AFTERTHOUGHTS

The Great Trends in Exploration and the Challenges Ahead

The difficulty in attempting to present a coherent picture of ocean sciences is that there is no such coherent picture – oceanography is whatever scientists interested in the ocean happen to do. Depending on the changing interests of the scientists practicing the art, ocean science can readily change focus and has done so many times over the last century. An early task was to make an inventory of what lives near the shore, and how. It was followed by exploration of coastal waters, and by systematic investigation of the global ocean – its physics, its chemistry, its biology, and its history and geologic framework. It is now the changing ocean that is at the center of attention. Motivations have varied as well. In the early years, questions concerning the rules and history of evolution were important, as well as the life histories of marine organisms, which documented in detail their exquisite adaptations to the environment and to each other. Also, it was the desire to understand, from first principles, why currents move the way they do, and how the physical environment controls the distribution of organisms.

The needs of fisheries and of navies provided the main impetus for expansion within the first half of the 20th century, and after World War II. These needs supported growing efforts in physical, chemical and biological expeditions and laboratory studies for more than half a century. Lately, with the increase in human impacts, first along the coast and then on a global scale, motivation has shifted again. Much of exploration now is linked to assessing the scope of the impacts of polluting coastal water bodies, of overfishing, and of changes in the physics and biology of the ocean that may be attributable to global warming.

When attempting such assessments, motivated by the desire to understand the response of the ocean to disturbance, and perhaps to guide remedial action where this is called for, a serious and pervasive problem soon emerges. It is that the natural condition, undisturbed by human influence, is no longer available for study, and has not been available for several decades. Thus, it is not possible to clearly separate natural background from response to human disturbance, except in theory.

As the nature of the ocean has changed, so has the science that deals with it. The great trends are well summarized in a review by Margaret Deacon, doyenne of the history of oceanography (1). She takes the period between 1880 and 1930 as the decades that laid the foundations for modern oceanography. It is a time of great expeditions, from the British *Challenger* Expedition at the beginning to the British *Discovery* Expeditions and the German *Meteor* Expedition at its end.

Perhaps the most famous of all the expeditions within this period was the *Fram's* venturing into the Arctic Sea, under the leadership of Fridtjof Nansen, explorer, all-around naturalist, and discoverer of important oceanographic processes, such as the drift-at-an-angle mathematically explained by Ekman. The needs of commercial fisheries and whaling, and a general desire to understand the physical and biological workings of the ocean, were important driving forces in this phase of research.

In her article, Deacon illustrates two discoveries from the founding period. One is the bottom topography of the Atlantic Ocean, as mapped by the *Challenger* scientists, which showed the existence of the Mid-Atlantic Rise, and different bottom-water temperatures on either side of the rise. The morphology of this mountain chain, elaborated in the early part of the 20th century, posed a puzzle that would be solved, eventually, by the concept of "seafloor spreading," in the 1960s. Deacon's other illustration shows longitudinal oceanographic sections through the western and eastern basins, for salinity, which demonstrate the complicated stratification of the Atlantic Ocean. The sections are from Wüst's synthesis of the *Meteor* survey. They are crucial for the understanding of the thermohaline circulation of the ocean.

An Atlantic bias is evident in Deacon's review, and quite understandably so: important contributions to this founding phase of research came from British, Scandinavian, and German scientists (2).

The 1930s saw great expansion into sophisticated instrumentation, including seismic surveying and gravity measurements, besides routine temperature measurements (by bathythermograph). Important insights came from experimental biological work on production in its dependency on light and nutrients, and on the vertical migration of zooplankton. In that decade, also, oceanographic work at North American institutions began to play an important role in the international scene, most prominently Scripps on the West Coast and Woods Hole on the East Coast.

In Woods Hole in Massachusetts, which had hosted the "Marine Biological Laboratory" since 1888, a new oceanographic research facility was created with the help of the Rockefeller Foundation: the "Woods Hole Oceanographic Institution," in 1930. Henry Bryant Bigelow became its first director (from 1930 to 1940). His interests were focused on fisheries sciences. In a report to the National Academy of Sciences (which laid out a program for research endorsed by the leading oceanographers in the U.S.) Bigelow emphasized studies of economic value (fisheries and also navigation), basic physical oceanography (with applications to biology and navigation), and life in the sea (zoology and botany, marine physiology, and bacteriology). The report was ahead of its time in pointing to upwelling as an important process worthy of study, and in identifying bacteria as a vital part of the marine environment (3). The insights regarding the importance of bacteria, one may assume, reflect the influence of two prominent founding members of Woods Hole, the chemist Norris Rakestraw, who pioneered comprehensive study of the marine nitrogen cycle, and Selman Waksman, a soil microbiologist. Other rising stars at the new institution were the Scandinavian meteorologist Carl Rossby working at MIT and the physiologist and all-around oceanographer Alfred Redfield.

In 1936, Harald Ulrik Sverdrup came to La Jolla to lead Scripps Institution of Oceanography into a new phase of exploration, with a new seagoing vessel, the *E.W. Scripps* (4). He initiated expeditions into the Gulf of California and systematic surveys of currents and of plankton in the waters off California, Oregon and Baja California. The peculiar whorls that characterize the California Current emerged, as well as the significance of upwelling. At the same time, Woods Hole scientists were discovering the Gulf Stream as a boundary phenomenon along the great wall that separates the warm waters of the Sargasso Sea from the cold coastal waters.

The "Ocean Bible," the treatise by Harald U. Sverdrup, Martin W. Johnson and Richard H. Fleming (1942) represents the most complete organization and summary of these founding years, in fact defining the field of oceanography for the next several decades. Its focus is on physical and biological oceanography and on that part of the chemistry of the ocean that is relevant to biological production (5). However, the treatise did not just stand at the end of a pioneering development: it set a new tone compared with much earlier work. It put the emphasis on dynamics, rather than the traditional description of the physical environment, on relationships of organisms to their environment, rather than on taxonomy and individual life histories, and on basic research, rather than on applications to fisheries and navigation. A shift from an Atlantic perspective to a world ocean perspective (that is, one centered on the Pacific) began to emerge in this new exposition of ocean sciences.

In the midst of these activities burst World War II, and a need to concentrate research on matters of concern to the Navy, especially submarine and antisubmarine warfare. Two long-term modifications of the overall research paradigm emerged: a shift to acoustics, for sensing the environment in a dark sea, and a move from fisheries biology as a rationale for doing ocean science to marine physics as a means to enhance the effectiveness of naval operations (6). Along with this expansion of the dominance of physics (including geophysics) came great advances in ocean engineering, which in turn benefited studies in marine biology including nutrient chemistry. For two to three decades after the war, this new pattern persisted. Gradually, the general ocean sciences regained ground as research support from the National Science Foundation grew, and as NSF split out separate programs for the various branches of oceanography.

In the 1960s and 1970s, after a time of unprecedented expansion of oceanographic research facilities, the landscape of doing ocean science changed again, and large-scale cooperative investigations became dominant features. At Scripps, these developments had been presaged by the “CalCOFI” program, aimed at studying the behavior of the California Current from a perspective of commercial fisheries, in collaboration with the state and federal agencies involved. The most important result of this program was the realization that climate change underlies the fluctuations of fish populations. With this realization, and with ENSO events emerging as a concern in ocean and climate dynamics, the role of the ocean in determining weather patterns and all questions regarding air-sea interaction gained prominence again – closing the loop to the origins of dynamic oceanography in the Bergen group around the meteorologist Vilhelm Bjerknes, early in the 20th century. In 1971, the meteorologist Jerome Namias, once mentored by Carl Rossby (himself an offspring of the Bergen group), made the transition from the U.S. Weather Bureau to Scripps, to begin building a climate research group at SIO. It became a fast growing part of Scripps, and was quickly integrated into national and international efforts.

One highly successful international venture centered at Scripps was the Deep Sea Drilling Project, initiated in 1964. From 1968 to 1983, the *Glomar Challenger* crisscrossed the seas and drilled the seafloor in a great effort to map the geology of the crust of the submerged part of the Earth. While the geophysics of the crust became known in the 1950s, the geologic make-up, in the early 1960s, still was *terra incognita*, an unknown area as large as half of Earth’s surface. Together, the geophysical discoveries of the 1950s and the drilling results of the *Glomar Challenger* gave us a radically new world view about the way the Earth works on long time scales.

In his brief review of the history of Scripps Institution of Oceanography, written at the end of his long and distinguished career, Roger Revelle singled out the following scientific topics for illustration: heat flow measurements by Arthur E. Maxwell (one of Scripps’s contribution to the new global tectonics, along with Russell Raitt’s work on crustal thickness, and Ronald Mason’s discovery of magnetic anomalies, among others), satellite-based productivity measurements of the California Current, the composition of the fauna near hydrothermal vents in the Galapagos Spreading Center, the rise of atmospheric carbon dioxide (Keeling Curve), acoustic tomography of the ocean, satellite-based tracking of drifting buoys in the California Current (showing mesoscale eddies), the coverage of the world ocean by the Deep Sea Drilling Project, and nearshore ecology (7).

In his “final word” to this review, Revelle argued that while much of the work at Scripps centers on problems of great concern to human beings, “the human dimension is pretty much left out of the picture.” He urged greater involvement in the study of human impacts on the oceans and the life within it, and a buildup of competence in questions of ocean policy (8).

Revelle’s concern with human impact has turned out to be most perceptive; such concern has received increasing attention within the last decade. We humans are now a geologic agent on a par with volcanoes and impacts from space; that is, we live in a new era that has no precedent. There now is an urgent need to understand the Earth's life-support systems, so we can mitigate our modifications of these systems and adapt to their changing conditions.

For a hundred thousand years, we humans have found ways to control natural forces and bend them to our advantage – using fire and fur against the cold, building shelters against bad weather, extracting sustenance from the biosphere on land and in the sea. Now we have to learn to cope with a new type of force of planetary proportions: our own activities. We have met the tragedy of the commons on a planetary scale.

Prime examples of the impact of this new force are in climate modification (that is, global warming) and in the overexploitation of biosphere resources, such as fishes, forests and soil. Much experience has accumulated regarding the management of fisheries, efforts that have had mixed results, at best. The experiences gained can offer valuable insights for the managing of other types of resources in the context of sustainable development (9). Knowing and avoiding past mistakes can improve chances for success.

Modern cultures – our ideas concerning proper behavior – go back several thousand years. However, almost all of our knowledge about the conditions and processes supporting life on the planet was gathered in the past century. Only in the last few decades have we realized the extent of our own impact on these conditions and processes. Thus, it comes as no surprise that this new knowledge has not yet been integrated into our traditions. We are faced with unprecedented challenges, but our toolkit for coping, built over millennia, is sparsely endowed (10).

Confronted with such problems, what is our task?

The obvious answer – readily supported by scientists, businessmen and politicians alike – is to increase knowledge about the workings of life-supporting systems. That the results of new scientific knowledge can improve decision-making is well illustrated by the Montreal Protocol on the protection of the ozone layer. The lessons from the ozone episode are straightforward. Scientists exploring the chemistry of the atmosphere, for the purpose of broadening our understanding of what processes maintain its composition, found unexpected behavior, with great potential for damage to human health, as well as to livestock and to crops. Among the chief suspects were newly developed chemicals thought to be entirely harmless, because of their great stability (chloro-fluoro-carbon compounds). Their release to the atmosphere, in comparatively minute amounts, was of no interest whatever, until they were linked to observed hazards. At that point of crisis and high risk, action was taken quite promptly. The problem persists, but mitigation is in sight. The healing of the damage to the atmosphere will take place on the time scale of a century or so. In the meantime, we and later generations, and all living things, will bear the unintended consequences of one of the ongoing experiments, in this case releasing seemingly harmless substances to the environment.

Some problems, such as the loss of biodiversity, are amenable to mitigating action, because they can be attacked on a regional basis, for example, by setting aside refuges large enough to protect a given assemblage of organisms. One great benefit of such set-asides is that they can serve as a source of seeds for re-stocking surrounding areas. Other problems are much less tractable, mainly because they are intricately intertwined with economics, and include many different stakeholders, from different political groupings. Perhaps the most serious of these difficult problems is the excess greenhouse effect. The great geophysical experiment is proceeding, and we don't know where it will take us. We do know that polar regions are changing in significant ways (11).

As emphasized throughout in this book, the ability of the scientific community to predict the consequences of overuse of resources and of global warming is quite limited. This does not mean that there are no serious problems ahead. It just means that we cannot identify them to the satisfaction of all who need to get involved in mitigation. The political problem that arises in consequence of uncertainty is obviously this: we cannot tell which is potentially more painful, the change of environmental conditions, or the cost of the actions proposed.(12) In any case, the cost of mitigation would presumably mainly fall to those who use much energy and live well (and are able to make decisions) but the risks are distributed to all, without regard to use of resources, and including future generations. The concept of incurring serious costs for the benefit of others is not commonly employed in generating policy.(13) It is unlikely to prevail where benefits cannot be demonstrated and the potential beneficiaries are not yet born.

A situation where decisions have to be made in the fog, without a clear view of what is ahead, is not without precedent to officers at sea, on the bridge. We might learn much from their behavior. They do not assume that the fog holds no dangers. On the contrary, they assume it is not safe to proceed without relevant information on what lies ahead. Were we to adopt their precautionary stance in respect to the future of conditions on the planet, we should change our economic behavior to minimize all adverse human impact on ocean, atmosphere, and biosphere.

Our future, obviously, is rarely in the hands of well-trained and cautious navigators. Whatever will be done will have to be based on a broad consensus of an informed public actively pursuing the goals of sustainability within a general setting of economic constraints. Hence, public education in the pertinent Earth sciences, including oceanography, ecology and atmospheric sciences, is one crucial ingredient of coping with future challenges. But equally important is an effective education toward environmental stewardship, that is, toward a sense of responsibility, as providing a balancing perspective on economic priorities.

The needs that will inform future research will focus on sustainability and on life-support systems. However, more than scientific understanding will be called for to meet the challenges; that is, a general desire to manage human activities for the benefit of a habitable planet. Without participation of a committed public, scientific knowledge will not translate into political action (14).

What type of action might be useful in furthering stewardship and sustainability?

Many different types of approaches can be envisaged and are being discussed. With regard to climate change, the focus is on replacing carbon-based energy with alternative energy sources including sun, wind, and nuclear power. In addition, the possibility of sequestering carbon dioxide underground, next to the power plants generating the gas, is being studied. As the climate warms, energy sources for air conditioning will be of increasing interest, including the cold water below the thermocline in the sea. Also, looming water shortages are directing discussion toward the need for desalinization of seawater, likewise an energy-intensive proposition. With regard to conservation, the shining example of the National Parks in the USA and elsewhere point the way: the need for setting aside sufficiently large regions to preserve a portion of the natural ecologic endowment of the planet. In the marine realm, the path toward set-asides for conservation includes generating the scientific underpinnings for judging the necessary size of restricted areas, and the nature of the proposed restrictions (15).

What the various problems of sustainability have in common is that in each case we need to avoid Hardin's Tragedy of the Commons; that is, rational exploitation leading to collapse of the resource. (16)

Notes and references

1. M.B. Deacon, 1996, *How the science of oceanography developed,* in: C.P. Summerhayes and S.A. Thorpe, *Oceanography, an Illustrated Guide,* Manson Publishing, London, 9-26.
2. M.B. Deacon, 1996, *ibid.* Figs. 1.12 and 1.20.
3. H.B. Bigelow, 1931, *Oceanography, Its Scope, Problems, and Economic Importance,* Houghton Mifflin, Boston and New York, 263pp.

4. Robert P. Scripps donated the ship, a two-masted schooner, christened the *E.W. Scripps* after his father and the man who helped get the institution started. (Helen Raitt and B. Moulton, 1967, *Scripps Institution of Oceanography: First Fifty Years.* Ward Ritchie Press, Los Angeles, 217pp.; R. Revelle, 1992, *The Scripps Institution of Oceanography, California,* in: E. M. Borgese (ed.) *Ocean Frontiers, Explorations by Oceanographers on Five Continents*, Abrams, New York, p.14-53.)

5. Geology appears only in the last chapter of twenty, with a review of sedimentation in the sea. (H.U. Sverdrup, M.W. Johnson, R.H. Fleming, 1942, *The Oceans, Their Physics, Chemistry, and General Biology,* Prentice-Hall, Englewood Cliffs, N.J., 1087pp.)

6. For many years, the vision and resources of the Office of Naval Research, established after the war, were crucial in the growth of both Scripps and Woods Hole, and in the growth of emerging oceanographic research institutes on all coasts of the United States.

7. R. Revelle, *op. cit.* Other items are photos of the institution and its ships, or similar images of a general nature.

8. R. Revelle, *op. cit.*, p. 53.

9. Regarding attempts at management, the Northeast Atlantic Fisheries Commission stands out. It was established after World War II (with discussions going back into the 1930s) with the idea to facilitate international agreements to regulate such items as minimum fish size and use of fishing gear, and setting values for total allowable catch. Innumerable agreements were signed between the interested parties, regarding fishing in international waters. Many of these agreements did not take into account the great susceptibility of fish stocks to climate change. (See K. Brander, 2003. *Fisheries and climate.* In: G. Wefer, F. Lamy, F. Mantoura (eds.), *Marine Science Frontiers for Europe,* Springer-Verlag Berlin Heidelberg, pp. 29-38.) In any case, the familiar pattern of regulation is one of too little, too late: some of the most important fisheries in the Northeast Atlantic have since collapsed.

10. The lack of an appreciation of ecologic principles – the economy of nature – has serious consequences in human affairs. It is fundamentally the reason that intelligent people trained in sociology and political science, but with no background in biology or Earth sciences, can come to the type of conclusions proffered in the upbeat works of the late economist Julian Simon, with statements that emphasize recent progress in human welfare and belittle the thought that natural resources are used at an unsustainable pace. (J. Simon, ed., 1995, *The State of Humanity,* Blackwell, Oxford.) More recently, the Danish political scientist Bjoern Lomborg has taken up Simon's cause. (B. Lomborg, 2001, *The Skeptical Environmentalist, Measuring the Real State of the World*. Cambridge University, Cambridge, UK.) When applied to anticipating future developments, Simon's approach resembles straight-line extrapolation in an environment without limits.

11. Changes include thinning of Arctic sea ice and widespread melting of permafrost in Siberia and Alaska, as well as the breakup of large ice-shelves off Antarctica. A summary of recent results of studies of changes in polar regions is in a special issue of the magazine *Science*: J. Smith, R. Stone, J. Fahrenkamp-Uppenbrink, 2002, *Trouble in polar paradise,* Science, 297, 1489, and articles following.

12. The dilemma has been well recognized for some time. As stated in 1990 by the geophysicist Frank Press, then President of the National Academy of Sciences: "Thus difficult policy decisions must be made on the basis of judgments between dimly perceived future risks and possible economic or other consequences that may be more immediate." (Preface, C.S. Silver and R.S. DeFries, 1990, *One Earth, One Future,* National Academy Press, Washington, D.C., 196pp.)

13. At least in ecology, self-interest commonly dominates behavior, even where altruism is suspected from appearances.
14. The trends are not favorable. World-wide, emissions in 2005 were higher than those in 1990 by 27%, despite much discussion of the need for reducing the release of carbon dioxide to the atmosphere. The total input to the atmosphere each year, as a consequence, is now near 8 billion tons of carbon. Increased globalization of the economy is not helpful in stemming the trend: with increased competition in producing goods for the world market comes a growing need for cheap energy, for each participant. Thus, moving out of carbon energy comes with a price tag in terms of position in the competition.
15. At Scripps, these questions are pursued at the Center for Marine Biology and Conservation, initiated and led by Nancy Knowlton, Jeremy Jackson, and Enric Sala. A substantial training program equips students with the background to tackle issues of conservation in the real world of public discussion and policy.
16. The remedy is regulation based on scientific understanding. If urged to give an opinion in this context, as an oceanographer, I would focus on the Antarctic Current as the region for which regulating access would make much sense. To me, it seems likely that an enduring presence of the enormous ice cap on the southern continent will ensure strong winds and deep mixing into the foreseeable future. Thus, high productivity should persist during summer months, regardless of what happens elsewhere in the ocean. If so, the region could serve as a kind of Noah's Ark, in continuing to support high-energy apex consumers (that is, seabirds and marine mammals). As the fish removal operations of the industrial fleets complete their work across the seas, fish farming will continue to grow, and so will the demand for feed for such farming. It stands to reason, then, that the remaining high-production regions in the Antarctic will increasingly attract the attention of industrial feed producers, and that large-scale krill removal will soon be the result. If this is to be avoided, the time to restrict removal operations is now, before the vested interest of powerful stakeholders makes certain that the tragedy of the commons prevails here as elsewhere on the planet.