

Ocean Past, Ocean Future

Reflections on the Shift from the 19th to 21st Century Ocean

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On the cover:

North Sea fishing circa 1880 (Boxing fleet: "Toilers of the Deep," Josiah Robert Wells and Charles Joseph Staniland) and ocean observing in 2010 (Image: E. Paul Oberlander).

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Abstract

In the 19th century humans knew little about the oceans, but other forms of life knew a lot. Our job the past 135 years has been to catch up and surpass other forms of life in knowledge of the oceans. The advance of observation through science and technology, including new carriers and processors of information, has vastly expanded the oceans knowable to humans beyond what a sailor's five senses could directly provide. By infiltrating the ocean with informationally connected sensors, humans are becoming the top experts on the oceans in the 21st century.

In 1880 Annapolis and nearby, Albert Michelson and Simon Newcomb, director of the Nautical Almanac Office, pioneered measurement of the speed of light. Yet, in the curriculum of ocean science at the time of Michelson, the limits of knowledge would jolt us today. From 1872 to 1876 the expedition of the *HMS Challenger* had used a line with a weight attached to take about 500 deep-sea soundings to create the first global picture of the depth of the deep sea. During 1879–81 the naval vessel *USS Jeannette* was exploring for the North Pole. Ice trapped, crushed, and sank the ship some 300 nautical miles north of the Siberian coast. Two of the 28 crew survived. It would take decades more for men to reach the Pole. Meanwhile, in 1880, crucial global time series measurements of the oceans began, including sea level and average surface temperature. In 1882 a Wilmington, Delaware, shipyard launched the first vessel built specifically for oceanographic research, the iron-hulled, twin-screw steamer *Albatross*, originally rigged as a brigantine.

The limits of knowledge implied by that rudimentary research vessel help us understand the importance of learning systems. Learning systems famously include immune systems, which learn to resist and expel various invaders, and also aggregates of nerves, such as individual brains. An obvious example of learning is a child acquiring language. A typical child's vocabulary grows in a wave from a few words at 20 months to more than 2000 five or six years later. Learning systems include groups of brains when organized in parallel architecture through language. Thus, a family, a corporation, or a navy can be a learning system.

Consider a learning system from the most basic point of view. There is an inside or In and an outside or Out. The In is endowed with sensors and computing machinery, trying to model the Out in the sense of anticipating the results of its interaction with the Out. The limits of sensors in quality

and quantity and the computing system behind them essentially bound limits to knowledge.

The In can be a single cell, a microbe, whose wall defines the In and Out. The In of course must also be informationally connected. Informational molecules, in a fraction of a second, can diffuse back and forth, carrying signals and performing calculations.

Strict physical connectivity may not be necessary to be an In. A marine sponge, among the oldest forms of life, consists mostly of empty space, but reacts as a coherent body. We may consider the In as the whole connected system. Coherent behavior, like that of a class of midshipmen tossing their covers on graduation day, implies an informational grip.

This conceptual jump, defining the In as informational connectivity, is important. Informational connectivity makes the parts move together, like the fingers of a hand. The fingers can play a piano or violin. Or, if I step on the tail of a dog, it will use its teeth to bite my leg. The members of a beehive also coordinate precisely and behave like a single animal. If I step on a bee, another bee may well sting my hand.

Having chosen information as the glue of the In, and having named bees as a spatially disconnected In, we can take another step. Subsets of humanity are linked by common language, that is, a common culture, and tend to occupy compact territories. In many ways, the group members feel themselves part of an In. They compete or fight carrying a sense of togetherness and identity, as all historians have noticed. Nations and beehives share biology, basic instincts.

Human sensory limits to knowledge

What strikes me about the oceans of Michelson's day is that while humans knew little about the oceans, other forms of life knew a lot. The job of the past 135 years has been to catch up and surpass other life in knowledge of the oceans. After all, whales can memorize magnetic maps, as humans do with optical maps, and navigate into the real thing.

The first, obviously limiting factor to knowledge is sensory capacity. The Greek philosopher Democritus said that nothing is in the mind if not first in the senses. The senses, defined in a broad way as the channels of interaction of the In with the Out, are the prime vehicle of information in the modeling machinery.

The first sense, and probably still the most important in the biosphere, is that of chemical recognition or identification. Single-cell organisms, like the T cells involved in the human immune system, have skins weirdly resembling industrial telecommunication facilities with antenna dishes facing everywhere. These chemoreceptors can identify molecules at the

surface and signal the internal computers. If identified as food or hormones, the molecules are admitted. By weight, most ocean life-forms are microbes, which abound like stars in the sky. One may say 90 percent of the oceans still operates predominantly on chemical signals.

Noses sense chemicals, and having a long evolutionary pedigree, olfaction has reached utmost sensitivity. The antennae of certain male moths, sniffing females, can detect a few molecules of scent, just enough to overcome the Brownian noise of the receiver. Smell has been extremely valuable to mammals, which evolved first as nocturnal animals. Mammals' nose receptors contain about 1000 different proteins specialized in identification of molecules or parts of them and can differentiate 10,000 odors. A kind of twin olfactory system, the vomeronasal system, detects pheromones and other molecules important for reproduction and social relations in many taxa. Pheromones may aggregate or alarm or mark a trail or territory.

Humans are just starting to learn to sniff in the oceans. For example, the search for so-called Black Smokers or hydrothermal vent communities on seafloors relies in part on putting a nose on a submarine. Taste as well as olfaction observes chemistry. Salt is the ocean's most famous flavor. Sensitive species measure salinity in parts per thousand, as humans have now learned to do.

Touch we might categorize as physical rather than chemical. Latitudinal migrations and ranges of many marine animals show their fine observation of water temperature, let's say on a centigrade scale. However, such animals have not become skilled at seeing heat and cold at a great distance the way humans have learned to do.

While most chemical sensors may have a very limited horizon, photons can have chemical effects from far away and enter directly into the cell's machinery without even a salute to the guards. Presumably because photons were disruptive, cells developed sensors for them. Light sensitivity required a new interface producing standard signaling chemicals out of a broad mix of photons.

Vision complements smell

Photosensitivity gave range, because light can come from a great distance in transparent media like air and water. In contrast, millimeters measure the territory of diffusing molecules. Earth's largest migration is the daily vertical migration of marine animals as the sun sets and rises. Each day at dusk, countless fish, jellies, and shrimp climb as much as 400 meters, the height of the Eiffel Tower. Through photosensitivity, astronomers have expanded human territory not just 400 meters but to 10 to the 10th light-years.

Vision probably began as light-sensitive spots to drive cells away from dangerous levels of illumination. Vision's evolution has produced wonderful machines. It helps that light travels in straight lines and the atmosphere is transparent to many electromagnetic bands. Eyes see distant objects but not around corners, so eyes and noses complement one another.

A review of eyes across animal species from the light-sensitive spots of bacteria to octopus and eagle eyes, which have some of the best machinery, shows how technical possibilities have been explored and expanded. Fishes benefit from lenses with finely adjusted gradients in the refraction index, which human engineers have difficulty reproducing. The final sensors use wave-guide properties. The receptors are near quantum limits inside the constraints of visible light and room temperature.

Eyes fall into two classes, those with split optics forming composite eyes of various descriptions and those with single optics. These optics can transmit with lenses, optical fibers, and pinholes, or reflect with mirrors.

Pit eyes get some directionality just by reducing the angle of view of sensors. Infrared sensors are the night weapon of sidewinder rattlesnakes and are also adopted in anti-aircraft rockets.

Single-lens eyes improve on pit eyes. However, matching the dimensions and available refractive index to produce a focused image on the retina-like sensors is hard, especially for aquatic animals where the cornea curvature is useless because of the high refractive index of water. The problem has been neatly solved a dozen times in evolution, by making onion lenses with a graded refractive index (Matthiessen lenses). In that way, for given dimensions the focal length can be adjusted. A larval fish can focus images from different distances. Apart from fishes, also cephalopods and gastropod mollusks, annelid worms, and copepod crustaceans have multifocal lenses.

Multiple lenses can be found in small copepod crustaceans, where two of the lenses are not in the eye, but in the rostrum (rather like eyeglasses). The parabolic surface of the first corrects the spherical aberrations of the others.

Scanning eyes give great luminosity but small field, as in a telescope. For example, the copepod *Copilia* has a "telescope" with an objective lens and an "eyepiece" in front of five receptors. The eyepiece and sensors then move in unison to scan the total image produced by the telescope. Scanning eyes with small fields are not uncommon. Heteropod sea snails like *Oxygyrus* oscillate the eye through 90 degrees in about a second. The snail's eye has a linear retina a few receptors wide and several hundred long. These scanning eyes read lines in a manner reminiscent of television images constructed from a linear time signal.

Submarine warfare involving sardines, sharks, dolphins, and gannets, as Galatee Films recorded in their 2009 masterpiece *Oceans* off the east coast

of South Africa, shows the senses of marine animals operate at the limits. I have briefly mentioned touch, and we know that fish avoid not only the noise but also the bow wave of ships. In fact, many animals feel tiny changes in pressure.

Now hear this

Sounds in the bands that propagate have properties similar to light, although their long wavelengths limit acuity. As in the nose, the signal in the ear is analyzed with extreme sophistication, witnessing long evolution and high survival value. For humans, the where is not given with much precision but the who is extraordinary. Hidden in the forest, bushmen can identify members of a different tribe by listening to a couple of words. Most of us can identify, that is, predict, a popular song from its first few notes.

Life's problem of receiving high-frequency signals with low-frequency electronics has been solved using mechanical resonators whose state of activity reveals the presence of the signal. In the case of acoustics, sperm whales developed sensors for long waves, useful for long-range communication in the ocean, by using their whole heads, filled with appropriate fluids, as antennae.

The poor definition associated with low frequencies can be vastly improved if the receiving animal also emits. It can stimulate action through its own action, a sort of questioning. Electric eels sense objects in the field they create. Bats can identify the distance and somehow the quality of an insect tens of meters away with their acoustic radars. Bats can also map with great definition and avoid wires and flying objects. Said differently, sensors are not necessarily passive. The signal can be stimulated by the action of the In, for example, the shrill cry of a dolphin or the smash of the Large Hadron Collider.

Science transcends evolution

Biological evolution stops when the advantages in terms of survival are exhausted. The eyes of an eagle, at the top in terms of acuity, are much better than human ones but far below the telescopes of the Naval Observatory. Perceiving other Earth-like planets would have zero advantage for eagles.

The main breakthroughs of modern sensory technology can be reduced to materials that made new architectures and functions possible and to fitness criteria, vastly removed from those of living things. Fitness in the 1950s elicited sophisticated mathematics to sort out seismograms of faraway atomic bombs from those of small quakes here and there. The Navy's heroic Long-Range Acoustic Propagation Program (LRAPP) of the 1960s–1980s

made historic progress on the directionality of ocean sound to locate enemy submarines.

The sensors and their elaborators are bound to the mechanisms and materials used to build them. For some reason, biology tends to concoct many fragile materials. Organic materials cannot produce intense and extensive magnetic fields. Consequently even if biological sensory systems could have done something, magnetic resonance perception could never develop, without science and engineering. A large telescope observatory invents nothing in basic principles, as even certain crabs are endowed with reflecting telescopes. Instead it plays on size, linked to materials and to an objective: looking into the sky to a distance of light years, which bears little significance to the fitness of any living individual or species on Earth. Except humans.

Let's now look at some contemporary observations of the oceans and their implications. First, we need to consider human motivations. We have already mentioned enemy submarines and nuclear tests. Consider illegal fishing, pollution, piracy, illegal immigration by boat, and narcotics trafficking. These activities help justify systems of surface vessel identification now in place in Europe and many other regions without even mentioning weather hazards and national security. Consequently, we make more ocean observations, for example, those related to climate (**Figure 1**).

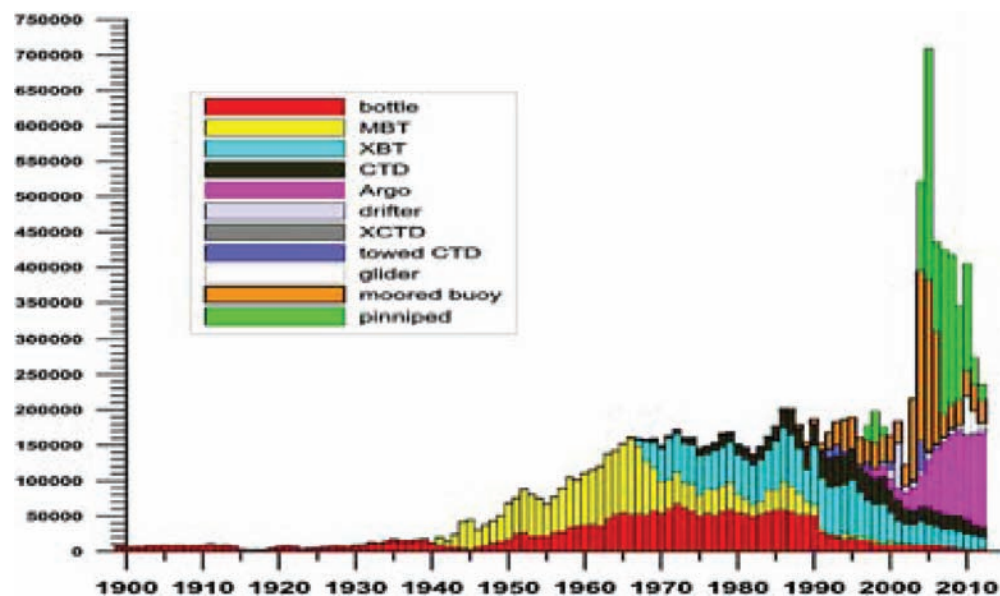


Figure 1. The forms of climate-related ocean observations have increased with modern technology and vaulted to new levels in the 21st century.

Credit: Tim Boyer, US National Oceanographic Data Center, National Oceanic and Atmospheric Administration

Variables observed include not only ships and temperature but surface currents, wave breaking, and sea state.

Each domain of motivation requires a suite of improving technologies shallow and deep, microscopic and macroscopic. For an expedition to explore polar marine biology, we send scuba divers for the shallows, remotely operated vehicles and landers for the abyss, and nets for the water in between.

What do humans now see? We see more than 600,000 ships on the surface at more than 200 million positions daily, an average of more than 300 positions per day for each ship, checked every 4 to 5 minutes (**Figure 2**). With each decade we resolve ships and wakes more finely. With gravity measures made from satellites and multibeam sonars mounted on the hulls of vessels, we map the seafloor in greater detail. The granularity would astonish the crew of the *Challenger*, which achieved immortality with only 500 measurements of the globe.

We also ally with other animals who help us to see and feel, such as elephant seals that carry tags measuring water temperature as they cruise from seamount to seamount feeding off the Antarctic Peninsula, sometimes as deep as 2300 meters.

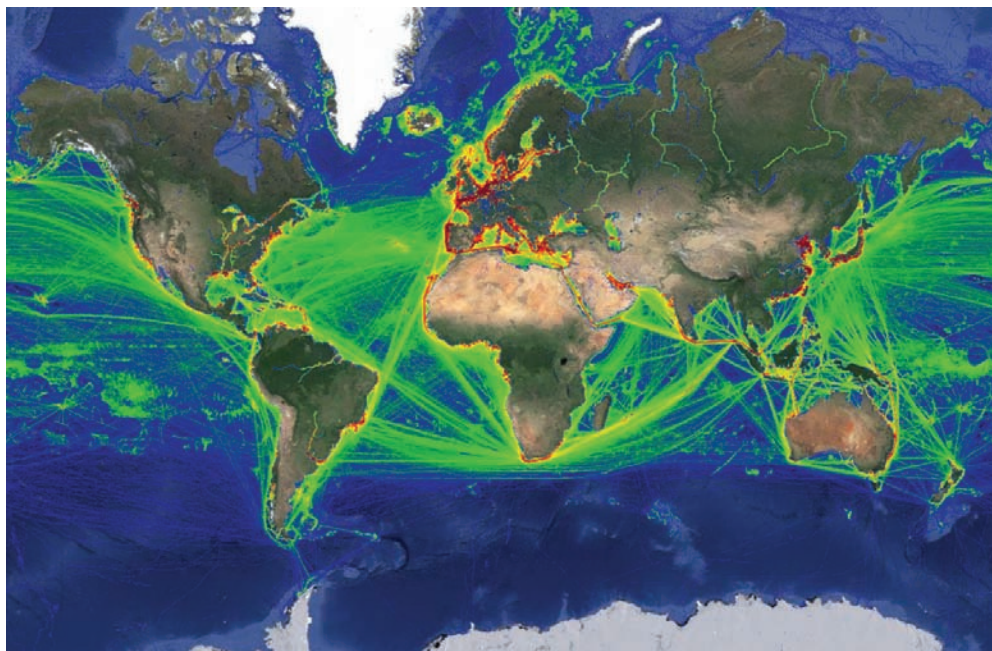


Figure 2. In 2014 the Automated Identification System provided more than 200 million position reports per day on about 600,000 different vessels.

Credit: MarineTraffic

With active acoustics, we can find a shoal of 250 million herring off Georges Bank in the Gulf of Maine (**Figure 3**). We listen to a ship and visualize its distinctive sonic profile. We can store information and inquire about a trend in ocean noise in the Santa Barbara Channel. We can create a soundscape of traffic noise in the seas all around Australia.

To detect climate variability and change, we set out 3000 subsurface Argo floats that collect and distribute information on temperature and salinity robotically for oceans free of ice (**Figure 4**).

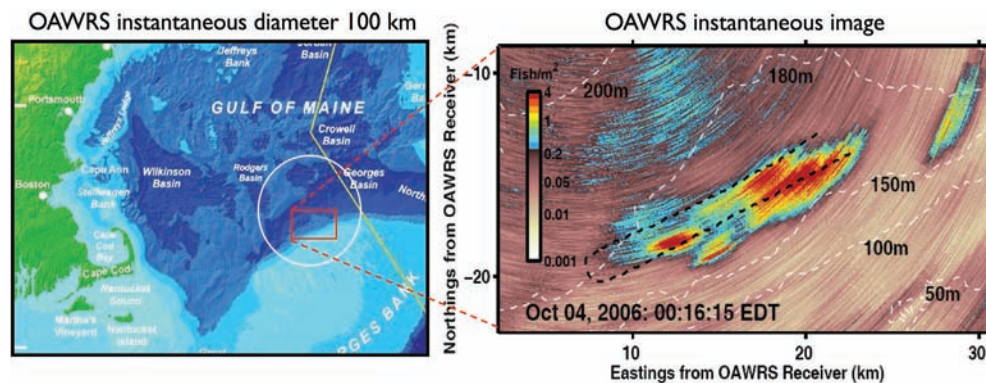


Figure 3. Ocean Acoustic Waveguide Remote Sensing (OAWRS) uses properties of spherical spreading to image schools of fish as far as 150 km from the sound source. Here, off the Georges Bank, a quarter of a billion fish (50,000 tons) gather in one place.

Source: NC Makris et al. "Ocean Acoustic Waveguide Remote Sensing (OAWRS) of marine ecosystems," *Marine Ecology Progress Series* 395: 137–160, 2009.
<https://doi.org/10.3354/meps08266>

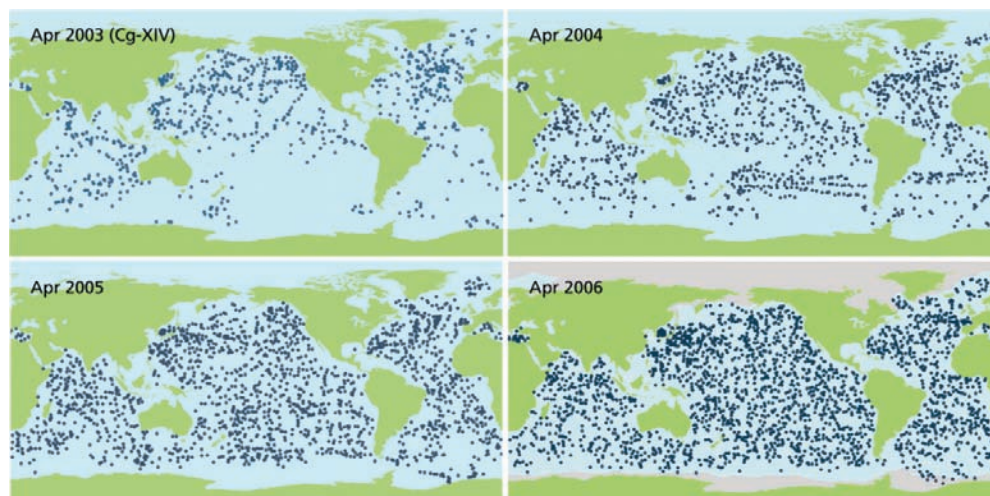


Figure 4. Buildup and global distribution of the Argo profiling float network from 2003 to 2006 benefits climate and seasonal forecasting. In 2015 about 4000 floats have been placed by about 25 countries.

Credit: <http://www.jcommops.org/new/>

We release thousands of drifters to learn how water flows from the Pacific through to the Indian Ocean.

We set out moorings that monitor the entire water column down to 6000 meters.

With the chemical nose mentioned earlier, and feeling for warmth too, we find Black Smokers on the seafloor.

We sieve seawater for DNA and use short sequences to ascertain what species have operated recently nearby (**Figure 5**).

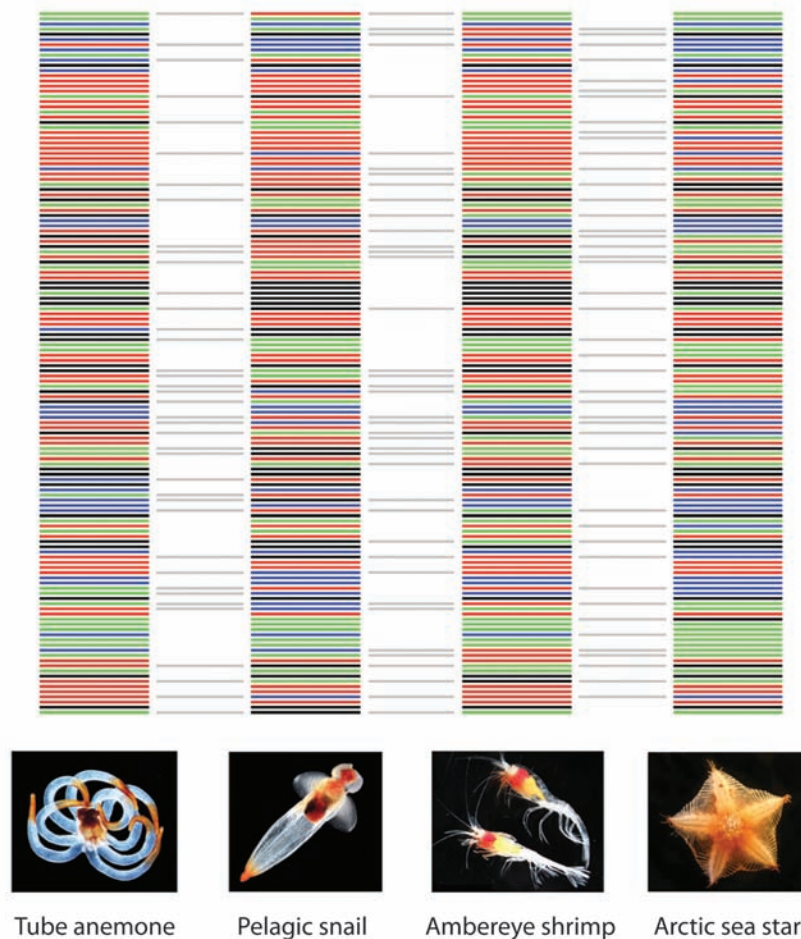


Figure 5. Genetic sequences from anemone, snail, shrimp, and sea star illustrate the analogy between a sequence of genetic units in the cells of a specimen and the barcodes on items for sale in a supermarket. Each of the four colors represents one of the four nucleotides—cytosine (blue), adenine (green), thymine (red), and guanine (black)—that compose DNA sequences. The gray lines between the colored bars signal genetic differences. Differences enable assignment of a specimen, even a fragment such as a fin or scale, to a species.

Barcodes: Mark Stoeckle

Images: Cheryl Clarke-Hopcroft, Russ Hopcroft, Bodil Bluhm, and Katrin Iken

Importantly, we can learn what we do not know, what we have not explored. For example, compiling reliable records of marine life shows that huge blank spots remain for the Arctic (**Figure 6**) and the eastern and southern Pacific. We can also slice through the ocean and learn that for most of the vast midwaters we have no observations (**Figure 7**). To offer a terrestrial metaphor, science penetrates into the big block of ignorance as the roots of a tree in the soil, branching and branching again, but leaving much soil unexplored.

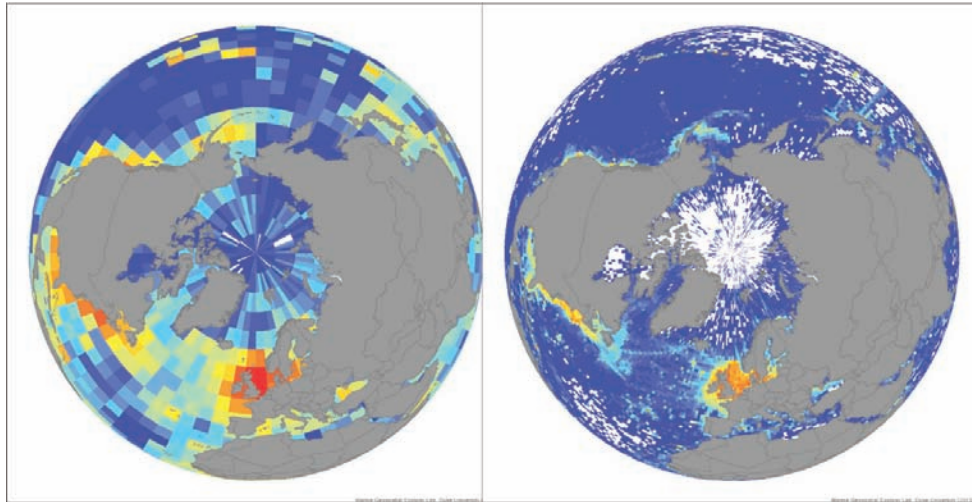
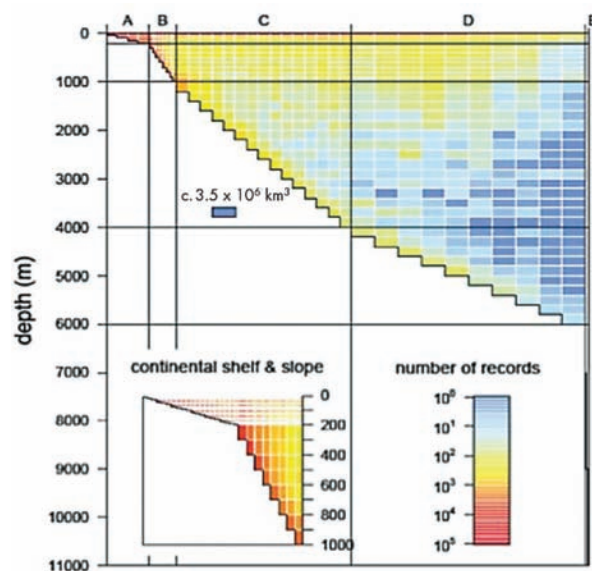


Figure 6. Maps of taxonomically reliable records of marine life in 2010 (5-degree cells, left, 1-degree cells, right) in the Ocean Biogeographic Information System. Maps indicating more records in red and yellow and fewer records in blue show large areas of the ocean unexplored.

Source: Ward Appeltans, Ocean Biogeographic Information System, <http://www.iobis.org/>

Figure 7. The database in 2010 of the Ocean Biogeographic Information System exposes, for biology, the still-to-be-explored ocean by depth as well as latitude and longitude. The records of marine life are concentrated near shores and in shallow waters, while the largest habitat on Earth, the vast middle waters, is largely unexplored.

Source: Ocean Biogeographic Information System, <http://www.iobis.org/>



The motivations and the gaps cause us in turn to create monitoring arrays. We listen for nuclear tests and earthquakes, submarines and whales. We invent new devices to carry sensors, some fixed, some drifting, some propelled. Nations knit these probes and vessels and aircraft and satellites into observing systems, such as that for observing the Yellow and East China Sea ecosystem. Groups of nations do the same, for example, to monitor the Indian Ocean. In fact, informationally connected, every platform can become part of the global observing system. Even if a Darwinian logic of survival somehow pushes the entire system, it feels almost as if evolutionary forces have run amok as the number of independent agents, or sensors, multiplies.

Summation

Every living thing has or is a machine for learning, remembering, and forecasting. The objective is to anticipate interactions with the external world. The two basic mechanisms to provide models are the sensors and elaborators of sensory signals. In a nutshell, modeling cannot go beyond observation.

Dr. Michelson understood that most breakthroughs in science follow breakthroughs in the precision of measurements or in the discovery of new information carriers. Electromagnetic waves, X- and gamma rays, and wave-particles of many descriptions have expanded the knowable for humans beyond our senses.

Computers provide speed. Their clocks may have frequencies higher than those of the brain and almost unfailing operation. Computers are progressively taking up human brain functions. They run the books of the banks, print in 3-D, and translate languages. Ships have been commissioned that require no sailors.

Looking forward, the sensory system and the computing system can still expand, as when new sensors shrink and proliferate, and appropriate mechanical interfaces are invented. Other signals not yet detected or decoded may expand the sources. Neutrinos were detected only recently and garnered the 2015 Nobel Prize. We return to materialist philosophy, nothing exists in the mind that is not first in the senses.

Of course, learning can become stuck here and there. But we see that nature had already overcome many limits to knowledge of the oceans. In Michelson's day and far earlier, many other forms of life could sense what humans could not. Since Michelson, humanity has largely caught up and now even zoomed ahead. The requirement is an ocean infiltrated with sensors, informationally connected, and that will be the 21st century ocean (Figure 8).

In conclusion, the expansion of the knowable from the 19th to the 21st century is basically linked to the improvement in sensitivity of the present carriers of information from the Out to the In and to the discovery of new information carriers. Power in the oceans will flow to those who lead in observation and computation linked to a nervous system that can respond forcefully.

Figure 8. From the 19th to the 21st century ocean. The *USS Albatross*, the first special-built U.S. oceanographic research vessel, contrasts with the diversity of devices and platforms now mimicking and surpassing marine life in humanity's quest to know the oceans.

