Engineering the Ocean

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Commentary: ***Karl S. Pister,***
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The Monterey Bay Aquarium was the setting for the 1850th Stated Meeting, hosted by the Academy's Western Center on November 3, 2001.

Speaker Marcia McNutt presented a series of fictional, but not fanciful, scenarios for human intervention in the ocean—and questioned whether we have the knowledge necessary to understanding the implications of our actions, the humility to admit what we do not know, and the ability to take the long-term view of what is the best policy for the planet. Commentator Karl S. Pister—former dean of the College of Engineering at UC Berkeley and UC system vice president for educational outreach—stressed the urgency of improving scientific literacy in the general population as a first step toward ensuring a positive outcome.

Marcia K. McNutt

Our future hinges on better understanding the complex, living ocean. The ocean is the lifeblood of our planet, critical to its health. We know of no examples of life in this universe that do not require liquid water for survival. Earth teems with life because it is an ocean planet. The ocean, with its vast capacity for heat storage, carries solar energy from the tropics toward the poles, thus maintaining a more equitable climate (and more water in the liquid state) than would be possible with atmospheric heat transport alone. The ocean provides natural ecosystem services such as carbon storage, nutrient cycling, and waste treatment. Most photosynthesis globally is accomplished by microscopic plants drifting in the upper ocean. The bounty of the

Speaker Marcia K. McNutt, president and CEO of the Monterey Bay Aquarium Research Institute.

seas provides an inexpensive source of high-quality protein for human consumption. The ocean remains the principle highway for commerce, and approximately 20 percent of our supply of fossil fuels is derived from reservoirs beneath the continental margins.

By the year 2025, 75 percent of the global population will live in coastal areas, the majority within sprawling interconnected supercities. This shift in population will have a huge impact on the health of the oceans, and coastal residents will be even more vulnerable to hazards in the near-shore environment, such as rising sea level, hurricanes, coastal erosion, tsunamis, marine pollution, and harmful algal blooms. Despite our dependence on the ocean and our vulnerability to changes in its state, our ignorance of what the living ocean contains and how it functions is staggering. The great era of ocean exploration began more than a century ago, but 95 percent of the ocean remains unknown and unexplored. We still don't know what causes dramatic shifts in climate, what limits ocean productivity, at what level fish can be sustainably harvested, how to harvest energy and raw materials economically from the seafloor, or what new pathways for sustaining life await discovery.

These questions are not new, but oceanographers have been hampered in their ability to address them by lack of low-cost, easy access to the oceans. I will describe the new technology that is fundamentally changing the way we go about exploring and observing the oceans, and fueling an explosion in new knowledge that will answer these questions. As this knowledge grows, the pressure will increase to use this information to further manipulate and exploit the oceans for humankind's benefit. What is still uncertain is whether we will be able to predict sufficiently the long-term consequences of our actions to ensure that the oceans remain healthy. Just as uncertain is whether we, as a society, are willing to enact policies that may curb our quality of living in the short term for the sake of healthy ocean systems in the long term.

Challenges of the Marine Environment

In order to understand how difficult it is to study the oceans, it is instructive to compare ocean exploration to space exploration—an area in which our nation has already invested heavily and reaped substantial rewards in new knowledge on the fundamental structure and history of our universe. Humans cannot live in space or in the oceans without substantial life-support systems. For that reason, human exploration of both environs is costly and dangerous. Fortunately, in recent decades, advances in computers, control systems, and robotics have allowed a shift from manned to unmanned missions. This trend will undoubtedly continue as we seek to go deeper into space or the ocean and to stay longer.

Once the necessity of engineering exploration platforms for human occupants is removed, the principal concerns become power and communications. In both of these areas, space exploration has a substantial advantage over ocean research. Solar panels are incapable of powering below the uppermost regions of the ocean. Whereas space is virtually transparent to the transmission of electromagnetic energy, the oceans are opaque to electromagnetic energy.

In dealing with these issues, oceanographers have developed two fundamentally different sorts of unmanned platforms and instrument packages. The tethered systems are connected to either a ship or shore via a cable, which is capable of bringing power to the undersea system and transmitting data both ways. Such systems have the least-stringent requirements for on-board artificial intelligence, as the cable effectively connects them remotely to the brains of the human operators. The autonomous systems typically have no physical connection to the surface or shore, and at best only intermittent communication with humans via acoustic transmissions or satellite relay when the package surfaces. They must supply their own power, typically through some type of battery, because supplying oxygen for internal combustion engines is problematic in the deep sea. Nuclear power is also an option, but it is so costly and rife with environmental concerns that it has not been implemented within the civilian community. Clearly, the autonomous packages must be quite sophisticated in their control systems, especially if they are mobile. They must be able to execute a preprogrammed mission, store the information collected, and be intelligent enough to avoid failure modes (e.g., colliding with obstacles, running out of power before returning the information to shore). Despite the necessary sophistication, the autonomous packages are, in general, less expensive than either manned submersible or tethered vehicles because they can be smaller and lighter, and catastrophic loss is an acceptable risk.

The rise in the popularity of autonomous vehicles and platforms for deep-sea study has gone hand-in-hand with the development of in situ instrumentation to sense the physical, chemical, and biological state of the ocean. The future trend will be to send data back to shore, not samples, by repackaging laboratory analyses so that they can be performed autonomously underwater. While this is a desirable feature for reducing costs and increasing real-time knowledge of the ocean condition, such a capability is essential for future exploration of extraterrestrial oceans, from which there is no return.

Oceanography of the future will rely on autonomous observatories, drifters, and rovers for exploring the oceans. Suppose that within the next few decades, thanks to a wealth of new observations returned by these systems, we understand, or at least think we understand, how the climate system works, what limits ocean productivity, the complete ecology of commercial fish species, and other mysteries of the ocean. The following entirely fictitious future scenarios are meant to give some examples of how this information might be used—or misused—to manipulate the ocean for mankind's benefit.

Future Scenarios

The year is 2025. Through intense efforts in public education, the human birth rate has stabilized, but the global population is still increasing on account of longer life expectancy. The 2025 population is concentrated along the coastal plains of the continents, with mounting costs to governments for disaster relief as a consequence of more frequent hurricanes and severe storms, exacerbated by rising sea level and global warming. Scientists are under increasing pressure to better predict, and even to mitigate, these natural disasters. Modern agricultural practices have been extended to all developing countries, maximizing harvests, but some people still go hungry. The only hope is to increase food production in the ocean, although international agreements on who owns the ocean are far from finalized.

All citizens of the twenty-first century want electricity and powered vehicles, but energy is very expensive because of the dwindling supply of fossil fuels and the high cost of carbon recovery, now required to mitigate greenhouse warming. Action needs to be taken, and the oceans are the only remaining source of untapped potential. The land is rife with examples of environmentally damaging exploitation by humans—cases in which mitigation of the damage has been costly, time consuming, or impossible. Have we learned our lesson? Will we do any better with the ocean?

Future Scenario 1: Climate's Down Escalator

By 2025, low-cost autonomous vehicles known as "drifters" have been endlessly circling the globe for several decades—passengers on the great ocean currents that transport heat from the equator toward the poles. Sinking of cold, saline waters in the North Atlantic draws the warmer equatorial waters northward via the great Gulf Stream. Each float riding this conveyor belt has a life span of approximately two years, during which time it relays via satellite to shore its position and the ambient temperature and salinity. The relay is direct whenever the drifter is at the surface, but more commonly it is via an expendable messenger released periodically from depth. An onboard control system moves a bladder to change the drifter's displacement in order to keep it at all times neutrally buoyant with respect to its surroundings.

Back at a central processing facility, computers are constantly integrating the information from the drifters. Positional data (e.g., indicators of where the currents are flowing) are just as important as information on the density of the water (inferred from its salinity and temperature). The data are combined with meteorological data and immediately integrated in a massive global ocean model that predicts the "weather" of the ocean, including temperatures, currents, and the locations and velocities of fronts. The models are run forward into the future to provide forecasts for shipping companies, naval operations, and the growing number of multinational companies that have commercial operations in the ocean. As with all forecasts, the accuracy of the prediction degrades as it projects farther into the future. But advances in the understanding of complex, nonlinear systems, along with the existence of better data to assimilate into the model, have resulted in fairly reliable forecasts for periods of a week or more.

In addition to providing ocean weather forecasts, the outputs from the model runs are integrated even farther into the future to provide estimates of ocean climate for a year or so in advance. While such climate forecasts are unreliable for predicting the ocean state at any one position, they are useful for predicting overall heating and cooling of the ocean, major changes in poleward heat transport, and variations in the intensity of the boundary currents. This information is vital to farmers, who decide what crops to plant on the basis of projections of temperature and rainfall from the ocean climate model. Much of the guesswork in the global communities market disappeared once the global ocean climate forecasts became generally available.

In the spring of 2025 the computer picks up a significant anomaly from the global drifters. Abnormal wind patterns in the western Indian Ocean are causing a substantial deepening of the thermocline. The computer model predicts that this situation will lead to a massive El Niño—potentially the most extreme event of its kind ever recorded. Even more worrisome, a forward projection of the climate models predicts that the El Niño will lead to an unusually warm winter and summer in the northeastern Atlantic, causing further melting of the Greenland ice sheet, already destabilized by global warming. Scientists are concerned: the computer scenario implies flooding of the North Atlantic with fresh water derived from melting of the Greenland ice sheet. This freshened surface water will be lighter than the surrounding salt water, and the computer model running the drifter data predicts that the sinking of the North Atlantic waters will be reduced by at least 50 percent. It is the sinking of surface water that pulls warm equatorial water northward (on the great "conveyor belt") to keep the temperate latitudes ice-free. Scientists invoke paleoclimate data to demonstrate that the flooding of the North Atlantic with fresh water 12,000 years ago temporarily interrupted the recovery from the last ice age by reducing poleward heat transport. Within the time period of one or two generations, continental regions at the latitude of Boston went from ice-free conditions to year-round burial under 20 feet of ice. Paradoxically, the warming triggered by the El Niño could plunge the planet into another ice age.

Despite the uncertainty in the climate forecast, citizens demand that their governments take action. Possibilities include dumping a tanker of oil in the western Indian Ocean to decouple the ocean from the anomalous wind stress, thereby averting or at least lessening the impact of the El Niño. Alternatively, large temporary dams could be constructed across the streams that drain the Greenland ice sheet to prevent the water from reaching the ocean. Are the uncertainties in the climate forecast large enough to make no action a viable option? Are any of the schemes likely to have the intended effect? Will inadvertent repercussions make the cure worse than the disease?

Future Scenario 2: Cure for Upper-Ocean Anemia

The concept is bold and, at least on paper, looks feasible enough to have attracted several billion US dollars in venture capital for the young start-up company Maritime Carbon Creditors (MCC). Industrialized nations are eager to buy carbon credits—evidence that they have removed carbon dioxide from the atmosphere to offset their own additions caused by the burning of biomass and fossil fuels. MCC offers a cheaper alternative than the more expensive practice of recovering carbon dioxide from smokestacks and sequestering it in geologic formations or in the deep sea. For a fee, MCC will deploy small autonomous underwater vehicles (AUVs) that fertilize the ocean with iron, now proven to be the limiting factor in primary productivity in many areas of the open ocean where nutrients are not limited. A second set of AUVs will monitor the ensuing plankton bloom caused by the fertilization. Depending on the intensity and duration of the bloom, the purchaser will be awarded a certain number of carbon credits.

The genius of the MCC plan is that the purchasers pay the total cost of the program. In addition, for another fee, MCC sells to commercial fishermen information on the location and timing of the fertilization operations, so that they can reap the benefits from the stimulation to the marine food web caused by the plankton bloom.

While MCC prepare to launch their first fertilization event, debate still rages over the merits of their plan. Because the majority of their operations will be in international waters of the equatorial Pacific and southern oceans, it is not clear that anyone has the jurisdiction to stop them. Some scientists argue that this is a win-win situation: the fertilization will mitigate global warming while increasing the productivity of the oceans.

Others warn that MCC has not invested in the autonomous genetic fingerprinting technology to monitor what species have bloomed. What if toxic algae respond to the fertilization? Because the carbon credits would still be earned, both the customer and the service provider would be satisfied in the short term, but the marine food web would be poisoned in the long term. What can be done to ensure that the operations go as planned?

Future Scenario 3: Northeast Pacific Power and Light Company

A large network of deep-sea cables sprawls across the Juan de Fuca plate, off the coast of Oregon and Washington. The network was originally installed in the early part of the twenty-first century by Northeast Pacific Power and Light Company to supply power and communications for studies of deep-sea hot springs along the Juan de Fuca ridge. At each of these sites, hot, cooling magma erupting at the midocean ridges drives a hydrothermal circulation system of deep-sea geysers that are at very high pressure and thus attain extremely hot temperatures (350°C) without boiling. Thanks to advances in technology and in understanding the longevity and stability of these systems, the fiberoptic cable network has moved beyond basic research for a very applied purpose: supplying energy to meet the demands of the mushrooming population along the western coast of North America.

Thermocouples harness the energy of the hydrothermal system by taking advantage of the large temperature contrast between the 2°C seawater and the 350°C venting fluids. The process is extremely efficient and produces no waste products other than chemical precipitates. These precipitates, including iron, copper, and zinc, are collected to supply the national need for raw metals. Indeed, the amount of iron alone deposited by this vent field is equivalent to the amount it would take to create another Mesabi iron range every 250 years. The deep sea power station is completely unmanned: autonomous and remotely operated vehicles monitor the state of the ridge system and supply routine maintenance to the power generation and metal extraction processes.

The success of the Northeast Pacific Power and Light Company has prompted a number of attempts to duplicate it by other power-hungry nations. However, only a handful of countries have active midocean ridges within their exclusive economic zones. Peru becomes the first nation to invest in a power and mineral company in international waters by establishing, at great cost, a plant on the power-rich southern East Pacific Rise. Some months after operations are initiated, the Peruvians note an unexplained loss of power along the transmission line. AUVs sent to survey the cable route note that an unauthorized trunk line has tapped into the main cable and diverted some of the power to Easter Island, which is under the jurisdiction of Chile. Peruvian leaders meet behind closed doors. How do they respond to this crime—with war ships or with an electric bill?

Meanwhile, environmentalists raise concerns about the long-term effects of siphoning off energy from the midocean ridge system. Could this ultimately bring plate tectonic drift to a grinding halt? Is the constant renewing of the surface and recycling of elements caused by plate tectonics a necessary condition for life on Earth?

Future Scenario 4: Icing Genetic Mutations

In 2025 the first Earth probe to visit Jupiter's icy moon, Europa, has landed. Immediately upon reaching Europa, an instrument package releases a chemical agent that begins to burn a hole through the icy crust of the planet. A mere 48 Earth-hours later, the instrument package descends to the liquid water interface, tens of kilometers beneath the ice—and just in time. The intense radiation field from Jupiter is equivalent to a nuclear holocaust in terms of cosmic ray energy— enough to fry the electronics in the instrument package, had it spent another day on the open surface of the moon. Upon reaching the liquid water, genetic probes immediately begin searching for any forms of DNA material that might indicate life. Europa is, unfortunately, a one-way trip. But the genetic code for Europa's rugged inhabitants is beamed home by transmitters deployed from the instrument package. Medical researchers hope that the genetic code from Europan life forms will hold the secret to reducing the incidence of cancerous mutations in terrestrial living matter, subjected to far lower doses of radiation than those found on Europa.

A report in the weekly periodical *Science* of the first successful attempt to splice DNA created from Europa's genetic sequence into *E. coli* prompts demonstrations outside the research facility. Who knows what processes will be mediated by that code sequence? Will this result in the ultimate genetically engineered cure for cancer, or a fatal infection that eventually destroys all terrestrial life?

Future Scenario 5: RoboTuna

A new creature prowls the seas in the twenty-first century. Long humbled by the elegance of nature in fitting form to function, researchers have finally built a robot tuna with all the speed and energy efficiency of its biological inspiration. The trick was in designing a tail that could shed vortices to accelerate the tuna through the water rather than apply drag. But RoboTuna has one great advantage over its natural counterpart: its brain is the highest form of artificial intelligence yet devised by man. The RoboTuna is the ultimate autonomous underwater vehicle: smarter than a real fish and equipped with more senses, but just as adapted to life in the deep sea.

The robotic tuna has become the latest tool in the attempt to revive several important commercial fisheries that collapsed in the early part of the twenty-first century as a result of overharvesting. It is equipped with a full suite of chemosensory and acoustic devices that are used to detect the onset of spawning and to track the recruitment of juveniles in the target fish populations. The nose of the RoboTuna is specifically designed to mate with docking stations on the seafloor, spread throughout the globe. Each RoboTuna periodically returns to these docking stations to download its information and recharge its batteries. So far, the information from the RoboTuna has proved invaluable for estimating the effectiveness of several conservation strategies for rebuilding wild populations of fish. For some species of fish, the RoboTuna acts as a shepherd, herding them toward the most abundant feeding grounds as determined by satellite information relayed to the robot.

While there is no question that the RoboTuna has increased the efficiency and the sustainability of fish harvests from the sea, it has also, unfortunately, magnified the difference between the haves and the have-nots. The large fishing conglomerates that can afford the RoboTuna have nearly put the family fisherman out of business. Carefully programmed RoboTuna herd fish away from the nets of the competition and, in the process, often destroy their fishing gear. Subsistence fishing in some nations is no longer viable. Although the concept of international waters still exists on paper, it is clear that whoever owns the technology owns the oceans.

Conclusion

Within the next 25 years, advances in artificial intelligence, undersea platforms, and autonomous in situ sensors will allow us to command and exploit the oceans as never before. There are certainly those who will say that engineering the ocean is a bad thing, and perhaps they are right—but with current population trends, we will probably have no choice. The preceding vignettes are designed to inspire the imagination as to what could be possible with technology that is currently on the horizon, and to point out some of the economic, scientific, environmental, and political issues that must be addressed simultaneously. Because the oceans are global, the solutions will have to be global as well, and therein lies the difficulty. In many ways, the technology is the easy part. The need will never be greater for inventors who understand and care about the sociological impacts of their discoveries, and for policymakers who understand the limitations of science and the long-term impacts of technology. As we engineer the oceans, we must be cautious in our approach, humbled by our ignorance, and farsighted in our policies.

Karl S. Pister

I should begin by professing a serious conflict of interest in commenting on Marcia's talk this evening. About a decade ago, David Packard told me that we had spent billions of dollars exploring space but had failed to invest adequately in ocean exploration. After all, he noted, our planet is more ocean than land. It was clear that he intended to do something about the imbalance. What I did not anticipate at the time of that conversation was that I would soon be invited to join the board of directors of the Monterey Bay Aquarium Institute (MBARI), where Marcia is now president and CEO. Funded by the Packard Foundation, the Institute was focused on designing and building new tethered and autonomous underwater vehicles and in situ sensors that are increasing our capacity to understand both spatial and temporal distributions in the ocean, as well as its inhabitants. I readily accepted the opportunity to serve on the board. Observing and working with David while he was chairman was an experience not to be forgotten—an experience that continues to inform my thinking about engineering as well as the ocean.

A foundational principle in David Packard's conception of MBARI was the close coupling of science and engineering through active collaboration between scientists and engineers in the undertaking of projects at the Institute. Marcia's remarks evidence the continued robustness of that philosophy in current thinking

Commentator Karl S. Pister (UC Santa Cruz) with his wife, Rita.

about marine science and engineering. To further illustrate this point, let me sketch a mental diagram of this interconnection. The discovery of new knowledge in science provides the raw materials from which engineers create artifacts and processes that in turn lead to technologies in service of society. However, in the process of creating new technologies, new science is often enabled as well, completing a cycle of creativity. As Marcia's various scenarios emphasize, the linking of science, engineering, technology, and society is seldom, if ever, neutral in its impact on and consequences for people and our planet.

It is in this context that Marcia's talk needs to be purposefully examined. She noted that by the year 2025, 75 percent of the global population will live in coastal areas, but that 95 percent of the ocean remains unknown and unexplored. She went on to describe new technology that is fundamentally changing the manner of exploration and observation of the oceans—technology that will enable manipulation and exploitation of the oceans for the benefit of society. The critical unanswered questions concern the sustainability of such interventions and their long-term consequences. It is instructive to connect Marcia's remarks to these vital questions. Since I cannot profess to be either an ocean scientist or an engineer, I will appeal to the work of others to make this connection. In a review paper published in *Science* (July 27, 2001), Jeremy Jackson of the Scripps Institution of Oceanography, along with 18 coauthors, reports that

> ecological extinction caused by overfishing precedes all other pervasive human disturbance to coastal ecosystems, including pollution, degradation of water quality, and anthropogenic climate change. . . . Overfishing and ecological extinction predate and precondition modern ecological investigations and the collapse of marine ecosystems in recent times, raising the possibility that many more marine ecosystems may be vulnerable to collapse in the near future.[1]

Sobering words indeed. How are we preparing new generations of researchers to address such issues? In a *Science* editorial (June 15, 2001), John Lawton of Imperial College in Silwood Park, England, wrote about this challenge:

> One of the great scientific challenges of the twenty-first century is to forecast the future of planet Earth . . . . Wrestling to understand these challenges is the young, and still emerging, discipline of Earth System Science (ESS) . . . The greatest challenge for the new discipline . . . is to provide prescriptions that will reverse current human abuse of planet Earth, signposting routes to a sustainable future. The biggest barriers to rapid progress are institutional. Comparisons between ESS and medical science are telling. Scientists and engineers from many disciplines routinely work together with institutions and organizations to improve human health. We would be startled if it were not so. The health of the planet is a different story. Although a few pioneering individuals and institutions around the world recognize the need for the strong interdisciplinary work that defines ESS, in the main we lack the organizations to nurture this new discipline.[2]

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1. Excerpted with permission from J. Jackson et al., "Historical Overfishing and the Recent Collapse of Coastal Eccosystems," *Science* 293: 629. Copyright 2001 American Association for the Advancement of Science. To view full text, visit *http://www.sciencemag.org.*

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I am pleased to note that Lawton mentions that UC Irvine offers a graduate program in Earth System Science. The richness of this field of study, as well as its complexity born of the intertwining of the natural and social sciences, is examined by Robert W. Kates et al. in another issue of *Science* (April 27, 2001). Their paper is titled "Sustainability Science," which is defined as a new field "that seeks to understand the fundamental character of interactions between nature and society." The authors propose a defining set of core questions for research in this field.[3] Answers to these questions would provide a major step forward in addressing the dilemmas posed by Marcia's scenarios:

> How can the dynamic interactions between nature and society—including lags and inertia—be better incorporated into emerging models and conceptualizations that integrate the Earth system, human development, and sustainability?
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> How are long-term trends in environment and development, including consumption and population, reshaping nature-society interactions in ways relevant to sustainability?
>
> What determines the vulnerability or resilience of the nature-society system in particular kinds of places and for particular types of ecosystems and human livelihoods?
>
> Can scientifically meaningful "limits" or "boundaries" be defined that would provide effective warning of conditions beyond which the nature-society systems incur a significantly increased risk of serious degradation?
>
> What systems of incentive structures—including markets, rules, norms, and scientific information—can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?
>
> How can today's operational systems for monitoring and reporting on environmental and social con-

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[3] Excerpted with permission from R. W. Kates et al., "Sustainability Science," *Science* 292: 641. Copyright 2001 American Association for the Advancement of Science. To view full text, visit *http://www.sciencemag.org.*

> ditions be integrated or extended to provide more useful guidance for efforts to navigate a transition toward sustainability?
>
> How can today's relatively independent activities of research planning, monitoring, assessment, and decision support be better integrated into systems for adaptive management and societal learning?

My own experience teaches that our institutions of higher education are long overdue in examining the impediments that traditional academic structures place in the interdisciplinary pursuit of such issues. It is time to move beyond more committee studies and begin to do something about it.

We have heard a splendid talk on engineering the ocean, in which new, critically important tools for developing and comprehending the science of the ocean have been described. We cannot stop there. Can we not find a way to "engineer" a better connection among science, technology, and society? It begins with quality K-12 education in the natural sciences for all students—complemented by a twenty-first-century definition, and delivery in our colleges and universities, of a truly liberal education, as well as by development and expansion of programs in Earth System Science. Scientific and technological literacy in the general population remains at a dangerously low level. For the sake of planet Earth and my grandchildren, I sincerely hope this state of affairs will change. The leadership of the Academy, together with the National Academies, could help break the comfortable inertia of the status quo.

The communication by Marcia K. McNutt is a condensed version of her chapter "Engineering the Ocean" in *The Invisible Future: The Seamless Integration of Technology into Everyday Life*, ed. by Peter J. Denning. Copyright 2001 by the McGraw-Hill Companies.