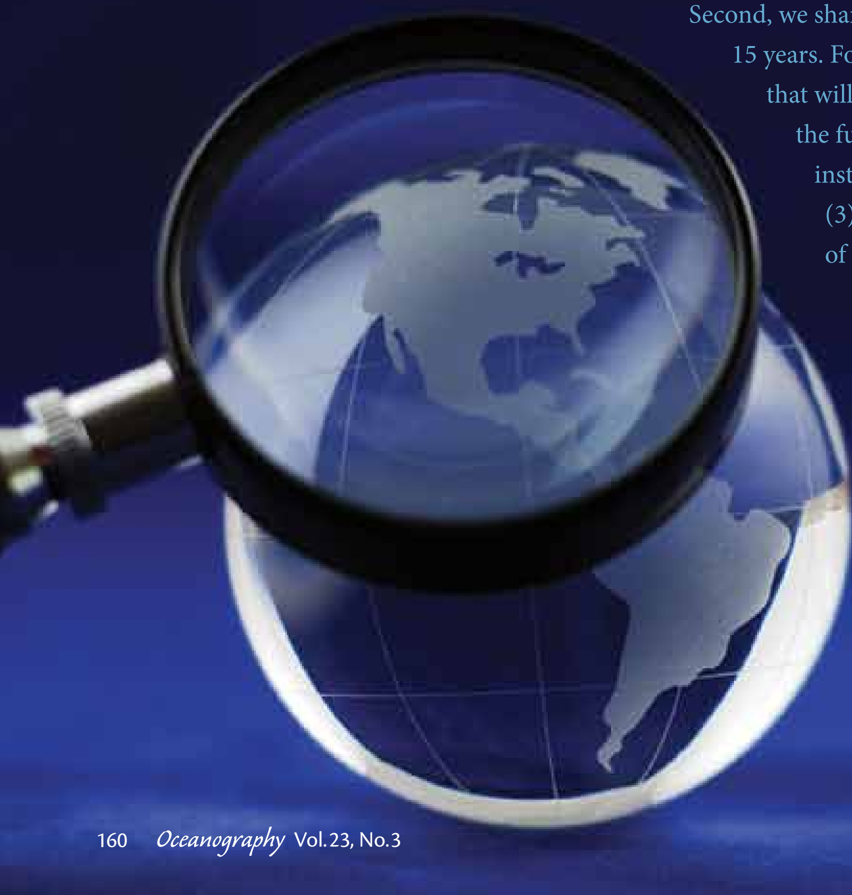
BY LUIS VALDÉS, LUCIANO FONSECA, AND KATHY TEDESCO

Looking into the Future of Ocean Sciences

An IOC Perspective

ABSTRACT. As the only United Nations organization specializing in ocean sciences, the Intergovernmental Oceanographic Commission (IOC) has the responsibility to promote basic marine scientific investigations globally. IOC has always given special attention to planning and forecasting new developments in ocean sciences, taking into account both the steady evolution of knowledge and fundamental changes leading to major scientific breakthroughs. Following that tradition, and in honor of IOC's fiftieth anniversary, we focus on two distinct objectives in this article. First, we provide a glimpse of past IOC scientific achievements. Second, we share IOC's vision for a marine science strategy for the next 15 years. For that purpose, IOC has identified three critical elements that will likely provide the scientific and technical means to redefine the future of ocean sciences: (1) science drivers, (2) ocean instrumentation and technological developments, and (3) strategic frameworks for cooperation. The third element is of particular importance because research at unprecedented geographic scales is required to improve our understanding of climate change and ecosystem functioning, including biodiversity conservation and management options. Because this effort calls for extensive national and international efforts, we also discuss the role of comprehensive international core projects.



INTRODUCTION

The ocean is the main defining feature of our planet, covering 71% of its surface, and is intrinsically connected to the majority of human needs and challenges. International in character, it represents the best example of a global common because it provides a medium of transportation and communication among nations. The ocean also provides food, water, and mineral resources with direct economic implications for people and societies. In the face of an increasing human population, there is overwhelming pressure to overexploit the ocean's living and mineral resources (Field at al., 2002). This is aggravated by the fact that the ocean is also the final destination of many pollution sources that originate on land. The ocean also plays a central role in climate modulation, which can be regarded as the main service that the ocean provides to people and to the ecology of the planet. This role has gained in significance, as recent research demonstrates that the ocean mitigates the consequences of climate change by redistributing heat and absorbing excess carbon from the atmosphere (e.g., Revelle and Suess, 1957; IPCC, 1990, 2007; Valdés et al., 2009).

For these reasons, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and the international community recognized the importance of the ocean with the establishment of the Intergovernmental Oceanographic Commission (IOC) in 1960. The United Nations then designated IOC as the focal point for marine scientific research and the link between Member States on conventions and agreements related to marine and coastal issues (Holland, 2006). As the only UN organization specializing in ocean sciences, IOC is responsible for promoting basic marine scientific investigations on a global scale (Roll, 1979) and has played a major role in ocean science progress.

IOC has always given special attention to planning and forecasting new developments in ocean sciences. The normal planning process involves recognizing scientific trends and identifying key scientific questions, searching for sources of research funds, and following scientific publications, technologies, and discussions. It also involves cooperation, promoting development of new ideas among scientific communities, and tracking advances in marine instrumentation, methods, and monitoring devices. In this way, IOC serves as an international marine science broker by promoting innovation, nurturing scientific programs, and promoting scientific excellence. Additionally, IOC analyzes emerging issues; disseminates information, data, and knowledge; and coordinates and evaluates scientific programs, best practices, assessment, and scientific services related to ocean sciences.

Periodically, IOC mobilizes its expertise to analyze the future of ocean research. For example, in 1969, a special IOC working group prepared a comprehensive outline for the Long-term and Expanded Programme of Oceanic Exploration and Research (LEPOR). There was a second assessment in 1989, and the third assessment, undertaken in collaboration with the Scientific Committee on Oceanic Research (SCOR) and the Scientific Committee on Problems of the Environment (SCOPE), was published in 2002 under the simple and suggestive title "Oceans 2020" (Field et al., 2002). The assessments are also reviewed internally on a regular basis (e.g., IOC, 2003, 2007).

"IOC HAS ALWAYS GIVEN SPECIAL ATTENTION TO PLANNING AND FORECASTING NEW DEVELOPMENTS IN OCEAN SCIENCES."

The periodicity of these prospective analyses shows clear evidence that strategic priorities in the ocean sciences are not static. In fact, we are aiming at a moving target, facing a changing environment in ocean research and coastal management. The rate of environmental change is unprecedented, and is aggravated by the fact that very few areas of the ocean remain pristine, unaffected by multiple anthropogenic interferences such as greenhouse gas emissions, eutrophication, fishing, habitat destruction, hypoxia, pollution, and species introductions (Halpern et al., 2008).

Forecasting ocean science priorities is not an easy task and is never perfect, perhaps because it is based on previous knowledge and short-term needs in marine science, or possibly because it assumes the continuation and extrapolation of existing trends. As a result, some potential major discoveries will be missed and some future trends will not be predicted. This negative outcome is not easily avoided as it is extremely difficult to forecast new discoveries, breakthrough ideas, or great insights that will change paradigms in ocean sciences (Seibold, 1999). It is also important to stress the strong influence of research councils and funding agencies in the selection of scientific priorities. It is natural to expect great advances in a research area they decide to support and fund, which could be regarded as a good example of a self-fulfilling prophecy. Nevertheless, successful science planning should take into account both steady acquisition of knowledge (evolution) and major scientific breakthroughs (revolutions). There are no infallible methodologies for anticipating the future; there are only schemes to reduce the uncertainty (Schwartz, 1996; Gunderson and Folke, 2003; Sutherland and Woodroof, 2009). As mentioned previously, the most common schemes consist of extrapolating current scenarios into the future, assuming that the present simulation conditions will remain in a steady state. It follows that the best indicator of future behavior is past behavior. However, this approach will probably fail to forecast nonlinear changes in the course of science and research that quite often are the most important ones. An alternative scheme is to follow a disciplinary approach, which necessarily restricts the scope of our projections to single topics (Sutherland and Woodroof, 2009). A third approach, more risky and uncertain, is to incorporate nonlinear events into the projections and then analyze contingent scenarios to assist long-range planning (Schwartz, 1996; Gunderson and Folke, 2003).

The present discussion has two objectives. The first is to review the main actions and achievements in marine research that have crafted the present personality of the IOC's Ocean Science Section. Second, it attempts to look into the future using the past as a source of information in order to formulate the main drivers for ocean research, suggest some examples of topics that are in need of urgent attention, discuss possible technological developments, and emphasize the importance of scientific networking as an essential strategy for achieving ambitious goals. IOC's fiftieth anniversary is an appropriate moment for this assessment and review, which is in complete accordance with the International Council for Science (ICSU) visioning process (Reid et al., 2009) as well as recently published marine science plans (JSOST, 2007; ICES, 2009; UK Marine Science Co-ordination Committee, 2010).

A GLANCE AT PAST IOC SCIENTIFIC ACHIEVEMENTS

Since it was founded, coordination of activities related to scientific understanding and practices has evolved at IOC. For instance, oceanographic research has expanded from individual initiatives to international networks, which not only has changed our approach to addressing global ecological questions but also has opened new opportunities for interdisciplinary research, for creating distributed facilities, and for transferring knowledge and technologies. IOC has contributed to advances in ocean science by catalyzing, coordinating, and communicating marine scientific research through participation in research and coordination of scientific programs on targeted themes as well as scientific networking though the sponsorship of global research programs. IOC's history of cooperation includes leading UN interagency groups and also working with other relevant international organizations. In terms of capacity building, technology transfer, and outreach, IOC has published the results of its programs in both scientific journals and in literature for the general public and decision

Luis Valdés *(jl.valdes@unesco.org) is Head, Ocean Sciences Section, Intergovernmental Oceanographic Commission of UNESCO, Paris, France.* **Luciano Fonseca** *is Program Specialist, Ocean Sciences Section, Intergovernmental Oceanographic Commission of UNESCO, Paris, France.* **Kathy Tedesco** *is Project Director, International Ocean Carbon Coordination Project (IOCCP), Intergovernmental Oceanographic Commission of UNESCO, Paris, France.*

makers. The Commission has also provided the framework for extensive scientific services and data archiving. Other important contributions are related to the development of standards and guidelines for data exchange, marine technology, and research.

All IOC programs reflect the quest for knowledge related to fundamental processes and dynamics that control the ocean. Early examples of IOC endorsement and promotion of scientific exploration of the ocean include the International Indian Ocean Expedition (1959–65), the International Cooperative Investigations of the Tropical Atlantic (1963–64), the Cooperative Study of the Kuroshio and Adjacent Regions (1965–77), and the Cooperative Investigation of the Caribbean and Adjacent Regions (1967–76). Later, IOC adopted the International Decade of Ocean Exploration (1971–80) to provide a general and intensified effort for ocean research. At that time, IOC encouraged cooperation among scientists from various developing and developed nations to promote capacity building and technology transfer and to ensure that the resulting data were made available to the global scientific community.

This interest in expeditions and in the exchange of oceanographic data highlighted the need for improved bathymetric charts of the world ocean, a need identified over a century ago, when the General Bathymetric Chart of the Oceans (GEBCO) project was established under the leadership of the government of Monaco (Carpine-Lancre et al., 2003). Since 1964, IOC has encouraged Member States to support the GEBCO project, which is currently operated under the joint supervision of IOC and the International Hydrographic Organization (IHO). This project engages an international group of ocean mapping experts who continue to develop and make available to the hydrographic and oceanographic communities gridded bathymetric data sets, the GEBCO Digital Atlas, the Gazetteer of Undersea Feature Names, the GEBCO world map, and complete sets of printed charts (see http://www.gebco.net).

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In addition to promoting these extensive research programs, IOC has coordinated scientific planning that addresses research activities driven by more specific objectives, such as weather, climate, ocean health, and fisheries. As early as 1960, the importance of protecting the marine environment had already been recognized by the community, which led to the establishment in 1965 of an IOC Working Group (WG) on Marine Pollution. This WG succeeded in preparing an acceptable definition of marine pollution and a classification of pollutants, stressing the need for better coordination to control these problems. In 1969, following an agreement among the International Maritime Organization (IMO), the Food and Agriculture Organization (FAO), UNESCO/IOC, and the World Meteorological Organization (WMO), with the approval of the Administrative Committee on Coordination (ACC), a joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP) was established. In 1972, the UN Conference on the Human Environment held in Stockholm requested that IOC create a program for the investigation of pollution in the marine environment. This request reinforced an activity already initiated within the Commission as one of the major projects envisioned by LEPOR.

In 1965, the WG on Ocean-Atmosphere Interaction was established with the objective of connecting the physical processes governing the atmosphere and the ocean. As early as 1979, IOC and SCOR formed the first Committee on Climate Change and the Ocean (CCCO), with Roger Revelle as its chairman. CCCO provided significant guidance to IOC on climate research and climate-related programs, which evolved over the next few years in close collaboration with WMO and led to an intergovernmental and interagency planning meeting on the World Climate Programme in 1980. The main outcome of this meeting was the establishment of a World Climate Research Programme (WCRP), sponsored in collaboration with IOC and ICSU. WCRP studies are specifically directed to provide scientifically founded quantitative answers to questions being raised on climate and on the range of natural climate variability. Within the WCRP framework, many successful interdisciplinary projects were supported, such as Tropical Oceans and Global Atmosphere (TOGA), World Ocean Circulation Experiment (WOCE), and Climate Variability and Predictability (CLIVAR), which is still active. TOGA (1985–95) was the forerunner to the development of the monitoring program for the prediction of El Niño and its recognition as a driver of the seasonal global climate (Voituriez and Jacques, 2000). WOCE (1990–97) was probably the largest ocean experiment to date, involving the efforts of 30 countries and producing a data set that is essential for climate research, as well as having many other uses.

In 1992, a second global conference on the environment was held in Rio de Janeiro, Brazil. This historic meeting influenced the evolution of environmental programs over the succeeding years. During the conference, the need for an integrated and comprehensive Global Ocean Observing System (GOOS) was recognized to provide information for oceanic and atmospheric forecasting, for ocean and coastal zone management, and for global environmental change research. This early commitment was made possible by new technological innovations and instrument developments that were incorporated into oceanographic applications. Today, there is general agreement that GOOS has been the necessary catalyst to systematically incorporate these new technological developments into observations of the ocean. Parallel to this electronic revolution in marine instruments, there were also great advances in the technology for data transmission and information exchange. IOC has been particularly successful in establishing data exchange and training programs with free public access through the development of the IOC International Oceanographic and Information Exchange program (IODE). The year 1992 also brought a highly successful IOC Harmful Algal Blooms (HAB) program, established in response to growing concern about the increase in global occurrences of these events. HAB contributions to research, training, and public awareness of the causes and episodes of these hazardous events have been significant. This concern contributed to the adoption in 1997 of an independent Integrated Coastal Area Management (ICAM) program. ICAM's objective is to build marine scientific and technological capabilities in the field of integrated coastal management through the provision of reliable marine scientific data, development of methodologies, dissemination of information, and capacity building. ICAM has achieved significant results and has published guidelines for integrated coastal area management (Belfiore et al., 2006) and for marine spatial planning (Ehler and Douvere, 2009).

Development of scientific advice on fishery research has been a constant part of the IOC agenda, although the program has remained relatively small. However, in 1992, the need to assign priority to fishery research was recognized by some major biological oceanography programs (such as Coral Reef Monitoring) and by international cooperative programs (e.g., Global Ocean Ecosystem Dynamics, or GLOBEC) within the International Geosphere-Biosphere Programme (IGBP). In recent years, the scientific community has agreed that study of the relationship between biological and physical elements is crucial to understanding and managing renewable marine resources. This combined ecosystem-based approach to marine and environmental sciences has been successful in creating awareness of the importance of fisheries oceanography.

Throughout IOC's history, major programs covering almost all aspects of ocean science have been initiated, and some have been successfully completed. Recent programs include the IOC/World Bank Working Group on Coral Bleaching and Local Ecological Responses, initiated in September 2000; the International Ocean-Colour Coordinating Group (IOCCG), established in 1996; and, more recently, the IOC-SCOR Ocean CO_2 Advisory Panel in 2000. A more detailed history of IOC and its past achievements in ocean sciences, services, and capacity development may be found in Field et al. (2002) and Holland (2006).

IOC VISION FOR A MARINE-SCIENCE STRATEGY: A 15-YEAR HORIZON

Parallel to the advances in research and technology that occurred in the last 50 years, new scientific challenges and new environmental risks have emerged. We are now facing important changes in the marine environment that are a consequence of our interference in pivotal processes that control the ecology of our planet. Public awareness about these problems has increased considerably in recent years, so that societies are now demanding from policymakers proactive positions and solutions toward sustainable use and management of natural resources. Concepts such as ecosystem-based management, integrated coastal zone management, and a precautionary approach have been exported from scientific and technical documents to the common vocabulary of policymakers. In the next 10 years, social pressure will probably encourage policymakers to reach agreements regarding limits on carbon emissions and establish planetary boundaries for other anthropogenic impacts. In some cases, these new approaches are already being implemented in common marine strategies at regional and international levels. They demand considerable effort toward increasing oceanographic and coastal ecosystem data acquisition, and toward promoting data analysis and technological assistance. Hopefully, these approaches will deepen our understanding of the role ocean dynamics play in the functioning of the Earth system, in climate change, and in the sustainability of life on Earth, which will certainly illuminate the boundary conditions for scientists to prepare accurate scenarios for a sustainable future.

IOC has identified three critical elements that will provide the scientific and technical means to redefine the future of ocean sciences: (1) science drivers, (2) ocean instrumentation and technological developments, and (3) strategic frameworks for cooperation. These three elements are interdependent and have a natural flow of interaction, so that a positive outcome in one will be reflected in the successes of the other two (Figure 1). The integration and synergy of these elements will help develop our understanding and our capability to forecast ocean processes. They will also provide the scientific information needed to support ecosystem-based management, particularly in coastal and nearshore environments. Hopefully, they will also accelerate the deployment of an ocean-observing system that will support advances in forecasting and in adaptive ecosystem-based management capabilities. These three elements are critical and necessary to expand the scientific vision of the ocean and ensure the ocean's legacy for future generations.

Science Drivers

Most probably, the main marine-science drivers for next 10–15 years will be climate change and ecosystem functioning. Some international councils and national programs (e.g., ICES, 2009; JSOST, 2007; UK Marine Science Co-ordination Committee, 2010) already have decided to support these research themes as priorities, and, therefore, we can expect great advances in these areas.

Climate Change

There is general agreement that our understanding of the role the ocean plays in modulating Earth's climate and ecology is still in its infancy, and that currently described adverse impacts to the marine environment are likely only a fraction of those that will be revealed more accurately in the coming years.

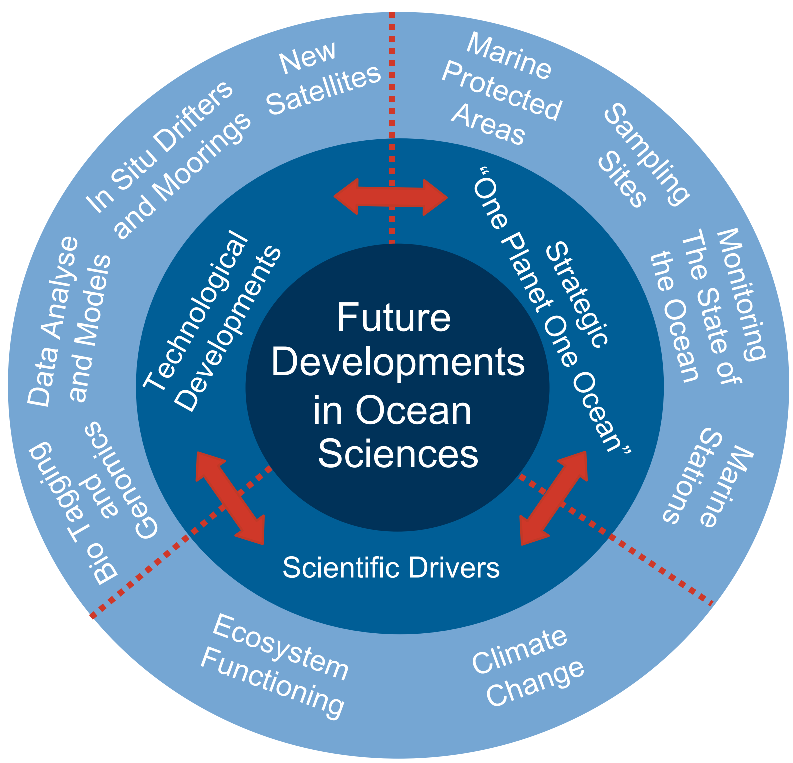

Figure 1. Critical elements identified by the Intergovernmental Oceanographic Commission for future developments in ocean sciences.

This limitation is due, in part, to the difficulty in separating the impacts of climate change from those caused by other natural or anthropogenic stressors. Whereas in other ecosystems the impacts of climate change are mainly driven by changes in temperature, in the ocean they are forced by both increases in temperature and the concentration of carbon dioxide (CO_2), modifying not only the thermal characteristics of the water column but also its physical structure and biogeochemistry. Both temperature and CO_2 may alter fundamental processes in the physiology of marine organisms at a level that jeopardizes the sustainability of entire ecosystems (e.g., coral reefs). As these changes in temperature and CO_2 continue, we risk serious degradation of marine ecosystems, which will result in undesirable consequences for human health and welfare.

Determining how climate change will affect all levels of biological organization requires observations, experiments, and predictive mathematical models based on reliable data. Normally, predictions can be done accurately if the processes studied are subject to continuous and monotonic changes, so that future states will depend substantially on past states (i.e., prognosis is based in diagnosis). This assumption holds for some physical and chemical processes; however, biology and ecology are very often governed by nonlinear and discontinuous changes (e.g., regime shifts). Prognosis is particularly difficult in those cases, as past events give us limited information on future trends. The challenge of predicting the impacts and outcomes of climate change becomes even more difficult when the combined effects of two or more variables are subject to positive or negative feedbacks, so that final impact on the environment cannot be predicted based solely on the sum of single-variable impacts.

Credible and timely scientific information is a necessary asset as nations engage in the process of responding to the challenges associated with climate change. Better science linked to improved risk management and adaptive management strategies will help scientists and policymakers cope with the high levels of uncertainty related to mitigation alternatives and with the range of impacts associated with climate change and variability. A much more comprehensive and robust science enterprise that incorporates a better understanding of the ocean's role in climate change is required to forecast more accurately the magnitude and the intensity of these changes at multiple scales, as well as to evaluate options for mitigation and adaptation. Examples of research topics on climate change that need immediate attention from marine scientists are summarized in Box 1.

Ecosystem Functioning

There is still a lot to be learned about ecosystem functioning and the complex interactions between biota and the physical environment. Ecological processes and biodiversity are essential to protect ecosystem resilience at local and global scales. In fact, resilience is an essential ecological characteristic to assure ecosystem recovery after adverse stresses and perturbations, as well as to help minimize the effects of natural or induced variability. Therefore, a better knowledge of ecosystem functioning is necessary for the sustainable management of marine ecosystems and also to maintain, in a broader sense, a healthy ocean environment. For instance, marine ecosystem management will be greatly improved if the underlying dynamics of ecosystem functioning at a variety of scales is properly elucidated. This will be achieved through development of complex adaptive and predictive models, and through comparison of their results with observations from managed ecosystems. Such activities should also be carried out in combination with laboratory-based experiments that test impacts of predicted future scenarios on keystone species and ecosystem models in mesocosms. This effort will improve our understanding of ecosystem processes and will provide practical tools for evaluating the effectiveness of local and regional ecosystem-based management initiatives.

New investments in exploration and novel methods for investigating ecosystem components and their interactions will be required in order to expand our understanding of ecosystem structure, function, complexity, and stability. A robust suite of indicators of ecosystem structure, function, productivity, and services must be evaluated and implemented at multiple scales (local, regional, basinwide). These indicators will help assess factors that stress and degrade ecosystems, such as eutrophication, harmful algal blooms, loss of coastal wetlands, shoreline development, overfishing of harvested species, invasive species, introduction and cycling of contaminants, changes in biodiversity, ecosystem productivity, and resilience. Additionally, indicators and metrics are needed to help monitor the restoration and recovery of degraded ecosystems. Given its importance to human welfare,

BOX 1. EXAMPLES OF RESEARCH TOPICS IN **CLIMATE CHANGE** THAT NEED IMMEDIATE ATTENTION FROM MARINE SCIENTISTS

1. GLOBAL AVERAGE TEMPERATURE WILL INCREASE BY 2°C. There is consensus among policymakers for accepting a world 2°C warmer. Even though this threshold may be acceptable for terrestrial ecosystems, it is probably too high for marine ecosystems. For example, in this scenario, the number of days with peaks in sea surface temperatures over 28–30°C will increase significantly in coastal waters of subtropical regions and in closed seas (e.g., the Mediterranean; IPCC, 2007). Research should be encouraged to evaluate the effects of extremely high sea surface temperatures on marine life, especially on the stability of some proteins.

2. STRATIFICATION AND OLIGOTROPHY. Global warming is strengthening water-column stratification and oligotrophy in temperate waters and ocean gyres, causing major decreases in marine productivity with undesirable consequences for marine ecosystems (McClain et al., 2004). More frequent and spatially dense observations are needed in order to understand the causes and implications of these phenomena and to provide the necessary inputs and boundary conditions for the development of more accurate numerical models, which could forecast ocean properties and behavior at the regional level.

3. UPWELLING SYSTEMS AND CHANGES IN WIND REGIMES. Upwelling systems are present in large areas of major oceans and are closely linked to atmospheric conditions. These wind-driven systems force cold, nutrient-rich bottom waters toward the ocean surface, fertilizing the euphotic zone, increasing primary production, and sustaining rich fisheries. Upwelling systems also drive the climatic conditions of adjacent continental land masses, which are usually deserts. In the current scenario of climate change, there are controversial hypotheses regarding future trends in the weakening or strengthening of the intensity and seasonality of upwelling systems. Further in situ research and new ocean circulation models are needed to fully understand the evolution and dynamics of those changes.

4. OCEAN ACIDIFICATION. Ocean acidification is a direct consequence of oceanic absorption of excess carbon dioxide from the atmosphere, causing irreversible changes in ocean chemistry and impacting marine life, particularly species that rely on calcareous structures (e.g., coral reefs, shellfish, and echinoderms, among others). The ocean is more acidic today than it has been for the last 800,000 years (ESF, 2009). Decreasing pH levels will reduce the ocean's capacity to absorb future carbon dioxide, leaving more emissions in the atmosphere. More research on ocean acidification is needed as the consequences of these changes for marine ecosystems are still unclear.

5. CARBON CYCLE AND OCEAN PRODUCTIVITY. Accurate estimates of regional and global sources and sinks of carbon are essential to coordinate better management practices and to assess the environmental sustainability of the use of some new carbon-based fuels (e.g., gas hydrates). Additionally, how global warming is affecting primary production and respiration, and consequently the capacity of specific ecosystems to sequester and recycle carbon (e.g., sea grasses, mangroves and salt marshes), remains largely unknown (Nellemann et al., 2009).

6. GEO-ENGINEERING (EARTH SYSTEM ENGINEERING). Despite the compromises that were agreed upon during the 2009 Copenhagen COP-15 (Conference of the Parties-15) meeting concerning control and target emissions of greenhouse gases, there are concerns that suggested mitigation actions may not be sufficient or may not be implemented in time to avoid adverse impacts from climate change. In that scenario, some geo-engineering methods are being considered for moderating the consequences of climate change. These methods include technologies for directly removing carbon dioxide from the atmosphere, and also technologies to manage solar radiation that reaches the planet's surface (Royal Society, 2009). The ocean can be directly used and directly affected by such techniques, for instance, ocean fertilization and the storage of CO_2 in deep-sea reservoirs. Although dispersing aerosols and other actions on the stratosphere could theoretically reduce temperatures globally by controlling incoming solar radiation, they will not reduce atmospheric carbon dioxide concentrations or ocean acidification. Intensive research is needed to evaluate the efficiency, risks, and consequences of these interventions and to assess their viability to mitigate impacts of climate change without creating new undesirable environmental consequences.

7. BIO-PHYSICAL IMPACTS OF CLIMATE CHANGE. The impacts of, for example, sea level rise, increase in wave heights, coastal erosion, storms and seasonal weather influences, density changes due to ocean-ice interaction in the high latitudes, and nonlinear changes in ocean circulation have been explored throughout the past several decades, but further research is needed to fully understand them. In addition, biological effects of climate change, such as changes in the distribution of species, migration patterns, and habitat location of fish stocks, need permanent efforts to monitor and validate model predictions and scenarios for sustainable management of living resources.

BOX 2. EXAMPLES OF RESEARCH TOPICS ON **ECOSYSTEM FUNCTIONING** THAT NEED IMMEDIATE ATTENTION FROM MARINE SCIENTISTS

1. ECOSYSTEM RESILIENCE. One key research question is to evaluate the role conservation of biodiversity has on the resilience of ecosystems in the face of adverse natural and anthropogenic impacts like climate change and fisheries. This assessment will also help explain the role of some species, including top predators, in the sustainability and balance of marine ecosystems. Recent efforts to develop ecosystem-based approaches for the management of coastal areas and coastal biodiversity are also connected to the sustainability of the use of ocean living resources.

2. BIODIVERSITY AND ECOSYSTEM FUNCTIONING. The wide-ranging decline in marine biodiversity is probably a consequence of habitat modifications and destruction, of increased rates of invasion by deliberately or accidentally introduced non-native species, and of the overexploitation of living resources, as well as other human-caused impacts. Species can vary dramatically in their contributions to ecosystem functioning. In fact, the loss of certain keystone organisms, which have high ecosystem value, can trigger a disproportionate impact on the community when compared to the loss of other species.

3. DISCOVERING MICROBIAL DIVERSITY AND FUNCTIONALITY. Microorganisms are primary drivers of global element cycles and are essential for the functioning of all ecosystems. They contribute substantially to the productivity of oceanic and continental ecosystems. However, the interconnection between microbial diversity and distribution and the metabolism, productivity, and functionality of ecosystems remains largely unknown. Since microbial organisms may make up > 90% of the ocean's biomass, and comprise a yet unknown diversity of genetic information and metabolic capacity that substantially exceeds that of animals and plants, discovering the diversity of marine microbes is the first step toward a better understanding of ocean life and is a high-priority task.

4. ECOLOGICAL CONSEQUENCES OF INVASIVE SPECIES. Lionfish, ctenophores, and crabs, among other dozens of invasive species, could be cited as examples of major ecological problems that need more attention (UNESCO, 2002; Sutherland et al., 2009). Until now, we have recorded many severe episodes of this serious ecological problem, but only a few have been properly monitored. We still need to evaluate the processes though which invasive species alter, stress, and reduce the resilience of marine ecosystems. Controlling measures to limit the transference of species are not fully implemented or respected at the moment. Monitoring programs should incorporate control of ballast water and other vectors for transferring species, as recommended by the Ballast Water Convention and subsequent publications (e.g., Tamelander et al., 2010).

5. DEOXYGENATION OF THE OCEAN. The intermediate-depth, low-oxygen layers of 300–700 m (oxygen minimum zone) in the central and eastern tropical Atlantic and equatorial Pacific oceans have expanded and become more anoxic since 1960. These zones have expanded and contracted in the past, with some periods exhibiting extensive areas of hypoxic conditions characterized by low levels of biodiversity. Models predict a further decline in the concentration of dissolved oxygen in the ocean as the climate continues to warm. Deoxygenation of the ocean is likely to have substantial effects on ocean ecosystem structure and productivity, making it essential to investigate the causes and consequences of this phenomenon.

6. SCALES OF ECOSYSTEM VARIABILITY. The structure and functioning of marine ecosystems result from the tight interaction between their different physical, chemical, and biological components, driven by fluid dynamic processes over a wide range of spatial and temporal scales. A considerable part of this variability may be correlated with physical forcing. For example, on small scales, water turbulence and viscosity may directly and indirectly affect the physiology of small marine organisms. At the scale of a few to tens of meters, advective and turbulent flows transport planktonic organisms and nutrients around the water column. Mesoscale structures such as eddies and fronts affect the dynamics of the ecosystem from low (primary producers) to high (fish) trophic levels. We need to identify and understand key processes across different scales of variability in order to accurately model and predict ecosystem dynamics (Valdés et al., 2007).

7. UNDERSTANDING THE DEEP OCEAN. The open ocean and deep sea beyond national jurisdiction of coastal nations covers almost half of Earth's surface and gives refuge to unique and varied biodiversity. Additionally, options for mitigating the impacts of climate change will certainly involve the use of the high seas and deep seafloor for carbon sequestration, sinks, and storage. These issues require international interdisciplinary discussion. Also related to these issues are the establishment of global regulation and governance of transboundary and high-seas marine protected areas and the consequent protection of biodiversity, connections to straddling fish stocks, and regulation of high-seas biodiversity (IDDRI, 2009).

8. IMPACTS OF NEW POLLUTANTS ON ECOSYSTEMS. Special attention should be given to marine pollution and impacts on habitats and ecosystems. For instance, during the past 40 years, world production of plastic resins has increased some twenty-five-fold, while the proportion of material recovered (5%) has remained constant, so that plastics account for a growing segment of urban waste. Once discarded, plastics are weathered and eroded into very small fragments known as microplastics. These particles, together with plastic pellets, are already found on most beaches around the world (Ogata et al., 2009), and we still do not know the impacts they will have on the marine environment and on the marine food web (Sutherland et al., 2009). The rapid identification of new pollutants and mechanisms to address them in an adequate time frame is another concern (e.g., the use of fire retardants in clothing and their subsequent reappearance in the Arctic marine environment, and antibiotics' role in generating antibiotic-resistant microbial strains, which is largely unknown).

the maintenance of ecosystem functioning should be included as an integral part of national and international policies designed to safeguard the health of ocean ecosystems. Box 2 summarizes some examples of research topics on ecosystem functioning.

Ocean Instrumentation and Technological Developments

We are currently benefiting from the expansion of the technological revolution that started in the 1960s. Since then, three phases of technological innovation have been incorporated into oceanographic applications, two of them related to ocean observations and the other to the use of information and analysis. First, there were developments in electromagnetic remote sensing (satellite era) and underwater acoustics. Then, new technologies for the analysis and dissemination of information and communication were made available for marine research. Finally, the revolutionary development of probes and in situ chemical and biological sensors that record a variety of information, including data on sentinel organisms and habitats collected from moored instruments and drifting buoys. These fundamental changes (or evolutions) provide an astonishing amount of data in near-real time to the oceanographic community.

More frequent and spatially dense observations are needed to determine how changes in climate and in ecosystem functioning will affect different levels of biological organization. With these, we should continue to see great advances in the development of arrays of oceanographic instruments; in situ and remotely sensed data acquisition, integration, and interpretation; information management; and computer simulation and visualization. Sustained missions and improved satellites with new sensor capabilities are necessary to realize the full potential of satellite-based observations. In situ sensors deployed on moorings and drifting buoys are necessary to complete the range of processes and depths. Both satellites and in situ sensors are needed to collect information for a sufficient time period to allow detection of subtle, background climate trends with three-dimensional resolution and to resolve parameters such as currents and sea-ice thickness, in order to draw a more complete picture of fundamental climate processes (Kroger et al., 2009). These new technologies are expected to provide observations with improved accuracy and range of measurements as well as better spectral and spatial resolutions (Gunn, 2009; Figure 2).

Bio-tagging is a promising approach that can be expanded to include advanced acoustics and mapping capabilities and other sensors, thus providing more accurate information on the ocean environment toward understanding processes that influence ecosystem productivity and better defining management options that respect the use of space by these species (Gunn, 2009; Costa et al., 2009; Kroger et al., 2009). Biotechnology applied to taxonomy and biochemical analysis (genomics) has improved in recent years, but we still need to demonstrate that these tools can be applied to resolve key questions and that they can be inexpensive and easy to use (Zehr et al., 2008; Scholin, 2009). Nanotechnology will be incorporated, sooner or later, into ocean observation instruments, but this new phase in technological development needs to mature before it can be fully implemented in the ocean sciences.

Better observations will also provide the necessary inputs and boundary conditions for the development of more accurate predictive models for climate and Earth system behavior. Those models are continuously increasing

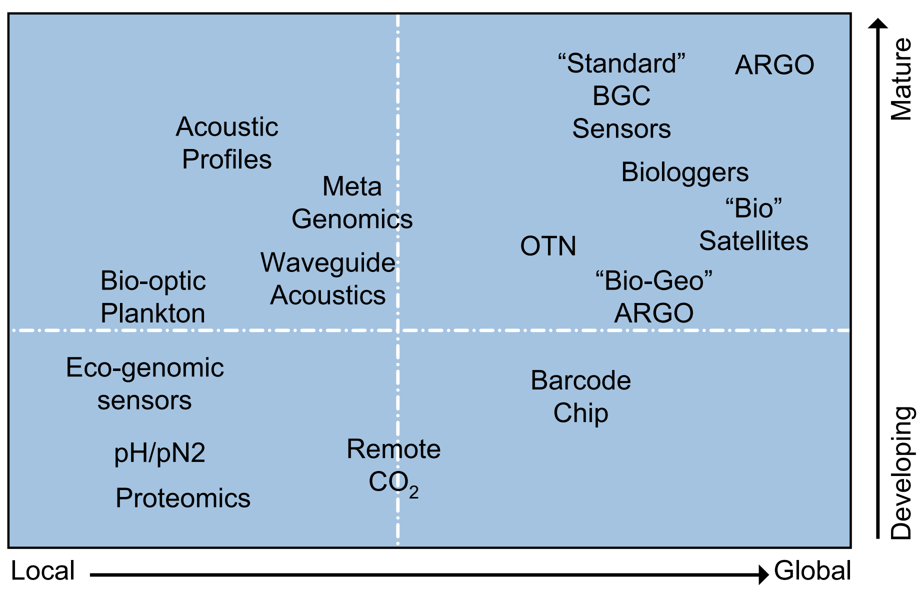

Figure 2. New technologies for observing global ocean biology. *Adapted from Gunn (2009)*

in complexity and sophistication and are necessary to complement observations and experiments. They are now incorporating more realistic scenarios that take into account a full range of anthropogenic impacts on the global environment.

In summary, fostering scientific and technological innovation will enable breakthroughs in our basic understanding of ocean biology, chemistry, geology, and physics as well as the interconnections among these disciplines. Advances in sensor capabilities, including nanotechnology, genomics, and robotics, are providing unprecedented access to and perspectives on the ocean environment. These new observations, made at improved temporal and spatial scales, may revolutionize our understanding of the ocean environment. Continuous access to the open ocean, coastal zones, and watersheds depends on novel infrastructure and technology, from sensors to satellites to unmanned vehicles. The development of innovative tools such as remotely operated and autonomous vehicles; molecular techniques and genetic sequencing; and physical, chemical, and biological sensors will facilitate new experiments and permit the study of processes ranging from isolated episodes to global cycles. Improving existing in situ sensors and developing new biochemical sensors requires the participation of the engineering and research communities. Additionally, research communities and resource managers will need to coordinate efforts to validate and find new applications for these improved measurements. However, bridging the gap between what is theoretically desirable and possible to what is feasible and practical is often the most difficult challenge in the design of monitoring tools (Kroger et al., 2009).

Strategic Frameworks for Cooperation: "One Planet, One Ocean"

Research at unprecedented geographic scales will be required to improve our understanding of climate change and ecosystem functioning, including biodiversity conservation and management options. During the OceanObs`09 meeting, there was a general call for the creation of a new framework of sustained ocean observations to be available in the next decades (see OceanObs`09 white papers at http://www.oceanobs09.net/cwp). This framework will integrate new biogeochemical and physical measurements with ecosystem observations, while preserving and supporting existing structures. A similar call was made in the UNESCO document *One Planet, One Ocean* (UNESCO, 2002)

Recently, attention has been shifting increasingly toward multidisciplinary "observatories," a clear advance from the traditional physical and atmospheric measurements collected largely by moorings and other in situ platforms. Both technological advances and the recognition that human activities are inducing major changes to Earth's climate system and ecosystems drove this shift. The new challenge—to understand the influence of climate on ecosystem functioning and biogeochemistry—will require an interdisciplinary approach that simultaneously captures all aspects of physical, biological, and chemical forcing mechanisms.

A number of regional and international cooperative networks for the study of targeted ecosystems have been established and have progressed considerably; these include the International network of Coral Reef Ecosystem Observing Systems (I-CREOS), the Ocean Sustained Interdisciplinary Timeseries Environment observation System (OceanSITES) for deep-ocean investigations, the European Network of Marine Research Institutes and Stations (MARS) focusing on regional marine biodiversity, and others listed in Box 3. However, essential research priorities like climate change and ecosystem functioning depend on the development and implementation of global networks of multidisciplinary capabilities. These networks should be able to address the physical, chemical, and biological properties of coastal ecosystems as well as marine ecosystems at appropriate temporal and spatial scales under multiple climatic regions. Deployment of a robust and global ecological observing system that could describe the actual state of the marine ecosystem and key processes will fundamentally change society's view of the ocean environment.

This ideal observing network will require extensive infrastructure, including: (1) in situ observatories in the ocean, on the seafloor, and across the land-water interface; (2) shore-based laboratory facilities for sample analysis and experimental manipulation; and (3) a wide range of survey capabilities together with observing-system maintenance procedures. In that context, marine laboratories around the world have great potential as infrastructures dedicated to the development of research, training, and education, as well as conservation of marine biodiversity. Marine laboratories are found

BOX 3. EXISTING NETWORKS OF OBSERVING FACILITIES, PROTECTED AREAS, RESERVES, MARINE LABORATORIES, AND OTHER ASSOCIATIONS

1. The **Association of Marine Laboratories of the Caribbean** (AMLC) was founded in 1957. An alliance of 36 marine laboratories with 300 individual members, it is an example of a regional network of marine laboratories formed to investigate marine biodiversity. AMLC is a governed by an Executive Board consisting of one representative from each institutional member plus a group of officers elected by the Executive Board. Scientific meetings are held every other year.

2. The **US National Association of Marine Laboratories** (NAML), organized in the late 1980s, is a nonprofit organization of over 120 members employing more than 10,000 scientists, engineers, and professionals and representing marine and Great Lakes laboratories that stretch from Guam to Bermuda, and from Alaska to Puerto Rico.

3. The **European Network of Marine Research Institutes and Stations** (MARS) was established in the early 1990s to unite marine institutes and stations, particularly (but not exclusively) those with coastal laboratories immediately adjacent to the sea. By representing marine institutes and stations and the scientists working at these sites, MARS welcomes all types of expertise and interests, including chemists, physicists, oceanographers, biologists, ecologists, geneticists, and scientists from other disciplines. Today, MARS is composed of 65 institutions located in 22 European countries.

4. The **Partnership for Observation of the Global Oceans** (POGO) is a forum created in 1999 by directors of the major oceanographic institutions to promote global oceanography, particularly the implementation of international and integrated global ocean observing systems. POGO is made up of 35 marine institutions distributed in 18 countries. The vision is to foster partnerships that advance efficiency and effectiveness in studying and monitoring the world ocean on a global scale.

5. Since 1999, the **OceanSITES** (Ocean Sustained Interdisciplinary Timeseries Environment observation System) project has been coordinating and facilitating the implementation of a global open-ocean network of sustained time-series sites. More than 60 institutions representing 22 countries operate about 60 long-term stations (30 surface and 30 subsurface) that monitor the full depth of the ocean, from air-sea interactions down to 5,000-m depth. OceanSITES is now an official component of the Global Ocean Observing System (GOOS) and is recognized and supported by CLIVAR (Climate Variability and Predictability program) and POGO. OceanSITES is positioned to become the global sustained time-series reference network for studying high-sea ecosystems at representative or critical sites in the climate and Earth system.

6. The **UNESCO Man and the Biosphere Programme** (UNESCO-MAB), World Network of Biosphere Reserves (WNBR) provides the scientific community with a network of well-preserved areas where anthropogenic impacts are minimized, and it contributes to the pursuit of the Millennium Development Goals, in particular those on environmental sustainability. The biosphere reserve concept, developed initially in 1974, was substantially revised in 1995. Today, the network comprises more than 90 marine reserves in 40 countries (Salvatore Arico, UNESCO, *pers. comm.*, 2010).

7. The **Marine Protected Areas** (MPA) concept has evolved from isolated, coastal, small-sized MPAs (mostly linked to small islands) to a more complex ecological and conceptual meaning. Now MPAs are integrated in networks, and are planned in open oceanic waters and/or the deep sea, extending protection to large areas beyond national jurisdiction. Currently, the available database of protected sites stores information on over 6000 MPAs. The global distribution of MPAs is heavily biased toward continental coastlines, with a few (recent) exceptions, but all of them provide the scientific community with natural, well-preserved environments where anthropogenic impacts are minimal. Globally, MPAs have grown very rapidly since the 1970s, coincident with various international conventions, particularly the Ramsar Convention, the World Heritage Convention, and the UNESCO-MAB program. This rapid growth in MPAs indicates that these international conventions may have a very valuable role to play in facilitating the protected-area designation process at national and local levels.

in almost every coastal country, often in relatively undisturbed locations, with ready access to representative coastal habitats and ecosystems, and many are government supported (or government via universities) with strong mandates for resource management. These regional marine laboratories encompass a unique and much needed geographic scale of environmental and ecological gradients, and their regional data sets (often including an invaluable historic data time series that, in some cases, stretches back more than 100 years) are fundamental to enabling comparative studies on marine biological diversity and its relationship to ecosystem functioning.

Far-flung marine laboratories share a common scientific culture and common traditions that predispose them to cooperative programs and to networking. For example, the Association of Marine Laboratories of the Caribbean (AMLC) has held annual scientific meetings for almost 30 years. In the late 1980s, US marine laboratories formed the National Association of Marine Laboratories (NAML), as well as regional groups such as the 35-member Southern Association of Marine Laboratories (SAML). More recently, in 1990, 65 European marine laboratories joined together to form MARS (Box 3).

This network will also offer crucial support to global scientific programs such as IGBP and WCRP, in which ocean data and routine observations contribute to regular reports on the state of the marine environment as requested by the UN General Assembly. But probably the single most important aspect of the network is the development of the user community that is essential for assuring the long-term maintenance of the observations.

Recent findings reported by IPCC (2007) show that the climate system is moving toward a more unstable state, which could lead to abrupt increases in sea level and global temperature. Therefore, detecting climate variation should be regarded as the highest priority. The proposed network would provide the information necessary to improve our ability to predict and monitor these trends and variations in climate. Analysis of these observations will allow the development of more effective adaptation and mitigation strategies, which may help reduce the consequences of climate change. Climate change is a global threat that does not respect borders, political boundaries, oceans, continents, or north-south divisions. Therefore, scientific cooperation, capacity development, and transfer of technology between developed and developing countries and a more integrated science process, in a spirit of solidarity, could contribute substantially to these urgent needs.

"SCIENCE INITIATIVES AT IOC ARE PRIORITIZED TO FOSTER HIGH-LEVEL SCIENCE AND TO BUILD NETWORKS OF SCIENTIFIC FACILITIES AT THE GLOBAL SCALE."

At a global scale, facilitation of networking will require substantial future financial support over the long term. Networking is critical for encouraging developing countries to engage significant means to reinforce scientific cooperation and education programs that would benefit the whole global community of countries. Such a network of laboratories and stations is a realistic and an achievable objective if it is properly supported by international councils. A network of coastal-marine laboratories based on existing facilities, and incorporating other initiatives and networks, including marine protected areas (MPA) and OceanSITES, could provide the necessary resources for training, capacity building, and knowledge transfer in both coastal areas and oceanic regions. In this perspective, a world association of marine stations and institutes would give impetus to the examination of high-priority global problems, including biodiversity from genes to ecosystems, marine geochemistry, fisheries, ocean health, and impacts of climate change. Expert consultation among scientists and managers, policymakers, and funding bodies is necessary to explore ways and means of putting these ideas into practice, a role that UNESCO-IOC can play along with its other partners worldwide.

THE ROLE OF COMPREHENSIVE INTERNATIONAL CORE PROJECTS

Extensive national and international efforts and cooperation will be required to address the ocean research priorities discussed in the previous section. This cooperation should involve many sectors of the marine and ocean sciences community, from academic institutions to governmental and nongovernmental organizations. The active involvement of end users of scientific information, including resource managers, policymakers, and individual citizens, will enhance the impact and value of our research initiatives. Integrating research priorities, scientific communities, and stakeholders in common goals under an international program is always a challenge, but the effort very often results in worthwhile achievements.

During the last 25 years, there have been calls for comprehensive international core projects designed to answer some key oceanographic questions, often related to the understanding of crucial ocean processes, and to the sustainability and health of the ocean system. A good example of these initiatives is GLOBEC, the IGBP core project, initiated by SCOR and IOC in 1992, with the aim of advancing our understanding of how global change will affect the abundance, diversity, and productivity of marine populations and their ecosystems. GLOBEC has now ended, and we can affirm its success.

Such projects, among others, should be regarded as very successful initiatives, and it is important to say that this integrated approach to accomplish large-scale science is actually expanding our knowledge about the oceanic system. These large-scale international programs are often created under the stewardship of international organizations like IOC, which follow their achievements during the entire lifetimes of the projects. As a result, these international organizations are in a privileged position to help identify the interconnected factors contributing to the positive outcome of one program, and with that establish a systematic methodology to facilitate the establishment of new core projects and programs.

At the SCOR summit meeting in 2009, several international organizations initiated a discussion on the international framework and principles for developing new large-scale research projects in ocean sciences. There was general agreement on a set of principles that a project must satisfy in order to qualify for adoption as a large-scale international project. For example: (1) the project should be of scientific relevance for understanding the ecology of the planet and the future evolution of our oceans and climate, (2) its objectives and approaches should not already be addressed in a comprehensive way by any other international research program, (3) the project should be based on multidisciplinary research and should foster scientific cooperation and integration of funding agencies, (4) its governance and financial structure should be transparent, and (5) its objectives should be achievable in short-to-mid term (10–15 years) and the results should be properly communicated. In order to satisfy these principles, the projects must comply with requirements summarized in Box 4.

Many recent advances in ocean sciences are the results of large-scale, internationally coordinated research projects. This new trend of associative approaches has opened new opportunities for networking, distributed facilities, interdisciplinarity, transfer of knowledge and technologies, and, particularly, achieving successful results that are cooperative and collective. However, collaboration among oceanographers, and among marine and environmental scientists, is still to be fully developed. Much work remains to achieve a true interdisciplinary collaboration that regards the ocean as part of the whole Earth system. Hopefully, the new large projects and programs that will emerge in coming years will have a consistent bottom-up development approach, and will receive broad support from the community, following the legacy of other successful initiatives.

CONCLUSIONS

Although multinational cooperation has promoted ocean scientific research for the past 50 years, the ocean remains relatively unexplored. Put into a larger context, more than 1,500 people have climbed Mount Everest, more than 300 have journeyed into space, and 12 have walked on the moon, but only 5% of the ocean floor has been investigated and only two people have descended and returned in a single dive to the deepest part of the ocean. On the other hand, no part of the ocean remains unaffected by human activities, such as climate change, eutrophication, fishing, habitat destruction, hypoxia, pollution, and species introductions. Therefore, the scientific study of ocean should be an international priority.

Clearly, the drivers for ocean scientific research are connected to sustainable use of the ocean and to understanding, mitigation, and adaptation to climate change. In that sense, the main ocean-related scientific problems of our time are interdisciplinary and call for cooperation between different branches of science. These problems need to be addressed on a global scale through extensive international cooperation, which is clearly the case with climate change and ecosystem functioning. Additionally, there is an increasing call for more social engagement, with science responding more effectively to societal needs. Thus, international cooperation is the key to ensure cohesion in marine science and development. For that, IOC will continue to maintain and extend institutional relationships relevant to UN agencies, international councils, global programs, and nongovernmental organizations, and participate in alliances and international

BOX 4. GENERAL PRINCIPLES FOR DESIGNATION AS A LARGE-SCALE INTERNATIONAL PROJECT

GENERAL PRINCIPLE	REQUIREMENTS FOR THE PROPOSED RESEARCH IN ORDER TO COMPLY WITH THE PRINCIPLE
Scientific relevance for understanding the ecology of the planet and the future evolution of our ocean and climate	1. It should produce scientific results that are original and robust, and must be able to promote scientific excellence. 2. It should be transformational; for example, it should provide significant advances and benefits for science at an international scale, even with potential uncertainty regarding its success. 3. It should impact many societal theme areas. 4. It should contribute to a greater understanding of ocean issues at a global scale. 5. It should provide high-value understanding to the broader scientific community.
Objectives and approaches not well addressed at present by any other international research project/program	1. Relationships with past and existing projects should be well documented and made public. 2. Science must require a substantial international approach not available in other existing programs. 3. Demonstration that a large-scale project/program is the best approach.
Implementation requiring multidisciplinary research and fostering scientific cooperation and integration of funding agencies	1. It should address high-priority needs of resource managers. 2. It should address mandates of governing entities. 3. It should promote partnerships to expand the national capacities, for example, by involving partners outside of ocean science, or by expanding the human dimension of the program. 4. It should establish effective links with policymakers and other users.
Transparency in governance and in financial structure	1. It should bring together national representatives and organizations to share their interests in specific topics and identify needs and goals. 2. It should foster the involvement of representatives of developing countries. 3. The architecture behind the program should be carefully planned for agile development. 4. It should demonstrate the availability of funding for core project scientific steering committees (SSCs) and international project offices (IPOs). 5. It should have transparent criteria of co-sponsorships.
Objectives achievable in short-to-mid term (10–15 years) and results properly communicated	1. It should have a well-defined lifetime scale with clear beginning and sunset for the project. 2. It should have clearly defined goals, milestones, and products. 3. It should be submitted to regular analysis to ensure that emerging issues, significant changes, and gaps in knowledge are detected at an early stage and corrected. 4. It should have a transparent and credible policy on communication and outreach.

agreements related to, for instance, ocean governance.

Science initiatives at IOC are prioritized to foster high-level science and to build networks of scientific facilities at the global scale. The drivers and priorities for the next 15 years identified in this paper are clearly stated in IOC's high-level objectives for science, which include climate change, ocean health, coastal research, and assessment and management of marine ecosystems.

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