spectrum of marine animals is shrinking toward the small.

The 90 percent depletion of the larger fish would affect both fishers and naturalists profoundly. The steady biomass in the water and ninefold multiplication of the smaller fish would not likely satisfy either of them. Without a census of the small as well as big species, the increase of the small might be overlooked. Both are necessary, but because we cannot count what we do not know, we return for now to species, biodiversity, and distribution.

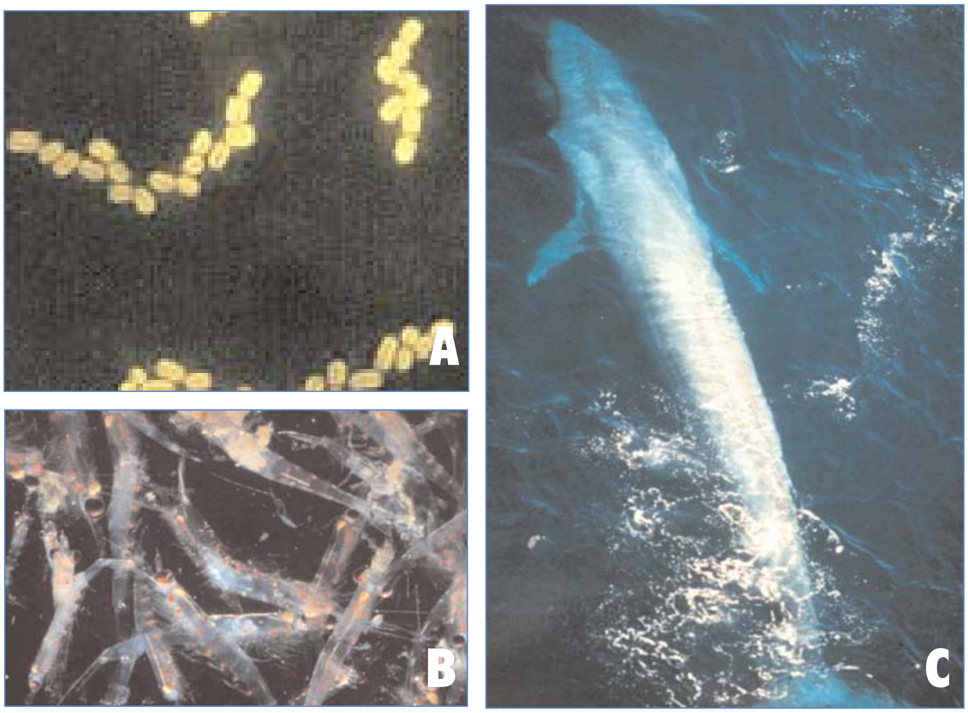


Figure 5. **Size and time dimensions of marine life.** The range of size in a single food chain illustrates the diversity of marine life. Powered by sunlight, the microscopic bacteria make food from carbon dioxide. At one-thousandth kg or 1 g, the shrimplike krill fed by the bacteria weigh 50 trillion times as much. At the top of the food chain, 100-ton whales weigh 100 million times as much as the krill that they strain from the sea. Because of their great numbers, however, the global biomass of microscopic bacteria outweighs krill, which in turn outweighs whale biomass. Bacteria only drift with currents, krill swim a very few km/hr, and at top speed of 50 km/hr, whales outrace most boats. Life cycles range from less than a day for bacteria, through a year or so for krill, up to more than 10 years for whales, but the bacteria have been on the planet many times longer than krill, and krill in turn much longer than whales. Sources: Kuylenstierna & Karlson (blue-green bacteria), NOAA/Department of Commerce (krill, blue whale)

	Blue-Green Bacteria (A) *Synechococcus*	**Krill (B)** *Euphausia superba*	**Blue Whale (C)** *Balaenoptera musculus*
Weight (kg)	5 x 10^{-16}	1 x 10^{-3}	1x10^{5}
Global Biomass (million tons carbon)	100,000	1000	10
Speed (km/h)	0.0001	1-4	20-50
Life Cycle	< 1 day	> 1 year	> 10 years
Years on Planet	2 billion	100 million	10 million

Food, Growth, and Biomass

Size Class	Biomass	Primary Production	Secondary Production
'Prokaryotes' <3um	82%	91%	
'Protists' <0.3mm	18%	9%	
'Zooplankton' <3cm	0.3%		93%
'Swimmers' <3m	0.07%		7%
'Megafauna' >3m	0.01%		0.5%
Million tons carbon	**145,000**	**50,000**	**7,400**

Light energy captured by small organisms feeds larger ones along a food chain of size classes, dominated and identified here by different groups of organisms. Their annual growth accumulates as biomass. The solar energy captured in food is primary production, and that converted into growth of larger organisms is secondary production. Measurements and global estimates show most life is small. Inefficiencies at each step in the food chain mean the oceans can support only small numbers of large animals like whales and other megafauna. Nevertheless, removing a few large animals from an ecosystem can change both abundance and species at lower levels. Source: calculated from Kerr and Dickie 2001

Time

The Cambrian and Paleozoic eras plus the modern extend time back some 600 million years. Fossils reveal that during those 600,000 millennia, 100 Cambrian families were extinguished along with three-fourths of the Paleozoic. On the other hand, 600 new families have appeared up to the present. The details of modern times, of course, interest readers, and the herring catches charted in Figure 1 show fluctuations during four centuries. These lengthy records were not planned, of course, but instead reconstructed from tax records and archeological discoveries.

Practically, one could plan a census extending over a decade or a score of years ahead. Even over those spans, however, an example demonstrates changes can be detected. Current critical trends and variations are detected in well-sampled species, typically from the records of commercial fisheries. A recent fishery with a global impact on the distribution of predators feeding at the top of the food chain has been documented and its analysis demonstrates what can be accomplished. Beginning in the early 1950s, fishing fleets began using standardized longlines on a global scale to catch tuna and billfish. In 1959 they caught more than 10 fish per 100 hooks in the red zones in the upper half of Figure 6. Fifteen years later, however, they caught no more than one fish per 100 hooks anywhere on the planet (lower Figure 6). Further analyses confirmed what the charts suggest. The abundance of the species declined to less than 10 percent of the prefishery level – globally. Although a valuable use of the opportunity of commercial records, Figure 6 cannot tell the concurrent and perhaps consequent changes in the species that tuna and billfish eat, nor the changes in competitors. That fuller picture must be drawn by a broader census of marine life.

III. THREE LARGE TASKS

A census of marine life logically divides itself into two tasks, learning what once lived in the oceans and projecting what will live there, divided by the watershed task of learning what lives in the oceans today.

What did live in the oceans?

Since written records began accumulating in archives and libraries some 500 years, fish stories have been saved. For a century or so, people have been interested in more than where fish could be caught. They have worried what impact people were having on the fish. John Cabot (1450-1498) provided an example of the first kind of record, where the fish could be caught, when he wrote that fish along the Canadian coast were "so numerous you could walk across the bay on their backs." Others wrote of native Americans spearing salmon migrating upriver from coastal waters and more recently about the disappearance of reef fishes from the Caribbean and the subsequent death of coral reefs. Fortunately, when fish are returned and protected, they again eat the plants that overgrow the corals, and the ecosystem may recover.

With skill and insight historical records can extend trends backward from the baseline of the present. Paleoecologists build a complementary history, for example, from evidence of abundance of traces of fish in sediments. In the race to detect trends from the baseline of the present into the future, the extension backward gives a head start. The herring catch recorded in Figure 1, for example, gives a four-century head start.

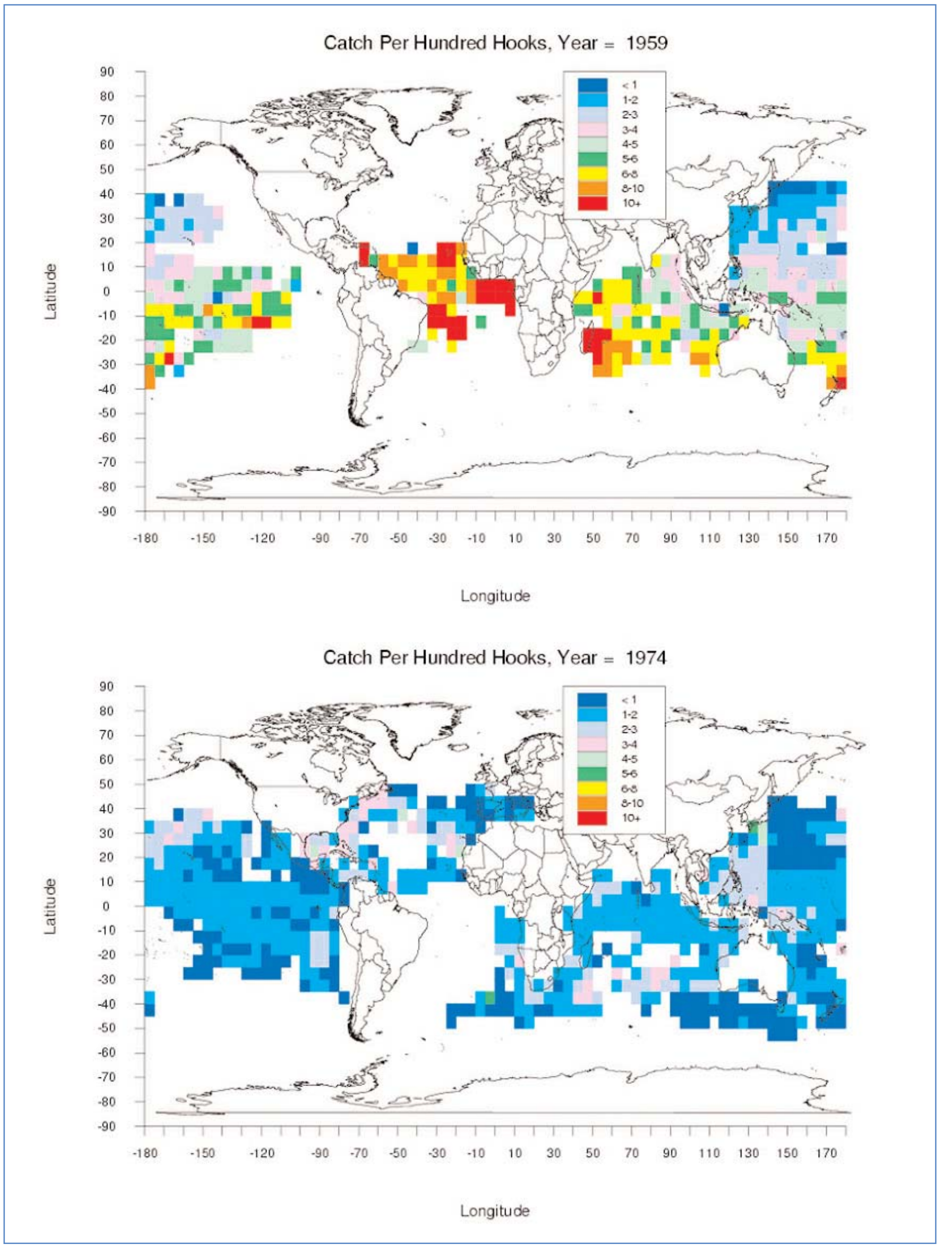


Figure 6. **Change in abundance of large fish.** Global observation can detect changes in only a decade or two. Beginning in the early 1950s, fishing fleets began using standardized, longlines on a global scale to catch tuna and billfish. In 1959 they caught more than 10 fish per 100 hooks in the red zones in the upper map. Fifteen years later, however, they caught no more than one fish per 100 hooks anywhere on the planet, lower map. Although a valuable use of the opportunity offered by commercial records, the catch of these big species cannot tell the concurrent and perhaps consequent changes in the species that they eat, nor can it tell changes in their competitors. Source: Myers & Worm 2003

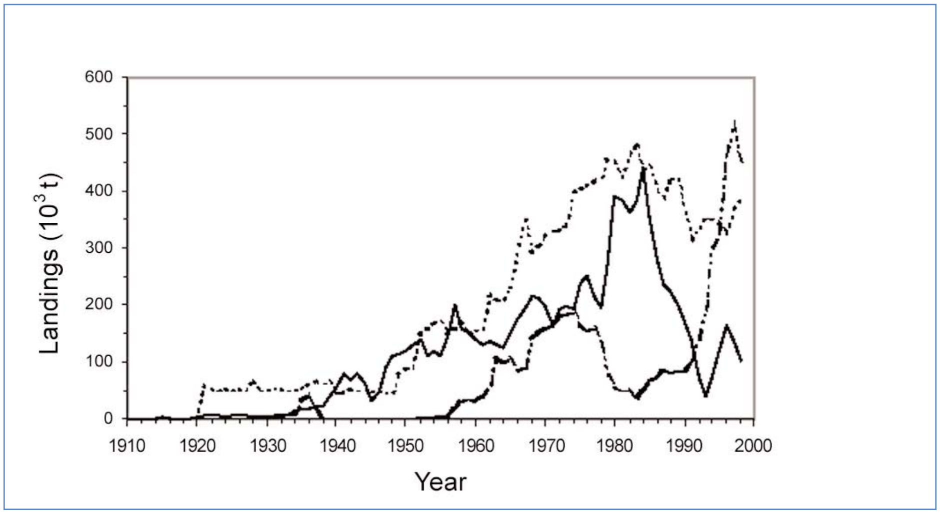


Figure 7. **Changing catch of cod, herring, and sprat.** The fluctuating catch of three species of fish together during much of the 20th century permits a search for causes of change. With accompanying observations of climate, nutrients in the water, and predatory marine mammals, investigators analyzed historical records for the causes of the changing populations. The lines show the commercial landings of cod (solid line), herring (dotted line), and sprat (chained line) in the Baltic Sea. Without some understanding of the causes of these former fluctuations, forecasting changes of fish and ecosystem following natural and man-induced perturbations will be unnecessarily difficult and uncertain. Source: Mackenzie et al. 2002

A shorter head start but one encompassing the catch of three species and permitting a search for causes of fluctuations begins about 1920 (Figure 7). With accompanying observations of climate, eutrophication, and predatory marine mammals, the investigators could explore the causes of the fluctuations. Without some understanding of the causes of these former fluctuations, forecasting changes of fish and ecosystem following natural and human-induced perturbations will be unnecessarily difficult and uncertain.

What lives in the oceans now?

Because this report is designed to be a baseline, the anchor of the present now occupies most of it. Section IV below draws baselines of the known, unknown, and unknowable in ocean realms distinguished by the techniques and difficulties of their exploration. The diaries of ancient mariners and their accessibility for scholars to read in archives multiply the usefulness of observations long ago. Just so, as knowledge of the present state of marine life grows, a standardized and accessible database for computers to browse will multiply the usefulness of what is known of marine life today.

What will live in the oceans of the future?

Marine life past and present undoubtedly interests people, intellectually. Practically, however, it is the future marine life that interests them. At first, practical interest might be thought to focus on what lives in the oceans today. A glimpse at the rapid changes in the century of fluctuations in three species represented in Figure 7 or decline in tuna and billfish between 1959 and 1974 graphed in Figure 6 shows that present marine life is transitory. Thus, knowing the future state – not the present one – holds practical interest. That heightens the urge to model the future. The ease and speed of calculation by modern computers heightens the urge even more.

To realize the practical worth of a census of marine life, scientists must compose models to predict what animals will live in the oceans of the future. They must be filled with the factual content of the census. Practically the models would predict how fishing, coastal degradation, and climate change would change marine life. Concurrently the models must provide concepts so that the observation will not be blind. At the same time the models are striving to predict what will live in the oceans, they must be tools for analysis of the past and present. They must help define the limits of knowledge: what is known and how firmly, what may be unknown but knowable, and what is likely to remain unknowable.

> Immanuel Kant cautions not to calculate before observing the past and present, and at the same time promises that modeling will assist observation itself.
>
> "Concepts without factual content are empty; sense data without concepts are blind ... The understanding cannot see. The senses cannot think. By their union only can knowledge be produced."
>
> *-Critique of Pure Reason, 1787.*

An examination of large predators, such as tunas, sharks, billfishes, and sea turtles that live on other smaller species, illustrates concepts informing models and models guiding observation. Hotspots of great diversity of species appear where tropical and temperate species overlap east of Florida, south of Hawaii, and east of Australia. These spots are important for many species at once, from plankton to sharks. Composing models with these facts, researchers predicted that protecting these spots from fishing would help threatened species more than closing any other area. Thus the interplay of concepts with content and observation is not blind.

IV. THE BASELINE OF KNOWN, UNKNOWN, AND UNKNOWABLE LIFE IN SIX OCEAN REALMS

A static census of the species now in the oceans might begin with a primary-school memory of the oceans from Antarctic and Arctic to Indian and Pacific plus important seas. Estimates of the diversity of marine species usually increase toward the equator, but Figure 8 suggests a much more complex pattern for big fish. Because this report forms a baseline for exploration, however, its ocean realms instead match the difficulty and technology of their exploration (Figure 4 and Table 1). We choose the name realms for these areas within which a difficulty or technology of exploration prevails. For explorers, we choose realms of the human edges, hidden boundaries, light and dark central waters, active geology, ice, and the microscopic. Some of the realms require subdivision into zones. For each realm and zone, we examine the known, the unknown, and unknowable.

The Human Edges

Nearshore

More than half of humanity lives within 50 km of the coast now, and projections raise the half to two-thirds by 2020. Thus, the majority of people can explore the nearshore – not far at high tide but farther at low.

People first exploited the sea near shore, walking out at low tide to eat its treasures. The first people to see an ocean may have walked out of an African savanna. Imagine their delight at a seemingly infinite supply of food that could not even crawl, let alone run away. Mussels, oysters, and their kin proliferate in the rich region where winds and tides deliver food from the phytoplankton pastures offshore, and streams deliver nutrients from the land. People still seem to appreciate the abundance of marine life near shore as they continue migrating to the coast.

The nearshore zone, including estuaries and bays, and the diverse ecosystems of coral reefs, rocky shores, and kelp forests provide essential breeding and nursery grounds for marine life. Seabirds abound in such numbers that they tell sailors that land is near. Its proximity to people brings waste from their activities.

The nearshore zone is relatively accessible to explorers and much is known about what lives there. Nevertheless, the lack of a challenge to explorers should not slacken the effort to measure changes in the census dependably along the millions of kilometers of the nearshore zone, which like the miner's canary, is crucial to detecting danger. A census must begin with a dependable baseline. Figure 9 separates the marine phyla with the most diversity of species from those with less, some relics of the earlier eras. The left panel of Figure 10 sets the rough baseline that science can draw now for these nine phyla. The first row of bars shows the number of species by groups in the nearshore zone. That the nearshore is only about 2 percent of the ocean's area but contains more than 6 percent of the known species, suggests it is relatively rich in species, in part because it has been intensively studied.

Despite the proximity of the nearshore zone to human settlement, some things will remain unknowable. Consider 3 cubic meters carved out of hundreds of kilometers of coral reef off New Caledonia in the South Pacific. The 3 cubic meters contained 130,000 molluscs belonging to 3,000 species, many not described. Extrapolation of these numbers confirms estimates that reefs contain fully 600,000 more species. Globally, mollusc species are currently being described at 300 per year. If all the taxonomists in the world describing molluscs worked on the 3-cubic-meter sample above, they would all be retired before it was finished! Being certain that all the species are found by extending the work to many more cubic meters challenges science. A volume, say, only 10 meters deep, 100 meters wide, and 1,000 meters long, a tiny fraction of the world's reefs, makes 1 million cubic meters.

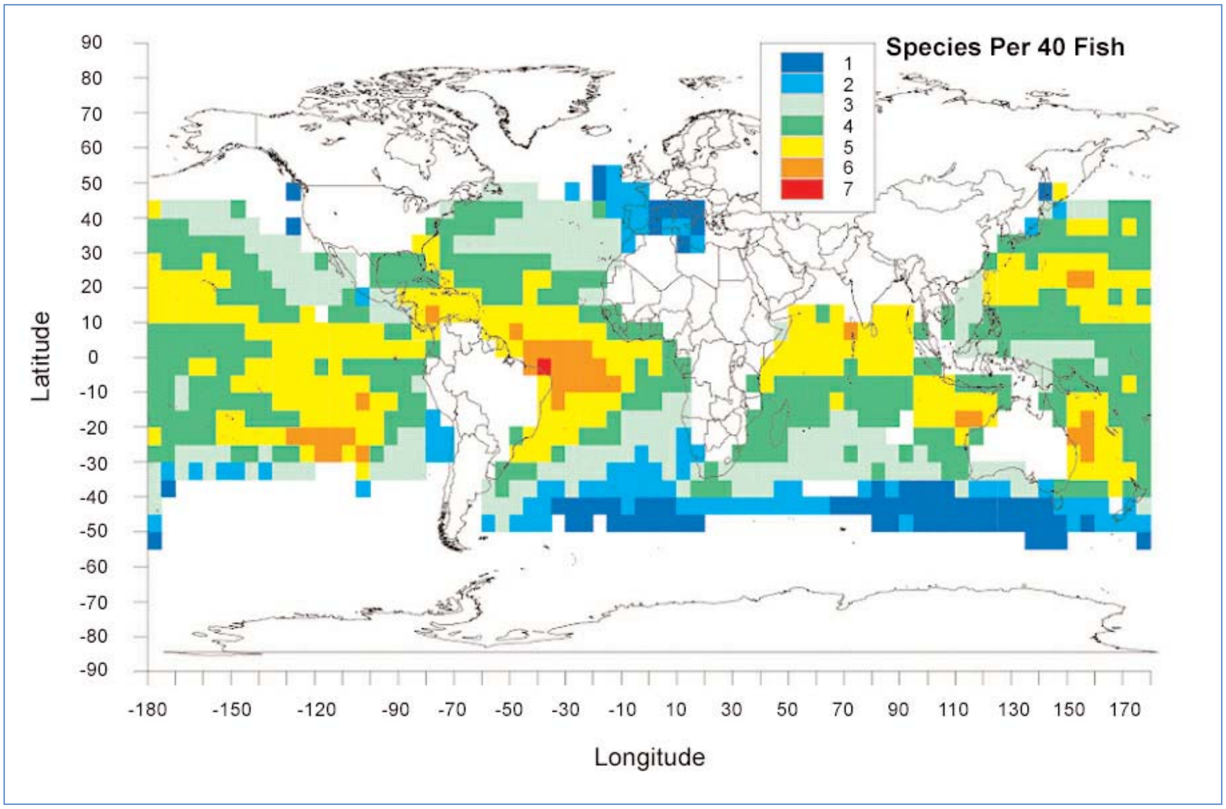


Figure 8. **Regional differences in diversity of large fish.** The number of species of big fish caught on longlines is a clue to the global diversity of marine life. The pattern suggests more complexity than an increase of diversity toward the equator. More detailed analyses of these records show clear localized "hotspots" of diversity for these big fish. Source: Worm et al. 2003

Realm	Zone	Area %	Major Unknowns
Human Edges	Nearshore Coastal	2 10	Distribution Abundance
Hidden Boundaries	Margins Abyssal Plains	7 84	Species Species
Central Waters	Light Drifters Swimmers Dark Mid-water Bottom-water	90 90 90 90	Distribution Distribution Species Species
Active Geology		2	Species, Distribution
Ice Oceans		7	Species, Distribution
Microscopic		100	Species

Table 1. Six ocean realms distinguished by the techniques and difficulty of their exploration. Some are divided into zones. Although vastness alone challenges explorers in some realms, all present challenging unknowns for discovery.

This brings us to the critical census question of the unknowable. If statistical models told us it would take a million cubic meters of reef to collect all the species, then even the nearshore species are unknowable. Coupling the challenges of the few specialized scientists and extensive sampling with such difficulties as typhoons and ice, mangrove swamps and isolated islands, means some species will remain unknowable even in the nearshore.

The first row of bars in the right panel of Figure 10 estimates the number of unknown – but knowable – species in the nearshore at 6,000 from all nine phyla. In light of the discussion above, the estimate is surely conservative.

Coastal

As humans changed from tools to technology, they moved from the nearshore toward the edge of the coastal shelf. An old Newfoundland shanty sings “This is the place where fishermen gather.” The first fishers to sail west across the Atlantic came to harvest cod. Nutrients from land and upwelling water fed the coastal fish abundantly.

Now nutrients plus such technology as ships with nets many kilometers long keep the coastal fisheries yielding 90 percent of total marine catch. The high 90 percent, however, cloaks the poverty of these fisheries compared with the waters 15th century explorers and native Americans fished. While humans affect fish directly by catching them, they affect them indirectly, too. The major cities of the world are coastal, and multiplying populations discharge agricultural, urban, and industrial waste, while coastal development paves watersheds and shores.

The interdependency of life in the moving fluid of the oceans, in particular the coastal region, suggests managing ecosystems as a whole both for fisheries and for the insurance and wonder of biodiversity. Managing an ecosystem begins with a baseline.

To date, 2,000 species of plants and animals have been recorded in the Gulf of Maine that Cabot explored. The 2,000 species range from microbes in bottom sediments to whales in the wind-driven surface. Globally, Figure 10 estimates a total of 12,000 species in this realm.

Although the riches and hoped-for riches in the coastal realm will continue drawing attention, it is impossible to take a conventional census of species like salmon that move continuously during their life cycle. Even knowing precisely how many salmon are in a particular bay today cannot foretell how many will be there tomorrow. There will never be enough equipment or ships to count salmon throughout the Pacific at the same time. However, reasonable abundance estimates can be made if migratory routes and speeds are understood. Listening devices on the seafloor spanning the continental shelf from near shore to the margin could monitor marine survival of thousands of species weighing as little as 20 g as they migrate along the coasts.

Even counting species in the coastal realm is bedeviled. Human activity transports species from one coast to another around the world. Neither introductions nor success seem to be predictable or avoidable.

On the other hand, consider the opportunity presented to identify and quantify the creatures in the Gulf of Maine. Because the temperature gradient from warm to cold is steep in the Gulf of Maine, a little global warming will move temperature zones a long way, which makes the Gulf a suitable sentinel for the effects of climate change. As a semienclosed sea on the edge of an ocean, the Gulf has steep gradients of temperature and tidal amplitude and diverse submarine and coastal habitats. For comprehensiveness, a census would include the Gulf of Maine, Georges Bank and adjacent Slope Sea, and the underwater mountains called the New England Seamounts. The census would encompass marine life along a food chain from microscopic bacteria through 1-gram krill to 100-ton blue whales. Billions of tiny worms and crustaceans live in the accumulated food on the bottom, missed by animals in the upper layer. Although some of the Gulf may seem pristine, it has a long history of fishing and shipping. Profitable species such as mackerel, herring, and lobster have flourished at times, but haddock and cod fisheries have now collapsed and wild salmon are endangered.

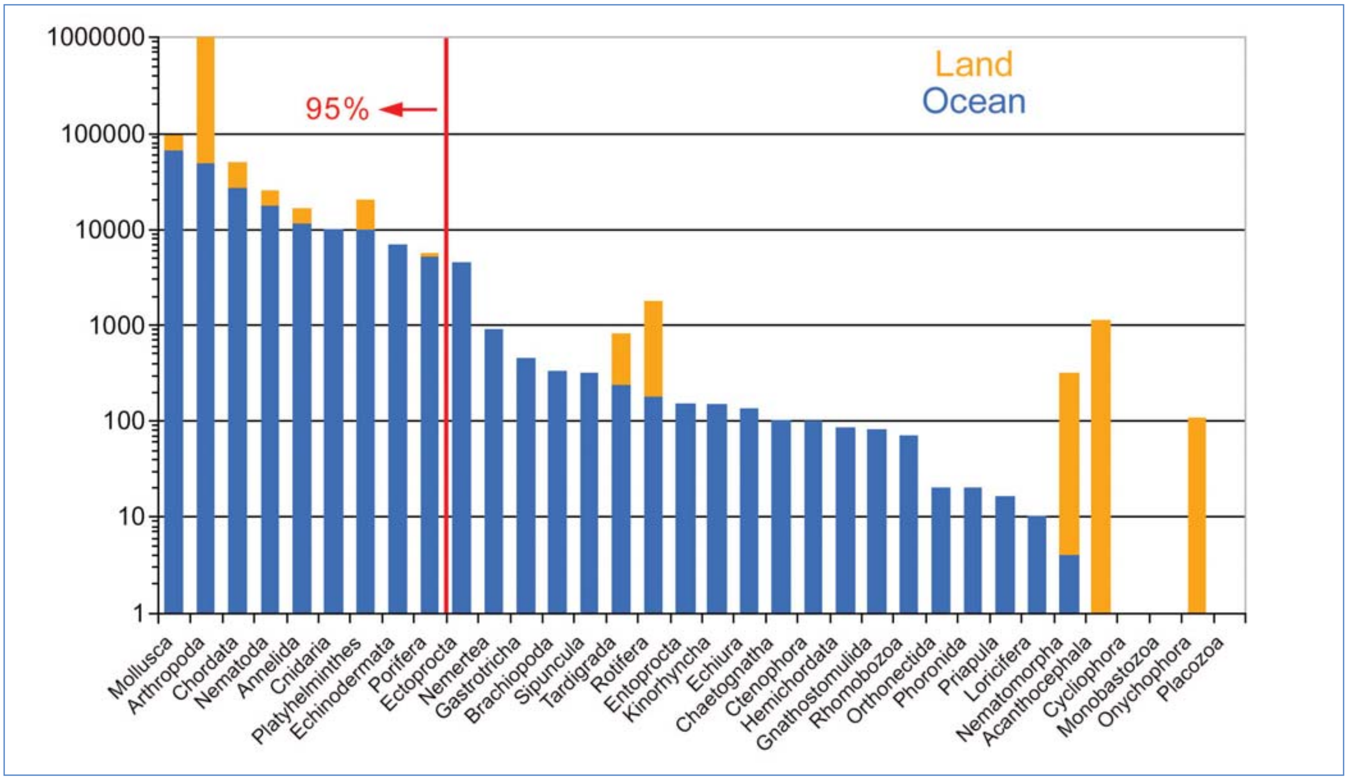


Figure 9. **Known species per phylum.** Most species of marine animals are in a few phyla. The phyla are the subdivisions of the animal kingdom. The height of the blue bars on the logarithmic scale indicates the number of marine animal species in each phylum. In the chart, nine phyla stand left of the red, 95 percent line. The analysis that follows focuses on these nine phyla that contain 95 percent of all marine animal species. On the logarithmic scale above the blue marine bars, orange bars indicate land species in each phylum. Note that the bars indicate number of species, not the number of individuals. Source: Brusca & Brusca 2003

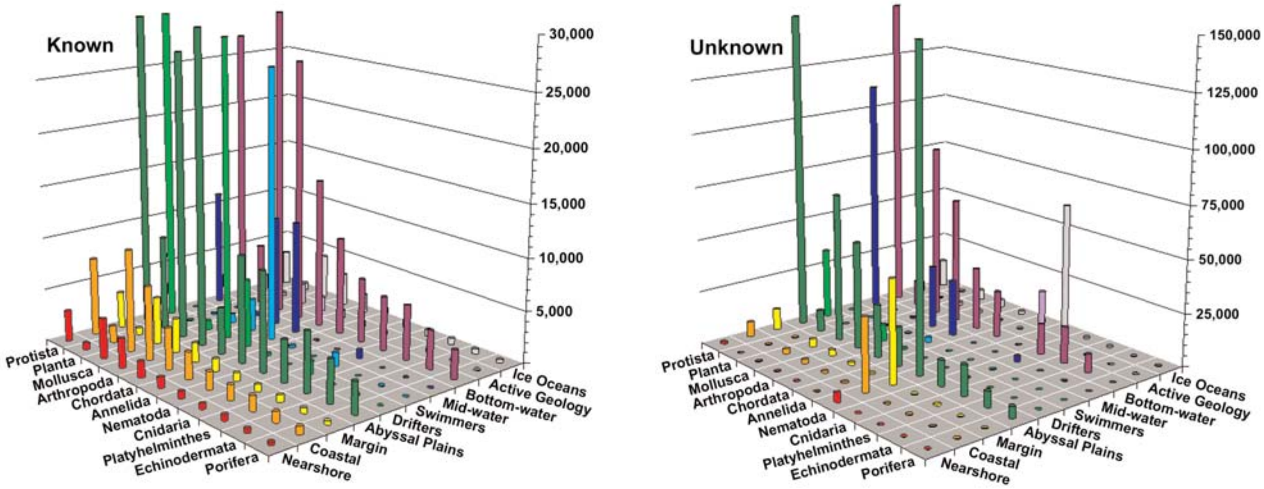


Figure 10. Estimated numbers of known and unknown species of the nine largest animal phyla, by realms. In the left panel are estimates of the known, and in the right panel, at a scale compressed fivefold for the greater numbers, are estimates of the unknown species. Single-cell (Protista) and plant (Planta) kingdoms are included for comparison. The known species were estimated from the number of known species and the area of each realm. The unknown numbers were estimated from the anticipated scientific effort devoted to phyla and to the sampling intensity in the realms.

The Gulf of Maine now includes a concentration of marine scientists with instruments and sensors appropriate for a census of marine life. The continuous change of water at a place in the ocean demands measurements of oceanographic properties as well as geographic location. For the requisite oceanographic and geographic context, acoustical and optical devices deployed from boats or operated remotely can be integrated with the Gulf of Maine Ocean Observing System, one of the most advanced "underwater weather" systems in the world. The Gulf's long historical record telling what used to live there can complement the census of what lives there now. Intense local interest suggests areas like the Gulf of Maine can be modeled in four dimensions, using databases of the known plus new exploration and censuses of the knowable. Models assembling "state-of-the-ecosystems" censuses from new knowledge plus the present knowledge of such connections as from bacteria and krill to whales are now a recognized requirement for sustainable fisheries.

The Gulf of Alaska offers an opportunity on a larger scale. The counterclockwise gyre of the Alaska Current and its cold, nutrient-rich waters support a diverse ecosystem. The ecosystem includes commercial species such as crab, shrimp, pollock, Pacific cod, mackerel, and halibut as well as sockeye, pink, and four other species of salmon. The ecosystem encompasses colonies of fur seals, harbor seals, spotted and ringed seals, sea lions, sea otters, kittiwakes, murres, and puffins. Oil spilling from the tanker *Exxon Valdez* in 1989 reminds that humans participate in the ecosystem, too. Teeming coastal migrations of marine life in this open gulf make understanding their movements even more important. As in the Gulf of Maine, fishers, sailors, and scientists wish to outfit the Gulf of Alaska for the assembly of the known with the knowable in a future census.

The Hidden Boundaries

Continental Margins

Beyond the coastal zone, continental margins and abyssal plains hidden beneath the waters bound the sides and bottom of the wide oceans. The New York Bight illustrates how canyons interrupt the gradual slopes of continental margins (Figure 11). At the limit of some continental margins are trenches more than 4 km deep. The deepest water and greatest pressure in the world lie at the bottom of the 11 km deep Mariana Trench in the eastern Pacific near the island of Guam.

Although fewer species are named on continental margins than on the coastal edges where fishers gather, the hidden margins support many of the same species and others associated with deeper waters (Figure 10). Like the realms of nearshore and coastal edge, the deeper portion of the continental margin is rich in unicellular protists, molluscs, and arthropods. In the upper portion of the continental margin, powerful currents circulating against the edge of the vast oceanic bowl fertilize a whole complex of life, which changes gradually downslope. The flow of the Gulf Stream around the northeastern Atlantic margin is 300 times that of the Amazon, the world's largest river.

The complicated habitats of the coastal margins make them a likely realm for new species to evolve. The canyons support dense and abundant assemblages of life on rocky bottoms. Oddities like the deepest plant and large, old corals and sponges living in trenches and canyons extend the range of species. Although difficult to explore, these special areas cannot be considered in isolation from the less dramatic expanses of the margins.

Because their distance from shore and depth – as at the limit of the Mariana Trench – have inhibited exploration of the margins until recently, it is hard to know even what we do not know. We do know that the sloping margins are often unstable and changing. New technologies and exploration for oil have revealed challenges few imagined a decade ago. Sonar and seismic images of the lower margins reveal that apparently uniform slopes hide mixtures of rock, sand, mud, and methane hydrates. Low temperatures and high pressures turn natural gas into an ice or slush that is buried under the mud like groundwater under the earth. Earthquakes, temperature changes, and the construction of drilling platforms can destabilize these mixtures and set off underwater landslides that alter local habitats completely. Some animals are buried, and others can feed on the energy-rich methane hydrates exposed. Periodic changes like El Niño or prolonged climate change affect the margins. The difficulty of continuous or even frequent observations in this realm hides how fast things are changing and will keep much unknowable.

Nevertheless, examples of discovery encourage the exploration of the margin, whose change and variety make it a likely source of the diversity throughout the vast abyssal plain below. The first hints of this came as the oil explorers began detailed mapping around the world and sampled promising sites for life that might be damaged by oil extraction. New approaches include fiber-optic cable networks and "landers" dropped from ships. Cable networks link sensors carrying information from the margins hundreds of kilometers across the coastal realm to shore. Like probes to another planet, landers sink to the margins, record events for months, and then release weights and float to the surface with their load of measurements and videos of life. Lander explorations of potential oil fields above the Porcupine Plain off Europe have found huge seasonal movements of mobile species. The potential to discover new life along with new oil in this realm is perhaps the greatest in the oceans.

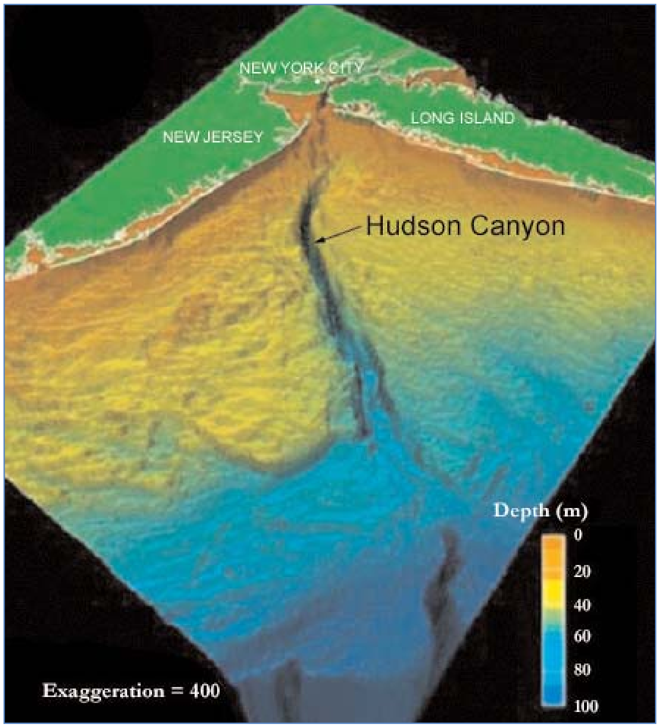


Figure 11. **A hidden canyon.** The New York Bight illustrates how canyons interrupt the gradual slopes of continental margins. Source: NOAA Ocean Explorer

Abyssal Plains

For aeons a marine "snow" of particles, some living and some not, has fallen through kilometers of water and accumulated in the abyssal plains at the bottom of the oceans. The silt of the plain extends wider than any other habitat on the planet and has accumulated 5 km deep in places, giving depth of silt the same scale as the ocean above. At more than 100,000, the many named species in the abyssal plain match its expanse and depth (Figure 10). The spectrum of species in this silt is rich in small organisms like unicellular protists, and various worms, but poor in larger animals like fish. The plain is home to as much as half of the species in several groups, including three groups of worms, crustaceans, and seastar kin. The accumulation of marine snow, its sheer volume, and its relative stability over millions of years account for this incredible diversity and abundance.

Altogether, the darkness, depth, pressure, and extent of the abyssal plain will combine to keep much of it unknown. Most species here appear to be extraordinarily sparse. Experts question whether even an intensive and expensive sampling program could describe the projected millions of new species.

The richness and extent of the abyssal plain, on the other hand, make it a happy hunting ground for new species, right panel of Figure 10. The hunting should be especially good for molluscs, crustaceans, and the roundworms called nematodes. Every technological improvement in diving will improve the hunting.

Hard nodules formed by bacterial action and enriched in heavy metals – such as manganese, iron, nickel, cobalt, and copper – litter the surface of the plain. Unusual, ancient chemical reactions nourished the bacteria, and easily extractable metals accumulated in the nodules. Although undersea miners have collected many samples, scientists have mined few of the samples for new species. The richness of the silt in the abyssal plain beckons the explorer, and commercial interest may even help pay the bills.

The Central Waters

The central waters of the oceans fill the vast bowl formed by the hidden boundaries. Sunlight penetrates and fuels photosynthesis within the top 200 m or so of water, enriching these waters that cover 70 percent of the planet and so feeding tens of thousands of species. A marine snow from the light zone falls into the dark zone between the light and abyssal plain, feeding still more species.

The Light Zone

The species in the light zone occupy two rows in the baseline of Figure 10. Plankton are mostly small or microscopic organisms, including bacteria and protists, that drift in great numbers in the water, and feed fish and other larger organisms. They drift because, for such small creatures, water seems as thick as honey. Because the swimmers are larger, they part the water easily.

The 50,000 species in the plankton row of the baseline Figure 10 are mostly protists and arthropods. That is, they are mostly unicellular organisms or miniature relatives of crabs. The plankton capable of photosynthesis, the phytoplankton, is the grass in the oceanic pasture, which converts carbon dioxide gas into 300 billion tons of food for tiny animals like krill that in turn feed the larger animals up the food chain. This is equal to all the food photosynthesis makes on land. Satellites that look at light reflected from the ocean give reasonable indications of the location, abundance, and even some kinds of phytoplankton present across most of the ocean surface (Figure 12). The farseeing eyes in the sky carried by satellites help find oceanic hotspots, equivalent to lush meadows on land.

The 20,000 species of swimmers indicated by bars in Figure 10 encompass both the largest mammal and the largest fish in the oceans. Even the largest swimmers, however, do not show up routinely in satellite images. Nevertheless, large ones, from whales to tuna to albatrosses and even some squid, can carry miniature electronic devices that report to satellites, which can thus trace the distribution and movement of some swimmers. Tuna, for example, traverse both the Atlantic and the Pacific oceans, some annually! For this dynamic component of the ocean life, the questions are less about species and more about distribution and abundance. If the same moving animals are counted on both sides of the ocean, catching one subtracts two from the misleading double count.

The uncertain movement of organisms in the light zone and the scarcity of scientists to monitor them render some knowledge unknowable. At their cruising speed of 20 km/h, the largest – the whales – could circle the globe several times in a year. The lush pastures of phytoplankton sometimes move thousands of kilometers in a year (Figure 12). Although the animal species found in the ocean have been cataloged for generations, generally by their physical characteristics, the corps of taxonomists who can identify species in particular groups is shrinking. At the same time, new molecular techniques are revealing that plankton is more complex than imagined. Apparently fierce competition in the light zone means that only small differences in shape evolve, rather like small differences in shape evolve in modern automobiles. Even using DNA sequences like barcodes to identify plankton species may not cope with the turnover rate of individuals within species in this huge zone with its abundant food.

Despite the currently unknowable in the light zone, examples of recent discoveries show the zone will yield to explorers. The assemblage of animals that live their entire lives in the light zone appears widely distributed, cosmopolitan, and even global. Nevertheless, DNA sequences can show many seeming cosmopolitan species, including foraminifera, diatoms, and copepods, cloak distinct species. Despite the global nature of the surveys and myriad DNA analyses needed, cooperation can make them feasible. International partnerships using ships of opportunity and a coordinated network of technicians, taxonomic experts, and biological oceanographers could complete analysis of at least the 4,600 described species in these three most abundant groups.

Analysis of continuous plankton recorders towed by commercial vessels in the North Atlantic for more than 50 years demonstrates the fruitfulness of collaboration. Figure 13 shows that the distribution of plankton species changed dramatically during the 1990s as the climate changed. The results of the collaboration could open the way to answering, "How did this change of plankton affect the large, long-lived animals atop the food chain?" Or answering, "Do the rapidly reproducing plankton species actually change their genetic characteristics in such decadal cycles, or just their distributions?"

Molecular methods of identifying species now open opportunities for discovering new species. Novel sequences of DNA will indicate the diversity in lush meadows and inevitably focus attention on little-studied areas such as the North Pacific, shown in Figure 12. Most of the knowledge and perhaps new cryptic species discovered in this component will be at the genetic level. Do all the tiny critters that look alike have the same genetics? If so, how do they stay genetically homogeneous over such vast distances? Can we expect climate change to wipe out some local species and dramatically alter global production, or are they able to adapt rapidly? If they do not adapt rapidly enough, could new genes be added that spread rapidly enough to alter carbon dioxide fixation? Photosynthesis of food from carbon dioxide, especially in the vast light zone of the oceans, supplies much of the oxygen that we and the chirping canary breathe.

The Dark Zone

Extending down more than 4,000 m into pitch-blackness, the dark zone's volume exceeds the volume of the 200 m light zone manyfold. Even in the dark most animals must feed ultimately on plants from nearer the surface, which deliver a marine snow into the dark zone. The snow of wastes, carcasses of large animals, and swimmers venturing below their normal light zone feed the animals in the dark beneath. The mass of organisms declines with depth, modified by mid-ocean ridges that affect circulation just as mountains affect weather.

At best the technology to explore these dark, deep waters is brand-new, and at worst it is still inadequate. The challenge of exploration, our criterion for distinguishing realms, justifies the two rows of species numbers in Figure 10. Some 20,000 species live in mid-water; arthropod crustaceans and chordate fish predominate, but strange floating jellyfish and molluscs are also important.

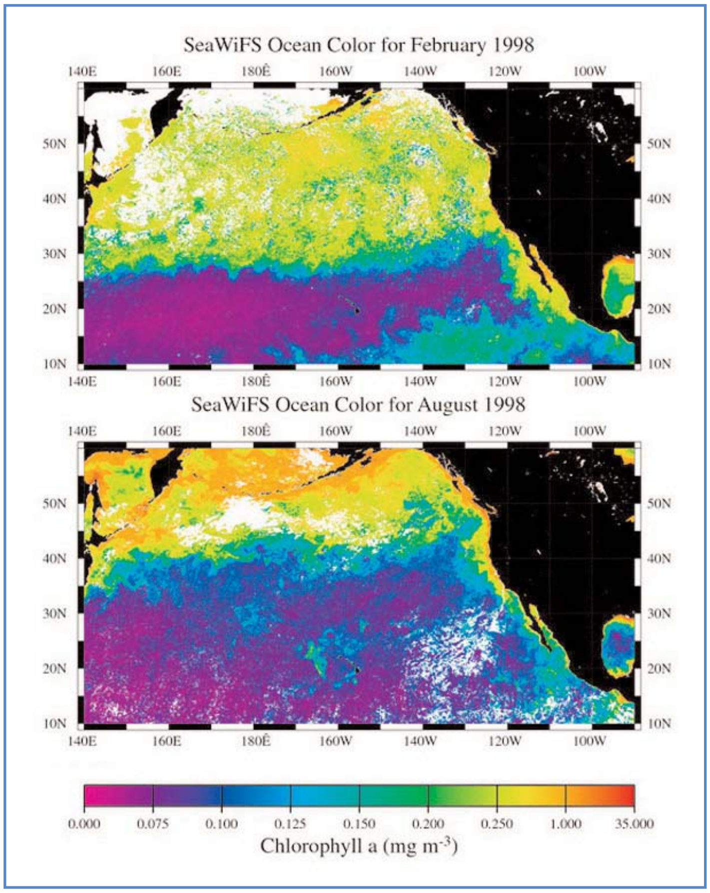


Figure 12. **Density of chlorophyll in surface water of North Pacific.** The plankton capable of photosynthesis is the grass in the oceanic pasture, which converts carbon dioxide gas into 300 billion tons of food for tiny animals like krill that in turn feed the larger animals up the food chain. This tonnage equals all the photosynthesis on land. Satellites that look at light reflected from the ocean find the location, abundance, and even some kinds of phytoplankton during the winter (top) and summer (bottom). Thus, the satellites find oceanic equivalents of lush meadows and track their movement. Source: Polovina et al. 2001

A broader spectrum of species distinguishes the bottom water where 100,000 live. Although molluscs and arthropods are the most frequent species near the bottom, Figure 10 shows a broad spectrum of species present in substantial numbers there. The falling snow collects at the bottom, so food is plentiful, if not especially varied. Creatures here can also rest on the bottom and do not need the strange and specialized floatation and swimming structures common in the mid-waters.

Two recent discoveries in the dark zone illustrate both the difficulty of exploration and the wonders to be seen. At the depths they inhabit, the two big and powerful animals pictured in Figure 14 can swim faster than most equipment can pursue them, and so they are nearly impossible to catch. The squid with arms like jellyfish tentacles has been photographed during oil explorations all over the world, but no specimen has ever been caught. Although nearly 9 m long, the squid in the photograph is small compared with the famous giant squid, which has never been filmed alive. Giant squid are better known because dead ones turn up in whale stomachs or float to the surface.

Although Big Red, the meter-wide jellyfish with muscular arms like a squid pictured in Figure 14, was glimpsed on video in 1993, 10 years passed before a specimen could be caught and named by the rules of taxonomy.

In the dark, either at 200 m or 5 km below our normal habitat, at crushing pressure, many species may never be caught and named. And, when they are caught and brought to our habitat, their shape will change. So the time needed to collect samples and so many animals to name will keep many things in the dark zone unknowable.

The very difficulty of exploring the dark zone challenges explorers. The potential for discoveries of species new to science is especially great for floating squid and octopus and gelatinous forms from many phyla below 1,000 m. Even though gelatinous species from the deep may have to be described from photographs, their discovery will nevertheless subtract from the unknown. Even among the best-known groups, the fish and crustaceans, there is still a striking lack of information about easily sampled groups. The easily sampled include small, shrimplike crustaceans called copepods and the somewhat larger, 2-5 cm animals that live in bottom water near ridges. The numerous unknown species projected in the right panel of Figure 10 reflect the difficulty of filtering out the very small and capturing the large, quick species in waters several kilometers away. Imagine trying to catch a butterfly or an eagle on the other side of town with a long-handled net or a radio-controlled model airplane. New technologies make this possible, but not easy.

There is much information on mid-ocean fishes, including those inhabiting deeper layers, yet surprisingly few studies have focused on the mid-oceanic ridges to learn the ecology and distribution of the fishes. An exploration of the Charlie-Gibbs Fracture Zone in June 2003 illustrates the opportunities, even close to major marine science centers in Europe and North America. The Fracture Zone is a 3,600 m deep pass through the Mid-Atlantic Ridge near 52°N, the deepest between the northeast Atlantic and the western basin. Russian and U.S. scientists dove to 4,500 m on its flank in the Russian Mir submersibles. Explorers encountered dense marine snow aggregates suggesting high production in the light zone with a rapid fall into the dark beneath. Never before explored by humans, the abundance of life was unexpected, particularly in rocky areas where beautiful sponge gardens and juvenile fish were seen.

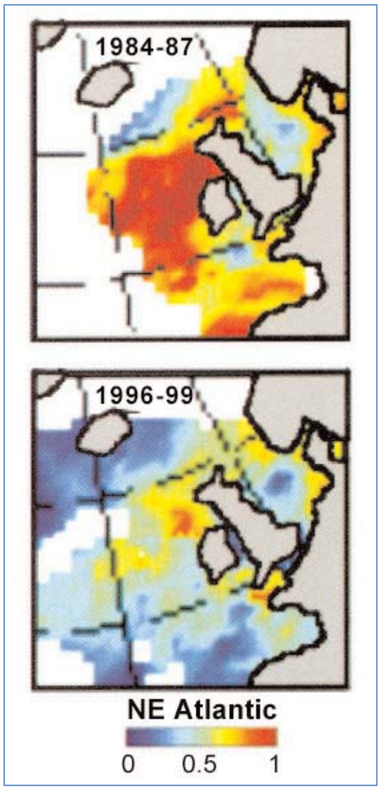


Figure 13. **Plankton abundance.** Continuous plankton recorders towed by commercial vessels in the North Atlantic for more than 50 years demonstrate the fruitfulness of collaboration between vessels of convenience and oceanography. The maps show the change in plankton abundance from 1984/87 to 1996/98 that the recorders revealed as they sampled along millions of kilometers. Source: Beaugrand et al. 2002, Sir Alister Hardy Foundation for Ocean Science

The Active Geology - Seamounts, Vents, and Seeps

As volcanic cones and eruptions plus earthquakes testify on land, seamounts, vents, and seeps testify to active geology under the ocean. To qualify as seamounts, illustrated by those near Hawaii, underwater volcanoes must rise at least 1,000 m from the abyssal plain without appearing above water as an island (Figure 15). At mid-ocean ridges interactions among the liquid magma from Earth's core, gases, and water at extreme pressures create high-temperature deep-sea vents rich in high-energy chemicals that feed bacteria at the base of unique food chains. At many continental margins, groundwater and oil seep out of rocks to feed bacteria. The disturbed flows at seamounts and the reactions that make food without light at vents and seeps allow biodiversity to evolve. Although the technology to explore these features may differ, isolation is common to both. Research at these sites shares the need for comparing species and behaviors that colonize and sustain rich but widely separated populations.

The left panel of Figure 10 sets the baseline of 6,000 species. Vents and seeps were only discovered 25 years ago, but 700 new species have already been described, from a few dozen sites. They are rich in immobile bottom molluscs and annelids that often encourage growth of bacterial associates to take advantage of unique chemistry. More mobile crustaceans are also around, but fewer are known, most likely because they avoid slow sampling gear. Within the active geology realm, seamounts, which interact with water currents, are especially rich in mobile fish and squid that feed on drifters trapped in eddies. Large mammals often dive to feed on them, and recently they have attracted a new mammal that is targeting them for fisheries. Recent explorations of seamounts found that 15-40 percent of the species collected were new to science and likely to be found nowhere else.

The water and oil seeping out of rocks draws a similar spectrum of phyla, but often different species in shallower water. Seeps are often associated with oil-bearing geology, so new information about them is accumulating rapidly as drilling moves offshore.

A detailed exploration of more than 30,000 seamounts is unrealistic. Only about 200 have been sampled to the present. Although the number of vents and seeps may be smaller, exploring all of them is also unrealistic. The 350°C water and dense black cloud of metal particles from vents hinders exploration locally but makes it possible to detect vents with probes trailing from surface vessels. The most interesting habitats in these systems are minute by ocean standards, typically 10 square meters. Finding them initially and then getting close enough to sample are major challenges. Any sampler dropped over the side will hit the vast abyssal plain, but much more sophisticated equipment with video or sonar detectors is required for this fine work. In contrast to the tiny venting chimneys of life, their cooler, slower, oily cousins, the seeps, may cover hectares of seafloor, but no one has yet dared estimate their global extent. The active geology that distinguishes this realm introduces a degree of chance that, like their myriad numbers, makes some knowledge of the realm unknowable. A vent may come and go in a decade or two.

The varied topography of the realm of active geology creates unique biological communities, whose differences should reveal the connection between physical characters and ecosystems and so allow generalizations over the thousands of seamounts, vents, and seeps of the realm. Like islands, they are isolated. The realm's active geology exemplified by the water above vents makes it a natural laboratory for evolving new species that may spread or remain isolated. A recent investigation of the biogeographic value of chemosynthetic systems has revealed that they are like oases in the deep, supporting life and spreading species richness.

The association between seeps and oil exploration means that they will probably be sampled first, but the deep vents may also contain critical information. The first research dives to vents at the Triple Junction in the Indian Ocean recently identified species also found at Mid-Atlantic Ridge vents. This connection between isolated spots separated by many thousands of kilometers was a surprise but could be explained by a deep cold current that forms in the North Atlantic and flows through the Indian Ocean all the way to the Pacific. Climate models predict that this "conveyor belt" could stop if the Arctic ice cap melts sometime in the next 100 years. Human assessors naturally ponder the climatic consequences for life on land, but the impacts on deep ocean life may be much more immediate. Figure 10 estimates 6,000 unknown species awaiting discovery in the realm of active geology, but the number could be much larger. The fraction of this realm that has been sampled to date is too small to reveal a clear pattern. Discovering the factors contributing to the unique assemblages of life in isolated topographic patches may be a key to predicting the diversity in the oceans.

The Ice Oceans - Arctic and Antarctic

In the cold and inhospitable oceans near the poles, photosynthesis still proceeds. Microscopic algal diatoms absorb light transmitted through the ice and feed a spectrum of life from crustaceans to fish to mammals, like seals and narwhals. Even animals at the top of the food chain and out of the water and on the ice, like the Arctic bears and Antarctic penguins, ultimately depend on these tiny plants at the bottom of the icy food chains. This frozen realm is distinguished both by its shrinking size as climate warms and by obstacles to its exploration.

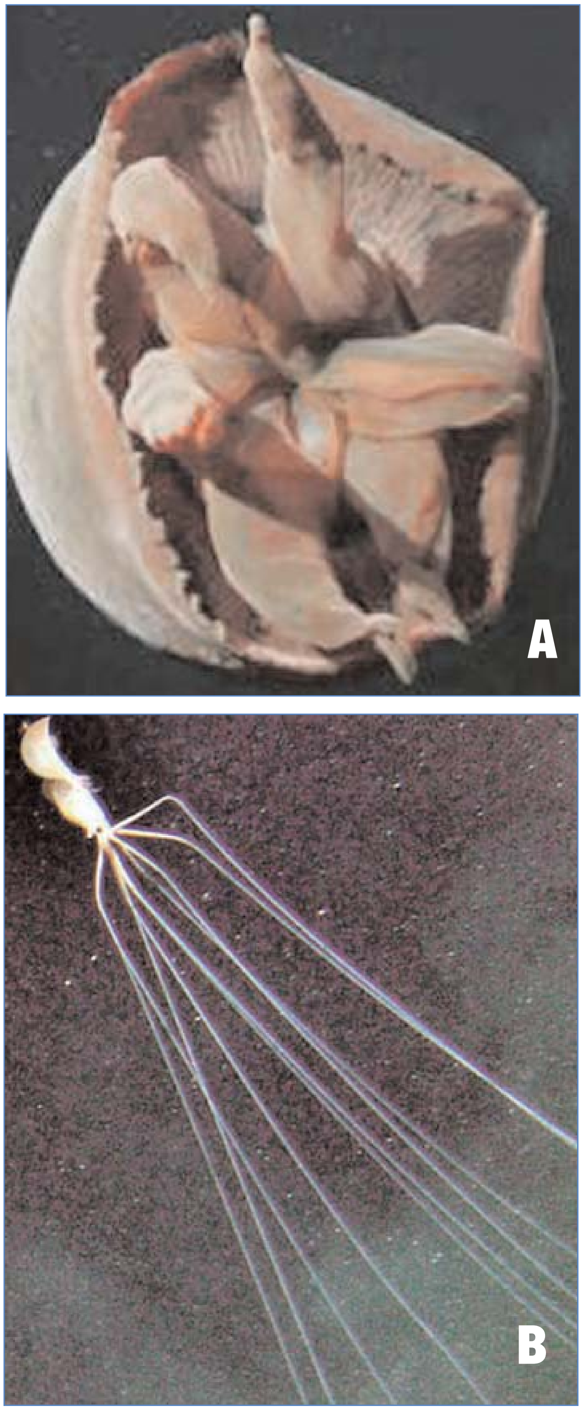


Figure 14. **Recently discovered animals.** Although sound and sonograms can determine the presence and locate an object underwater, most taxonomists identify species by their appearance in the light. (A) Big Red (Tiburonia granrojo) can reach up to a meter across. The jelly was "discovered" and named by researchers at the Monterey Bay Aquarium Research Institute (MBARI). This photograph was taken during a remotely operated vehicle (ROV) dive on the Gumdrop Seamount under the direction of scientist Dave Clague. Image courtesy of MBARI/NOAA. (B) The 9 m long squid with arms like jellyfish tentacles on the right has been recorded on video taken during deep-sea dives around the world, but no specimen has ever been taken. Image courtesy of NURP and the National Undersea Research Center at the University of North Carolina, Wilmington.

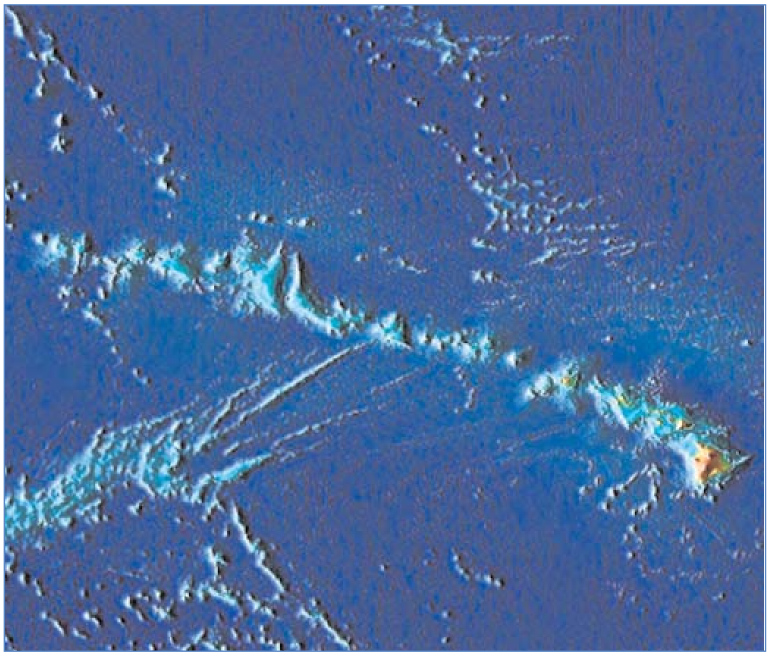


Figure 15. **Hawaiian seamount chain.** Seamounts are ghosts of volcanoes. Illustrated here by ones near Hawaii, they rise at least 1,000 m from the abyssal plain without appearing above water as islands. Underwater volcanoes, vents, and seeps all testify to active geology under the ocean, but seamounts need not be active. Courtesy of NOAA/NGDC, Boulder, CO, USA.

Each ice ocean affects climate and will be affected by its change. Nevertheless they have distinct characters (Figure 16). Nearly surrounded by the barrier of continents and Greenland, the Arctic is the smallest and least explored ocean, and its Canada Basin the least-disturbed and least-sampled water on the planet. In contrast, wind-driven waters churn around Antarctica as in a giant mixing bowl, moving organisms among the Atlantic, Pacific, and Indian oceans.

Although the Arctic is the smallest ocean, remote and made inaccessible for most of the year by heavy ice, some small drifting animals, such as copepods, are reasonably well studied. Marine life is reasonably well explored in the shallows of the large continental shelves like the Chukchi, Bering, Laptev, and Kara. Much money and great scientific effort have been invested to understand Antarctica's role in planetary climate and biology. During the last decade, knowledge of its role in both atmospheric and oceanic dynamics has advanced dramatically. Biological sampling has been extensive. Despite the harsh and unique environment, the number of species in the icy oceans has approached 20,000 (Figure 10).

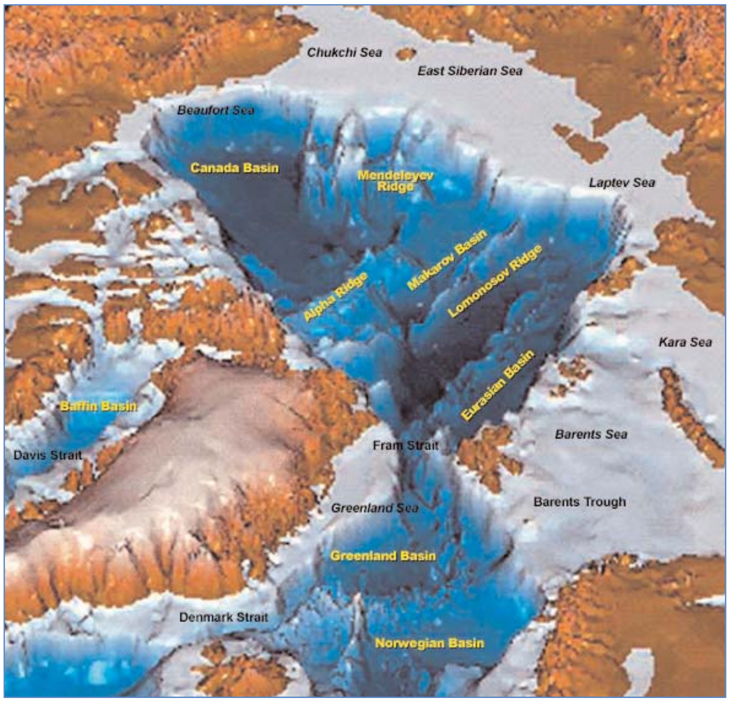
The polar realms exemplify regions difficult to explore and still unknowable for practical reasons. The sea ice and plankton communities are especially poorly studied during winter. Delicate groups, such as gelatinous plankton, protozoa, and animals living in cracks in the sea ice are virtually unstudied for their species richness and distribution. The coastal fjord systems of the Canadian Archipelago and Greenland are among the least explored areas, and the Eastern Siberian Shelf is still comparatively underexplored. Harsh conditions saved the Antarctic region from human influence until technologies finally made it accessible, and now international treaties keep it largely free from exploitation. The difficulties of exploration plus unforeseen changes that may accompany warming plus a lack of economic incentive may for a long time keep much unknowable in the icy oceans.

Because harsh conditions dominate the reasons life in icy oceans may be unknowable, technology can change the unknowable to the unknown. Submarines, beginning in 1931 with Sir Hubert Wilkins' attempt at a polar voyage and extended by the 1958/9 journeys under the North Pole and surfacing by the nuclear-powered Nautilus and Skate, show technology can first render the unknowable the unknown and then the known.

The right panel of Figure 10 estimates that in the ice oceans the unknown species are richly nematodes and protists. Large opportunities lie in interpreting the samples already collected in Antarctic waters and in exploring the neglected cracks in the sea ice, the coastal fjords of the Canadian Archipelago and Greenland and the Eastern Siberian Shelf. A recent international expedition to the Canada Basin using the newest under-ice technology, discovered and filmed large schools of arctic cod between the layers of pack ice. Normally bottom feeders, they were grazing on upside-down algal pastures. This surprising upside-down world encourages exploration under the ice.

The Microscopic

The cross section of Figure 3 does not show the final realm, the microscopic, because it is ubiquitous. The distinct technology for exploration of organisms hidden or nearly hidden from sight by their small size, however, separates the microscopic as one of our realms. The realm encompasses the prokaryotes and protists, the minute microbes without complex cell differentiation that do not belong to the kingdoms of plants, animals, or fungi. In Figure 10 the realm of microscopic cuts across the other realms. One might say that the citizens of the microscopic realm hold dual citizenship, many in the realms of drifters in the light, in bottom water, and in the abyssal plain. The microbes in the oceans make up for their minute size by their numbers. The 10^{30} microbe cells in the ocean constitute more than 90 percent of the mass of all living things in the oceans. Some of the cells that perform photosynthesis make oceanic food from carbon dioxide, while others break it down. Others turn the nitrogen, sulfur, iron, and manganese cycles. And still others may have created the oil deposits now being pumped.



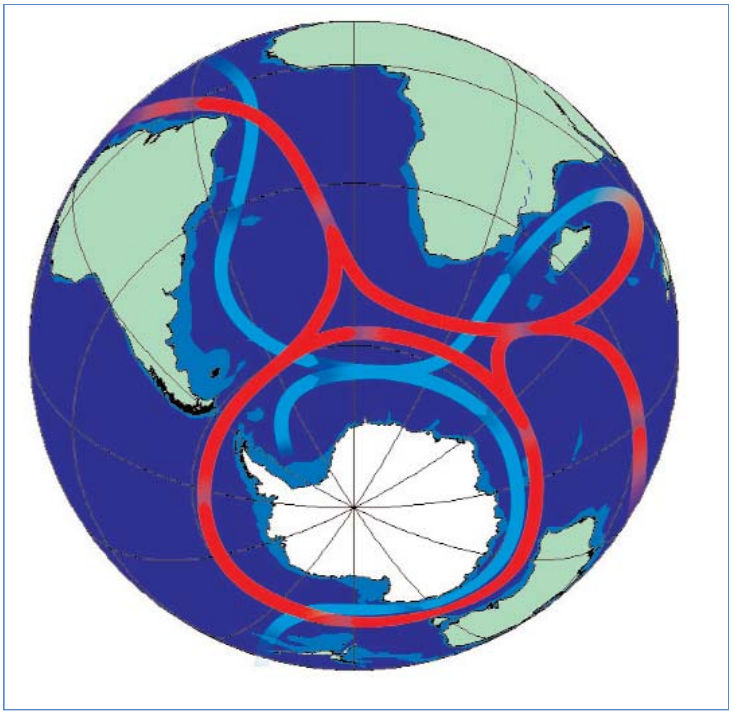


Figure 16. **The polar, ice oceans.** Isolation from other oceans characterizes the Arctic Ocean, and circulation typifies the oceans around Antarctica. Images courtesy of Arctic Research Office, NOAA and British Antarctic Survey.

Because prokaryotes have simple shapes, microbiologists have separated relatively few kinds by morphology, staining, and metabolism. Even students of protists using a wider range of characters for differentiating between kinds have described fewer than 30,000. Recently new species of microbes have been found very deep in seafloors.

Although molecular analysis may give clues to microbial evolution, the ready switching of genome fragments among microbes will obscure the time when species and physiology branched. Also uncertainties about global change will frustrate prediction of microbial biodiversity. Myriad possible interactions and pathways will beset predictions of future evolutionary trajectories.

Analyses of genomes are being accelerated by advances in gene sequencing and by high throughput in studying genes, the proteins they encode, and their pathways. Aiming these new techniques at the 10^{30} microbe cells in the ocean promises the discovery of diversity, much rising to or above the level of differences between species. The discovery a quarter century ago of Archaea, an entirely new domain of microbes distinct from bacteria and living in extreme environments, foreshadowed the explorations that DNA genomics makes possible. The new methods can speed such analyses.

A 12-year study of the gyre of warm water circulating in the neighborhood of Hawaii provides another example of discovery. Where the marine community had been thought uniform and stable, exploration across time discovered instead that changed circulation increased the abundance and activity of nitrogen-fixing microbes. The shift in microbes, attributed to the 1991/92 El Niño, altered the community from one limited by nitrogen to one limited by phosphorus.

A microbial soup stirred by wind and tide fills the great bowl of the oceans. New studies of microbial genomes are uncovering the mind-boggling diversity among the myriad microbes that permits the selection of populations to fit the circumstances brought by the stirring within the bowl. Some of the diverse microbes suffer fewer disadvantages from less phosphorus, some from less nitrogen, some from less iron. And conversely, some of the diverse outpace others when phosphorus, nitrogen, or iron becomes abundant. Thus, who converts carbon dioxide from the air into food, and how much they convert, changes. Then the atmosphere that supplies the carbon dioxide changes, and the life that eats along the food chain alters, all the way to the whales and the fishers straining the oceanic soup. Genomics and a tenacious census can make these microscopic mechanisms and global outcomes of marine life known.

V. TECHNOLOGY FOR DISCOVERIES

Because humanity is terrestrial without the lungs of dolphins or gills of fish, exploring beyond the baseline of present knowledge depends wholly on technology. New technology can enable subtraction from the unknown. Revolutionary technology can even subtract from the practically unknowable. A sample of technology shows the promise of success.

Commercial and Military

Because a day at sea in a scientific vessel costs from $10,000 to $100,000, the goal of research can rarely sustain exploration by itself. Thus, the Nautilus went beneath the polar ice for military reasons. And the foundation of the 400-year record of Figure 1 is commercial fishing. Commercial vessels towing instruments recorded the decade of plankton abundance in Figure 13. Exploiting the opportunities offered by the increasing world fleet of commercial ships, the platforms for pumping fuel, and the observations already made can be called a new technology.

The plankton recorders that the Sir Alister Hardy Foundation has been supplying to shipping companies to tow across the North Atlantic for more than 50 years made Figure 13 possible. The ships towing the recorders are called vessels of convenience. Oil tankers now tow recorders in the North Pacific, and soon supply vessels in the southern oceans will join them in towing. The Ocean Biogeographic Information System (OBIS) will incorporate the catch in these recorders as they sample along millions of kilometers. The voluminous data will be both opportunity and challenge for analysis.

The world's fishers have been reporting their catches to the UN Food and Agriculture Organization for decades. Recently OBIS made such information more practical to analyze. The OBIS group for the Gulf of Maine combined the fishery information with the number of overwintering fish species, with satellite indications of photosynthetic pigment for synthesizing food, and with bottom currents. The combined picture suggested a critical habitat for fish on the Canadian side of Georges Bank. Remotely operated vehicles inspecting pipelines photographed the squid for Figure 14. Participants in components of the Census of Marine Life (CoML) are integrating into OBIS the priceless samples collected by oil companies in Britain and Brazil and by mining prospectors in the Pacific abyssal plains. The organization to take advantage of opportunities can be called a new technology.

Sound

The word technology implies instruments, and much new technology is. Sound can both count and identify marine life. The distinctive voices of animal species identify them by their acoustic signatures. Tiny coded ultrasonic tags in juvenile salmon record their passage through listening "curtains" along the coast. Sound emitted by instruments can show their shape. In the beginning, SOund NAvigation and Ranging (SONAR) was simply a listening device created to detect icebergs and submarines. Later sidescan sonar transmitting sound from a towed mechanism explored a cross section perpendicular to its path. Now experimental units send out broadband sound that creates virtual images like fetal sonograms. The sonograms visualize individual fish and even differentiate species. The Norwegian research vessel *G.O. Sars* was designed to test the limits of the most advanced sonar in the MAR-ECO project. Scientific cruises like these calibrate and interpret sonar images, but global sampling requires commercial cooperation. Researchers in the Gulf of Maine and in South America census projects of CoML are standardizing and calibrating continuously recording sonar on fishing vessels. They can become vessels of convenience to explore the middle depths as the plankton recorders underlying Figure 13 explored the upper level.

Light

Although sound and sonograms can locate an object underwater and sometimes identify it, taxonomists identify species by their appearance in the light. A photograph, for example, identified the 9 m squid in Figure 14. In clear water a predatory shark can identify its prey in a cone of vision some 60 m ahead. One can envision exploration with a device combining sensors as sharks combine senses as they hunt. Already a TV camera combined with a multibeam sonar has simultaneously identified and located fish and the surrounding plankton that they eat. On a broader scale, a lidar emitting pulsed laser beams from an aircraft flying overhead has scanned wide areas for animals swimming near the surface of the ocean and identified coral reef habitats.

Up close, a signature of luminescence can identify animals. Luminescence characterizes more than 90 percent of the animals in midlevels of water. The spectrum of luminescence plus the luminous shape outlined comprises the animals' signatures. Far away, an airborne TV camera can detect schools of fish by the luminescence from the plankton that the fish stimulate as they swim by.

Telemetry

The allies called vessels of convenience tend to travel standard routes, avoid difficult seas and seasons, and cannot conduct sampling that compromises their primary mission. Oceanographers need allies of other species.

Wherever the ocean is productive, predators evolve to find and feed on the marine life. If some top predator is not going to some water, little biology is there to know. The original idea was to trail or shadow predatory animals to find concentrations of organisms, but improved telemetry by satellites has made them full allies. For example, elephant seals were fitted with transmitters that revealed their positions when their heads were out of the water. Recorders on their backs measured depth and temperature. These allies have annually reported their trips for thousands of kilometers from California to Alaska since 1997 (Figure 17). In three years, nine seals reported 76,000 temperature profiles as they dove down hundreds of meters several times each day. Sharks, tuna, and albatrosses have reported similarly. Several species tagged in the same region reveal what is in their food chain. Ten species are now reporting to satellites from the North Pacific.

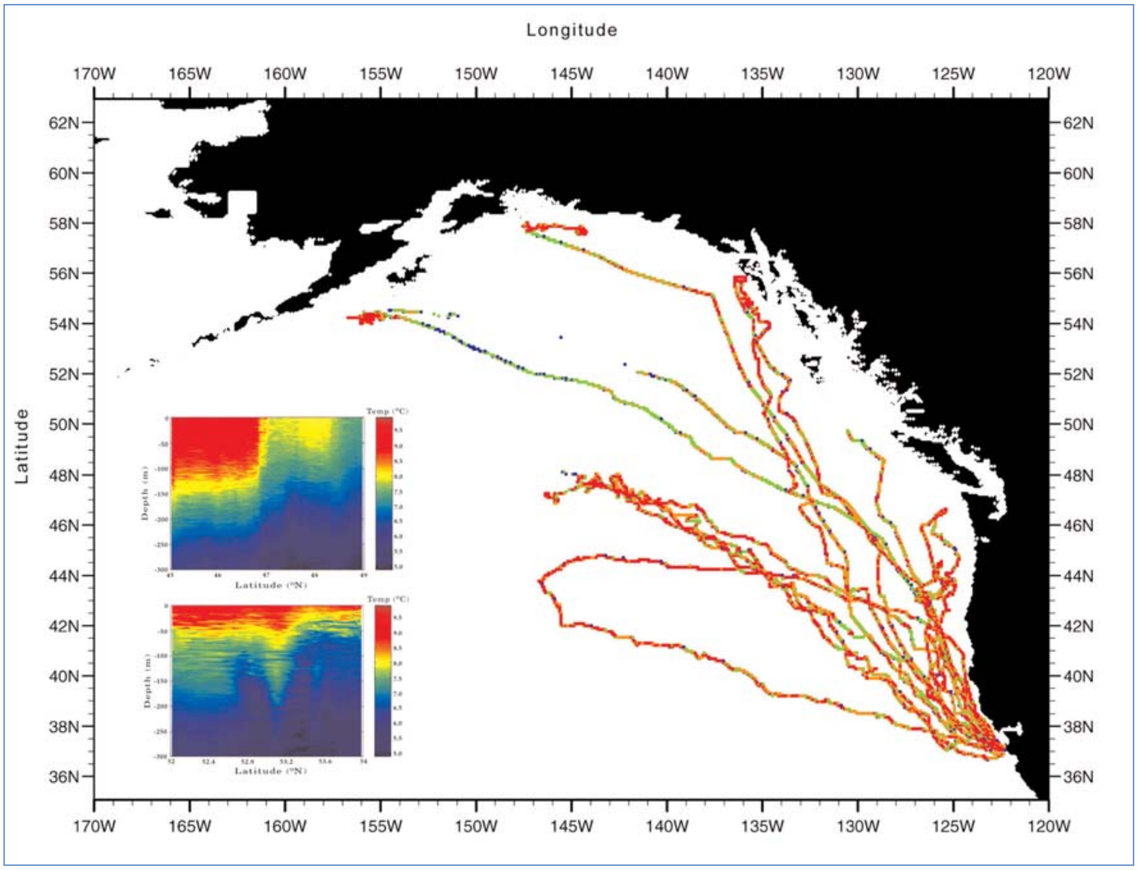


Figure 17. **Exploration of the Gulf of Alaska by seals from Monterey Bay.** Fitted with electronics, marine animals—like vessels of convenience—become allies of oceanography. Elephant seals were equipped with transmitters that revealed their positions when their heads were out of the water, while recorders on their backs measured the depth and temperature of the water. Since 1997, they have annually reported their trips for thousands of kilometers from California to Alaska as mapped. In three years, nine seals reported 76,000 temperature profiles as they daily dove hundreds of meters. The inset shows some temperature-depth profiles returned along hundreds of kilometers, defining currents and ocean layers rising from 5°C at 300 m to 10°C at the surface. Ten species are now reporting to satellites from the North Pacific. When several species are tagged in the same region, they reveal what they eat. Sources: Boehlert et al. 2001, Block et al. 2002

Genetics

The information collected by vessels of convenience, sonar, and allied animals floods archives already well stocked. The addition of species foreseen in Figure 10 needs new technology. The analogy comes to mind of a supermarket identifying its myriad goods from oatmeal to shoelaces and lightbulbs to frankfurters. The market must know which good needs restocking, which price needs cutting and what to charge an impatient customer for the 30 items in the cart. The universal product or barcode meets the need. It can distinguish 100,000 million species of products by 10 options at 11 positions on a short, printed strip of paper.

The recent saga of sequencing the human genome has familiarized all with the fact that along genes the options of four compounds encode the information to differentiate a human from a worm. A scanner for the compounds should turn the compounds along genes into a barcode already printed on genes by nature and thus cope with the flood of information about marine life.

Provisos must, of course, hedge this simple vision. The whole genome of the many samples scooped from the ocean remains costly to decode. Happily, only part of a cell's genetic material need be targeted for decoding. To be practical, a gene target must be easily amplified into a quantity for analysis. It must be essential and thus present across a wide spectrum of life. And like genes used for criminal identification, it must vary enough to resolve closely related kinds of organisms without merely differing among individuals. The cytochrome oxidase I gene in the mitochondria or powerhouse of cells has been nominated for the barcode of marine animals. Thanks to the technology developed for the human genome, sequencing a cytochrome oxidase I gene costs less than the jar to store a specimen and the time to label it.

The establishment of what might be called "ground truth" holds the challenge for establishing a barcode of life. The barcodes of known specimens as in museums must be determined to provide the references for comparison. Comparison with the references can then identify some specimens as already known and named and thus ensure that others are most likely new. Barcodes can assist the few marine taxonomists to focus their precious powers of description on the new and special. Placing the barcodes and images of the references on the Internet will, of course, then realize the hopes embodied in the analog of the supermarket scanner.

CONCLUSION

We know much about ocean life. From whales to bacteria, scientists have named 210,000 species in the oceans. Much of the known is new. A generation ago we did not know that hot vents oozed on the ocean floor into unique fauna and flora or that great squids swam far below drilling platforms. In this generation we have reached back and begun to visualize the oceans before fishing. We can now see the Caribbean as Columbus did, teeming with 30 million green turtles rather than the million today. Envisioning turns into explanation, for example, of the changing energy flow through the community of life on Georges Bank when fishers remove cod and haddock. Ahead, sharing and using observations already made; exploring with submarines, sonar, and cameras; tracking with telemetry; and decoding genes, we can add thousands of species to the census of marine life. Ahead, we can begin assaying numbers and biomasses to get the quantities and distributions that constitute a proper census.

Expecting great surprises, we cannot fully know what we do not know and what is unknowable. In this report we have provided a baseline encompassing all the ocean realms, a framework for prefiltering the explorations that will most probably yield the great surprises about marine life, past and future. The baseline is itself a prefilter, a hypothesis, to help us to explore. Discovery is ahead.

GLOSSARY

Domains - alternate
Archaea - prokaryote
Bacteria - prokaryotes
Eucarya - eukaryotes

Kingdoms - alternate
Protista - protists (unicellular)
Planta - plants
Animalia -animals

Animal Phyla - example
Mollusca - clam
Arthropoda - crab (crustacean)
Chordata - fish
Nematoda - roundworm
Annelida - tubeworm
Cnidaria - jellyfish
Platyhelminthes - flatworm
Echinodermata - seastar
Porifera - sponge

Science Term - alternate
nekton (pelagic) - swimmers
plankton - drifters
    phytoplankton - producers (photosynthesis)
    zooplankton - consumers
photic - light
aphotic - dark
mesopelagic - mid-water
epibenthic - bottom-water
megafauna - animal over 3 m (whale)

Common Term - alternates
algae - blue-green bacteria, protists, kelp
microbe - bacteria, protists

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The Census of Marine Life (CoML) is a global network of researchers in more than 50 nations engaged in a 10-year initiative to assess and explain the diversity, distribution, and abundance of life in the oceans—past, present, and future. It is governed by a number of international, national, and regional steering committees coordinated by an international Secretariat based at the Consortium for Oceanographic Research and Education.

The Unknown Ocean: Baseline Report of the Census of Marine Life

2003

CENSUS
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