3.6 OCEANOGRAPHY

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Contents

Glossary

Accretion: An increase in the mass of a body by accumulation or clumping of smaller particles.

Atoll: Ring-shaped coral island nearly or completely surrounding a lagoon.

Autotrophs: Organisms able to fix carbon from inorganic to organic form using light or chemical energy.

Bathymetry: Topographic maps of the seafloor including depth.

Biota: Plant and animal life of a region.

Chemosynthesis: The synthesis of organic compounds from inorganic compounds using energy stored in inorganic substances such as sulfur, ammonia, and hydrogen. Energy is released when these substances are oxidized by certain organisms.

Continental shelf: Gradually sloping submerged extension of a continent, composed of granitic rock overlain by sediments. Has features similar to the edge of the nearby continent.

Continental slope: The sloping transition between the granitic of the continent and the basalt of the seabed. The true edge of a continent.

Coriolis force: In a frame of reference moving with the Earth, the basic law of Mechanics has a form which slightly differs from the simple expression valid in fixed axes of reference. The main correction, due to the rotation of the Earth around its axis, may be expressed as the action of an additional force, the "Coriolis force," which tends to deflect any projectile or ocean current perpendicularly to its velocity.

Eddies: Patches of turbulent flow.

Eigenfrequency, Eigenmode: The eigenfrequency of a linear oscillator is the natural frequency at which it will oscillate following an initial perturbation. An oscillator may have several eigenfrequencies and each corresponding oscillation is called an eigenmode. Under the action of a periodic force which has the same frequency as one of the natural frequencies of the oscillator, the latter will undergo amplified oscillations. This is called a **resonance**. In a complex three-dimensional non-linear system like the ocean, the terms "eigenmode" and "resonance" are used in a more figurative way to denote respectively the wave motions that the ocean can propagate and the interactions between processes of similar time and length scales.

Energy spectrum: Borrowed from Fourier Analysis theory, energy spectrum is used figuratively to denote the distribution of energy over different time scales (inversely, frequencies) or length scales (inversely, wave numbers).

Fringing reef: A reef attached to the shore of a continent or island.

Habitat: The normal abode or locality of an animal or plant.

Heterotrophs: Organisms unable to fix carbon from inorganic to organic form and depending on existing biomass to develop.

Hierarchy: A classification in graded subdivisions.

Hydrothermal vents: Spring of hot, mineral, and gas-rich seawater found on some oceanic ridges in zones of active seafloor spreading.

Marginal seas: Seas at the ocean's margins

Nitrogen fixation: Supplying the needs of nitrogen by fixing nitrogen gas

Nutrient: Any nourishing substance.

Particulates: Solid particles partly carried along by the sea.

Photosynthesis: The process by which autotrophs bind light energy into the chemical bonds of food with the aid of chlorophyll and other substances. The process uses carbon dioxide and water as raw materials and yields glucose and oxygen.

Physiological and behavioral performances of living species refer to a combination of biochemical and mechanical functions, modes of action and responses to stimuli of organisms, which may be strongly affected by environmental constraints.

Plate tectonics: The theory that the Earth's lithosphere is fractured into plates, which move

Our Fragile World: Challenges and Opportunities for Sustainable Development. pp. 1145–1163. © 2001 EOLSS Publishers Co. Ltd.

relative to each other and are driven by convection currents in the mantle. Most volcanic and seismic activity occurs at plate margins.

Population: A group of living organisms all of one species and separated by some natural process or barrier from other such groups in time and space.

Primary production: Fixation of carbon from inorganic to organic form, whether by photo- or chemoautotrophy.

Production by a population is its total elaboration of new flesh (or plant material) irrespective of whether the individuals containing that production survive to the end of the time interval over which production is calculated.

Radionuclides: Radioactive nuclides.

Redfield ratios: The essential nutrients and carbon dioxide are taken up (and released, when living matter is metabolized) in approximately constant ratios to each other and the oxygen produced (or consumed). The ratios calculated by Redfield are 1P: 16N: 106C: 138O_2, where P, N, C, and O_2 stand for phosphorus, nitrogen, carbon, and oxygen concentrations.

Scale: The time (length) scale of a phenomenon is the typical time interval (distance) over which it varies significantly. If one considers a variable y of time (space) and a typical value of it, y_c say, one can define the time (length) scale of y as y_c divided by a typical value of its time (space) derivative. The time (length) scale of a periodic phenomenon is its period (wave length) divided by 2π, i.e. the inverse of its frequency (wave number).

Spectral window: A band of time scales and length scales of the processes and interactions on which a particular study is focused.

Thermohaline: Related to the temperature and salinity distributions.

Variables, parameters: A variable is, in mathematical terms, a characteristic of the system described and predicted by the mathematical equations constituting the model. These equations may be *differential equations* describing the time evolution of the variables suitably averaged over some region of space or *partial differential equations* describing the time and space evolutions of the variables. These equations must be complemented by *initial conditions* (i.e. the values of the variables at some initial time of computation) and *boundary conditions* (i.e. the values of the variables at all time along the boundaries of the space domain under study). When the equations are reduced to differential equations by averaging over space, only initial conditions must be specified, boundary conditions being incorporated as additional forces in the differential equations by the preliminary space averaging. A *parameter* is a characteristic of the system which is not described and predicted by a specific equation of the model, but which is inferred from observations or sideways models and appears in the parameterization of the model's equations as an empirical (constant or variable) coefficient.

Summary

The geographical and geodynamical importance of the ocean, in a global perspective of sustainable development, is emphasized. Historical, recent, and ongoing progresses of ocean sciences are stressed and the essential processes which dominate the physics, chemistry, biology, and geology of the marine environment are briefly described, underlining the importance of interactions between these traditional disciplines and the need to take into account the multiplicity of time scales, length scales, and levels of hierarchical organization of the ocean system in all observational and modeling studies.

1. Introduction

Photographs of the Earth taken from space show a beautiful planet of blue and white colors. The ocean gives the blue color and the clouds the white one. The dominant color of the Earth is blue because the ocean covers about 71 percent of the planet's surface. With a mean depth of some 4 km, the ocean is a vast, fascinating reservoir of water, food, minerals, and energy.

Ocean science is relatively young. In his caustic analysis of "The Age of Physical Oceanography," Rui Xin Huang writes:

> Most branches of sciences go through a "life" cycle similar to the human life cycle, which includes the stages of infancy, childhood, adolescence, adult and old age, eventually, death.
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> *High-energy physics (almost perished)* was one of the hottest sciences in this century and thus it attracted many gifted scientists. If judged simply by the number of Nobel Prize winners, it was on the top of the science landscape. However, it is now, for the most part, history. The fast decline of high-energy physics is not due to the fact that it is no longer challenging, but rather it is too expensive and has very little direct impact on society.
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> *Aerodynamics (old age)* started around 1930 and reached its peak in the 1960s. Now computer simulations are as good as wind tunnel results. Although many unsolved problems remain, aerodynamics is no longer a young science. After the Apollo landing on the moon, aerodynamics reached maturity. Government funding declined quickly. As a result, many scientists left aerodynamics and entered other new research fronts, such as geoscience and life science.
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> *Meteorology (adult)* started around the beginning of this century. It developed very quickly due to the strong demand for weather forecasting and the collection of a large database. Now weather forecasting on the synoptic scale has become a routine engineering problem. There remain many questions related to smaller scales or very strong nonlinear processes associated with severe weather forecasting. The most challenging problems are associated with understanding and forecasting climate changes, which are intimately related to the dynamics of ocean circulation.
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> *Physical oceanography (adolescent)* was started a long time ago with tidal observations and theory, but is moving much more slowly than meteorology. We have just barely completed the first picture of the world ocean. Meteorology, which is generally considered our

> twin, has a much shorter history and within the past 50 years has developed much faster. There are two main factors that have contributed to the different fates for these two disciplines of science. First, there is strong demand for weather forecasting, which is the primary driving force for the atmospheric science. Second, data collection in meteorology is conducted more conveniently. Since there will be a stronger demand for climate forecasting and for an understanding of the global environment, physical oceanography will enjoy its golden period in the next ten or twenty years. Physical oceanography is still young, and there is a bright future in front of us. This is good news for all oceanographers.
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> *Environmental science (child)* is one of the youngest sciences. As the impact of human activity on Nature becomes more noticeable, understanding these effects and preserving our environment become more and more pressing issues. It is expected that environmental science will be one of the most important branches of science in the next century.

The author is here mainly concerned with *physical oceanography* and its possible effects on climate. However, the ocean system is a whole, with physical, biogeochemical, ecological, and socioeconomic processes interfering, competing, and comforting each other. Similarly, we should remember that ocean science grew out of the perpetual confrontation between marine physics, chemistry, and biology, generating interdisciplinary overviews, novel equipments and techniques of observational surveys, and world-wide cooperation.

In addition, human activities are fundamentally *affecting marine* ecosystems at global scale via fisheries, aquaculture, introduction of non-native species, modification or destruction of critical habitats, and through the addition of nutrients and pollutants, with a particular severe stress on coastal zones where 50% of the world population may dispose of less than 10% of the ocean surface. The ocean also plays an essential role in the regulation of major biogeochemical cycles and their climatic impacts and is a reserve of essential living and non-living resources and the serious-minded exploitation of these resources is a cogent part of environmental management in a global perspective of sustainable development. *Interdisciplinary ocean science*, in this respect, belongs to the environmental sciences regarded by Huang as the youngest of all.

The ocean as one of the media of sustainable development must be considered in its natural complexity, made of intricated interactions of processes belonging to different disciplines—physics, biogeochemistry, ecology, economics, sociology—with different levels of hierarchical organization and different (time and length) scales.

Perhaps the notion of *time scale* is the most common and easiest to grasp. Everyone knows the difference between a bus leaving every five minutes and a coach with one departure a day; children have learned that, on the beaches of the North Sea, they will not see any significant change in tidal levels in a few minutes. On the other hand, they will be completely misled by tidal mechanisms if they reappear to observe it, at random, after several days or weeks. They instinctively associate the tidal process with a time scale of a few hours. This gives them a sound feeling of how to intelligently sample variations in tidal elevations, and how to correlate them with a great variety of other processes from the uncovering of beaches and reefs to variations in coastal ecosystems and the distribution of debris along the shore.

Looking further, it is not difficult to see that the geochemical and ecological processes have dominant time scales associated with global biogeochemical hierarchical organizations resulting from different rates of chemical reactions and physiological, behavioral, and ecological functions, confronted to the multi-scale physical environment which one instinctively perceives. Socio-economic anthropogenic interferences have also their own operating patterns and routines and, extrapolating to variations in space, one can easily have a vision of the natural interdisciplinary complexity of the ocean. At the same time, one can easily imagine, with the same intuitive wisdom as the child observing the tidal excursions on the beach, that processes of similar time- and length-scale are likely to have a more "privileged," efficient, direct (i.e. "*resonant*") interaction than processes of very different scales.

A picture thus emerges of a *structuration* of the ocean's diversity, where multidisciplinary processes and interdisciplinary interactions can be ordered, sampled, analyzed, and modeled according to their typical scales of variations in time and space, allowing for a better understanding of all the physical, biological, socioeconomic, and other interplaying mechanisms which may enforce or jeopardize sustainable development.

The simplest way to understand the predominance of processes of well-identified (time and length) scales, within the expanse of the geophysical variability of the marine system, is to remember the motion of a spring. A spring has a natural frequency of oscillation (the so-called "eigenfrequency" which is a function of its mass and elasticity). The inverse of this frequency defines a time scale at which the spring can most effectively convert energy (from potential to kinetic form, for instance) and generate large amplitude motions from external solicitations, however small. In addition, the application of an external force can produce forced oscillations of the spring at the frequency of the force.

Marine geophysical processes of different time scales can be, similarly, associated with specific external force mechanisms or internal *eigenmodes* of behavior of the system.

For instance, solar radiations are an essential source of energy. Light from the sun is indispensable for photosynthesis and primary production, a constitutive element of the marine food chain. It is thus not surprising to find strong diurnal and seasonal signals in the Ecohydrodynamics of the upper layer of the sea. Similarly, lunar and solar tidal forces have well-defined frequencies and generate wave motions in a band of time scales corresponding to their frequencies and those of their principal harmonics. The wind acting on the sea surface and, in general, all air-sea interactions, affect the marine system in well-defined ranges of time scales related to the typical times of change of the weather patterns.

On the other hand, seawater is naturally stratified because water density is affected by temperature (solar heat coming from above, for instance) and salinity (the concentrations of dissolved substances). The stratification in the sea is, in most cases, *stable*, i.e. heavy water lies underneath lighter water. This creates a *restoring force*: if one parcel of water is displaced up or down, it will experience a gravity force tending to return it to its equilibrium level. Possible overshooting will generate waves. These waves are called "*interval waves*" to stress the fact that they propagate in the stratified interior of the ocean and not in well-mixed boundary layers. Their frequency is the Brunt-Väisälä frequency, proportional to the square root of the vertical gradient of density. Typical values of the Brunt-Väisälä frequency in regions of significant internal wave propagation are in the range 10^{-4}, 10^{-2} s^{-1}. One may thus associate with the vertical stable stratification an *eigenmode* of the marine system with time scales of the order of minutes to hours.

The geofluids are naturally studied in axes of reference fixed with the rotating Earth. In such a system of reference, the main correction for the motion of the reference frame is the existence of the "fictive" *Coriolis force* that tends to deflect any projectile or ocean current perpendicularly to its velocity. Students who have tried to throw a ball on a rotating table in the physics laboratory know very well that it does not travel in a straight line, but actually turns and comes back after describing a circular trajectory. This effect may be seen as the action of a restoring force and, in the ocean, it is indeed the source of so-called "*inertial*" oscillations and waves. The inertial eigenmode will have time scales, set by the vertical component of the Earth's rotation vector, of the order of a few hours in mid-latitudes, comparable with the scales of the dominant tides and many wind-force events. There is also, in most cases, a significant overlap between the inertial and internal scale bands of the eigenmodes.

In addition, the Earth is (globally) spherical. Although this may be difficult to visualize, the sphericity is responsible for some forms of restoring mechanisms (reminiscent of certain effects of bottom topography) that may give rise to the generation of waves and wave packets. The main parameter in determining the time scales associated with these so-called "Rossby" eigenmodes is the latitudinal gradient of the vertical component of the Earth's rotation vector ($\beta \sim 10^{-11}$ m^{-1} s^{-1}). Hence, for waves or wave packets affecting the whole water column, with a horizontal size of the order of a hundred kilometers ($L \sim 10^5$ m), one finds time scales of the order of $(L\beta)^{-1}$, i.e. a month or so.

Internal waves, inertial oscillations, and Rossby waves, associated respectively with the stratification of the ocean waters, the Earth's rotation, and the Earth's curvature, may, as much as the familiar surface waves at the air-sea interface, give a vision of an ocean controlled by well-defined *restoring forces* acting as ordering agents of the ocean system. External forces may seem to have similar functions, imposing the time scales of energy transfers from astronomical and atmospheric sources to the ocean (what better example of this hypothesis than the M_2 lunar tide?). However, one must remember that the ocean is a *non-linear* system and that processes excited by external forces, channeled or amplified by the activation of eigenmodes, interact between themselves and generate an ever-spreading manifold of phenomena of different (time and length) scales. The ocean, in this perspective, appears more or less as a battle-field: on the one hand, there are well-organized forces (even if they are not devoid of some variability) which may come from astronomical and atmospheric forces or be associated with eigenmodes of vibrations of a stratified rotating ocean on a spherical earth; on the other hand, omnipresent non-linear interactions tend to spread the energy and the information over a wide range of scales and, one way or the other, drive the energy towards the smallest scales where it is ultimately dissipated into heat. It is therefore not difficult to visualize the energy spectrum of the ocean as a succession of peaks (where the energy is poured from outside or channeled by eigenmodes), separated by valleys alimented by energy transfers fostered by non-linear interactions.

The study of ocean hydrodynamics cannot therefore be done without some form of (observational or theoretical) alternative focusing on one or the other main events. This requires means of (i) separating a targeted set of processes belonging to a well-defined range of (time and length) scales, i.e. a "*spectral window*"; (ii) appraising the long-term, long-range trend laid upon these processes by larger scale phenomena; and (iii) assessing the role of smaller scale fluctuations in smoothing out transitory and ephemeral variegations which can only blur the vision through the spectral window.

Biogeochemical and ecological processes are also characterized by typical reaction rates, which may depend on various factors—concentrations, biomasses, light intensity, temperature, etc.—but can be easily quantified, and these in turn bring out specific ranges of time scales where, in terms of biogeochemical and ecological processes, "things are bound to happen." Similarly, socioeconomic anthropogenic interferences with the natural system, following the planning of management policies, can be associated with characteristic times of interventions. On the peaks and valleys postcard of physical processes, one must superimpose the same spectral distribution of biogeochemical, ecological, and socioeconomic processes.

The non-linear interactions that one has identified between physical processes happen, in exactly the same way, between physical processes and biogeochemical/ecological/socioeconomic processes and between the latter. Any inert or living particle in the sea is transported by currents of all time scales and variability which may produce organized water mass transports or small scale mixing which may, differently but equally efficiently, deeply affect biogeochemical and ecological systems from the displacement or diffusion of essential chemicals or contaminants, to physiological and behavioral performances of living species, population dynamics and marine productivity. Biogeochemistry, ecology and socioeconomic management of the marine system rely on the conveyor and assembly line of physical processes to execute optimally the functions of finding appropriate nutrients and energy, feeding and reproduction, escaping predators, locating prey or mates, securing habitats and population diversity, harvesting at all levels of the food chain up to the final exploitation of the ocean's (living and nonliving) resources by man.

It is easy to understand that, even more than for the study of physical processes, the study of the multidisciplinary ocean system will not be possible in a multidimensional space of non-linear interactions if one cannot frame a limited number of spectral windows (i.e. bands of length and time scales). Here, one can observe an overall resonance between energy and information being forced into the system and eigenmechanisms taking over (directly or through instabilities of primary spin-ups) to distribute these, as well as biogeochemical/ecological/socioeconomic processes tuned to the same scales of global forces. The identification of these Spectral Windows (note the use of capitals to emphasize that one is no longer simply probing the hydrodynamical variability but the whole interdisciplinary manifold of marine processes) is prerequisite to the understanding, ordering, and modeling of the marine system in an ultimate global perspective of sustainable development.

2. The Oceans

The most unique feature of planet Earth is its great expanse of oceans. Among other things, the oceans are the origin of life, and are responsible for its sustainability. The word "ocean" originates from classical Greek, *Okeanos*, meaning the outer sea. In contrast to the Mediterranean, an ocean was originally thought to be a great river flowing around the earth. Today, the term is used in reference to any of its four principal geographical divisions: the Atlantic, Pacific, Indian, or Arctic. As great bodies of salt water, the oceans cover 71 percent of the earth, and so quite naturally they have a lot to tell us.

People who study the oceans are called oceanographers, and oceanography (or marine science as some would prefer to call it) is an interdisciplinary science studying the environment of the oceans including the waters, currents, depths, sediments, plants, and animals. It embraces a range of scientific disciplines including physical, chemical, biological, and geological phenomena and processes in the world's oceans; in solving a particular problem, it is frequently necessary to invoke the assistance of several disciplines.

There are four major oceans. The Pacific, the largest, extends from Antarctica northward to the Bering Strait, which separates the Pacific from the Arctic Ocean. The boundary between the Pacific and the second largest ocean, the Atlantic, is the line forming the shortest distance from Cape Horn of South America (70°W) to South Shetland Island. The boundary between the Atlantic and the third largest ocean, the Indian, is placed at the meridian of the Cape of Good Hope (20°E). The boundary between the Pacific and the Indian Ocean follows the line between the Malay Peninsula through Sumatra, Java, Timor, Australia (cape Londonderry), and Tasmania, and follows the meridian of 147°E to Antarctica. Definition of the fourth ocean is somewhat blurred, some defining the Southern Ocean as the waters surrounding Antarctica and extending northward about as far as the southern tips of the continents; others define the waters surrounded by Eurasia and North America as the Arctic Ocean, which connects to the Atlantic through the Norwegian and Greenland Sea.

The ocean floor can be divided into physiographic provinces using criteria such as depth, relief, gradient, and composition. Two groups of provinces are generally recognized: continental margins and open oceans. The deepest point on our unsmooth globe, the Challenger Deep in the Mindanao Trench in the west Pacific, east of the Philippines, plunges 11 524 m beneath the surface of the sea. It is easily deep enough to engulf the tallest mountain, Mt. Everest at a mere 8 848 m. Although the temperatures there are continually near-freezing, forms of life are still found. Further, the oceans are so vast, at 361 million km^2, and so deep, averaging 3 729 m, they occupy a volume of 1 348 million km^3. With a volume of 293 million km^3, even the second smallest of the four major oceans, the Indian Ocean, is large enough to contain more than double all the land on Earth (125 million km^3), with room to spare.

Between the oceans and the continents are the shore, continental shelf, slope, and rise. The shore is the band between the high and low tides. Continental shelves are shallow platforms adjacent to land masses, many are characterized by an irregular topography comprising banks, basins, and valleys, but some have relatively smooth floors. The seaward limit of the shelf, with a gradient of 1 in 500, is usually defined by a shelf break, a distinct gradient change from the gentle shelf to the steeper slope.

The continental slope has a steep gradient of 1 in 20 and extends to the deep sea of about 4 000 m depth. Often the slope is dissected by submarine canyons. Material is transported mainly by the turbidity currents at the foothills of continental slopes, and forms the continental rise. This is composed of a long wedge of sediments, usually several kilometers thick. Between the land and the four major open oceans are seas. The largest sea is the South China Sea and, defined by shoreline length, the largest bay is Hudson Bay.

Because of proximity, humans are more familiar with the seas (which are smaller), than with the vast open oceans. For instance, as early as five centuries BC the Chinese *I Ching* (or *Book of Changes*) had already described coastal tides. As far back as classical mythology, both the dangerous rock of Scylla and the whirlpool Charybdis opposite it, in the Strait of Messina between Sicily and Italy, were personified as female monsters. And, in 350 BC Aristotle observed the tidal currents and waves across the Strait of Chalcis. In fact, the Mediterranean may very well have been the first sea to be scientifically studied. In 1661 the Royal Society of London (R.S.L.) reported superposed flows across the Strait of Gibraltar, joining the Atlantic and the Mediterranean, and their effect on the climate.

The first systematic effort to explore the seafloor of the open oceans was that of US Naval Officer Matthew Fontaine Maury who published "The Physical Geography of the Sea" in 1850. Maury showed a rudimentary bathymetry of the North Atlantic. Global coverage of the oceans dates back at least to the *HMS Challenger* expedition of 1872–1876, which systematically collected observations of the oceans stopping every 200 miles. At each station, depth to the seafloor and temperature at various depths were measured by lowering a sounding rope over the side. Water samples were collected and the bottom was dredged for rocks and deep sea marine life. The *Challenger* expedition set the pattern for all expeditions for the next 50 years. The establishment of the oceanographic museum in Monaco between 1899 and 1910 during the reign of Prince Albert facilitated, for the first time, regular time-series measurements of marine and climatic parameters. Other than the work by the R.S.L., the first oceanographic expeditions to the Mediterranean Sea were conducted between 1908 and 1910. These studies paved a solid foundation for modern marine sciences.

A relatively young discipline, modern oceanography was born only in the 1940s, partly from the urgency of the Second World War. For instance, it was in these years that the U.S. Scripps Institution of Oceanography (SIO), founded as a coastal marine station in 1903, grew from a coastal marine station to an oceanographic research laboratory. Woods Hole Oceanographic Institution (WHOI) was established in 1930 because the U.S. Navy and the government officials saw the need to establish an East Coast equivalent to Scripps to concentrate on the Atlantic Ocean. In 1940, the threat of submarine warfare provided the national imperative to understand the marine environment. The current format of oceanography, which involves an interdisciplinary grouping of marine physicists, biologists, engineers, chemists, and geologists, was largely an invention of the US Navy to meet its specific needs. Many observations relevant to US Navy's investigations undertaken for the purpose of anti-submarine warfare turned out to be key ingredients for future revolutions in plate tectonics or paleoclimate reconstructions. For example, detecting the presence of submarines acoustically required knowledge of the shape of the bottom of the ocean and the sediment type, magnetic detection required knowing the ambient background field, etc.. Since then, international interest in the oceans has grown partly due to three main reasons:

- *The role of the world's ocean in climate change.* The world's ocean is a huge source of heat, and from this point of view is of extreme importance for long-range weather forecasting and climate change evaluation. Ocean currents transport heat from the tropics to polar latitudes, which leads to milder weather conditions. The oceans serve as a reservoir of dissolved gases, and global cycles of "greenhouse" gases.
- *Problems of ocean pollution* and its impact on marine organisms and human health resulting from human economic activities and otherwise. These include oil spills, pesticides, heavy metals, radionuclides, sewage sludge, etc.
- *Ocean as an object of economic activity* (recreation, reclamation, oil extraction, ore fields, fisheries and aquaculture, ports and harbors, navigation, etc.).

Each branch of oceanography is quite a distinct science, with its own methods and instruments, and to some extent oceanography may be regarded as a specialized, multidisciplinary science encompassing physics, hydrodynamics, chemistry, biology, geology, engineering, coral reefs, and pollution. This means scientific concerns in the oceans tend to involve more than one discipline, so that addressing most issues often calls for collaboration among scientists, engineers, managers, and even divers with different experience and skills. Because of the vast scopes of many oceanic processes that observe no national boundaries or borders, marine science also depends heavily on cooperation among countries and regions. Further, processes and phenomena covering a wide range of time and space scales are characteristic of the oceans. As a result, integration is fundamental. In response, major global programs, such as the International Geosphere Biosphere Program and the World Climate Research Program have been set up by organizations around the world to deal with the oceans.

The main task of oceanography is to investigate the oceans as an integrated dynamic system, characterized by a delicate, complex system of interactions among the biota, the ocean boundaries with the solid earth and the atmosphere. Life originated in the oceans and has prospered on the earth for nearly four billion (10^9) years. In that time climate has fluctuated drastically, from ice ages to epochs of extreme heat. The climate, however, would have fluctuated even more were not for the role played by the oceans, where currents move heat around very efficiently because of the large heat capacity of seawater. The top meter of the oceans stores as much heat as there is in the entire atmosphere.

The ice ages and epochs of heat are measured in terms of hundred thousands of years, but now man is upsetting these natural rhythms by adding the gaseous by-products of civilization to the atmosphere. Notably, carbon dioxide, chloroflurocarbons, nitrous oxides, and methane have trapped enough heat in the atmosphere to raise the Earth's average surface air temperature by a half-degree Celsius during the past century. These greenhouse gases, if unchecked, could alter climate patterns worldwide, thawing polar ice caps and mountain glaciers, boosting sea level, inundating coastal zones, and more.

In 1995, after years of intensive studies by many countries of the world, the Intergovernmental Panel on Climate Change (IPCC), sponsored by the United Nations, concluded that "the balance of evidence suggests that there is a discernible human influence on global climate." IPPC projected that in the next hundred years global average temperature will rise by 1° to 3.5°C. That may not seem much, yet the "Little Ice Age," an anomalous cold snap that peaked from 1570 to 1730 and froze the River Thames in England, was caused by a drop in temperature of only 0.5°C. About 60 percent of the warming observed since 1850 is contributed by CO_2 due to fossil fuel burning and deforestation, and about half of this "excess" CO_2 has entered the oceans through the air–sea interface. The oceans, with an enormous capacity, will eventually soak up all anthropogenic CO_2 via biological and solubility pumps but so far this does not seem to be happening fast enough.

The coastal zone is the interface between land and the sea and its boundaries depend on several ecological and anthropogenic (economical, political, administrative, and legal) issues. In a broader context the coastal zone may include the coastal hinterland, the lowlands, sand dunes, beaches, estuaries, the coastal waters, and the shelf sea up to the exclusive economic zone (EEZ), because activities that seem remote do affect and interact with this zone. The coastal area is characterized by a variety of forms: rocky shores, sandy beaches, estuaries, lagoons, intertidal flats, wetlands, and islands. These provide habitats for specific biological communities including intertidal communities, mangroves, seagrasses, coral reefs, and the open ocean communities. Different forms and habitats are closely interlinked and act as a unified system. They house numerous resources which support a significant proportion of some impoverished coastal populations.

For the sake of simplicity, however, the complex field of marine sciences can be divided into the subdisciplines discussed below:

3. Physical Oceanography

In the introduction to the APROPOS Workshop on "The Future of Physical Oceanography," one finds the following concise and complete definition:

> Physical oceanography is concerned with how water moves and mixes in the ocean, and how water carries and distributes dissolved chemicals, nutrients, plankton, sediment, and pollutants. Physical oceanography is a branch of applied physics whose goal is to understand, model and predict ocean processes using mathematics and fluid mechanics. The discipline is increasingly intertwined with atmospheric and climate studies: understanding the energy and momentum transfer through the seas and across their boundaries is a major goal of all these fields. Physical oceanography includes the study of estuaries and lakes and also encompasses the study of large bodies of water on other planets and moons (for example, Europa).
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> A central challenge of physical oceanography is the range of space and time scales which must be encompassed by any successful effort to understand the fluid. Watching the wind blow leaves across a lawn, it is difficult to imagine that this force can be responsible for driving the vast surface circulation of the Pacific Ocean, yet this is the case. Capillary ripples roughen the sea surface so that the wind can grip the water and this immense friction results in waves that grind into distant beaches and reshape the shoreline. The wind also deposits momentum into the deeper ocean. This drives gyres within which water spirals for decades. Over centuries and millennia the entire stratification of the ocean changes in response to cooling in high latitudes and evaporation in the subtropics. On these planetary scales, the ocean serves as a reservoir for heat, fresh water and anthropogenic products.
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> Observing these processes demands a combination of *in situ* and remote measurements, including acoustic, electromagnetic and satellite-based techniques. Recent advances, such as autonomous sampling, acoustic tomography and tracer releases are producing an increasingly global and complete picture of the three-dimensional ocean circulation. Because of new technologies, oceanic processes that are seen dimly, or not at all, will be uncovered. Understanding these new data with fluid mechanics, applied mathematics, powerful computers and modern descriptive tools is the future of physical oceanography.

The ocean is primarily an immense water reservoir set in motion by atmospheric and solar forces, winds, and heat fluxes. Oceanic currents and mixing processes re-deploy heat and water within the ocean and this, in turn, affects the atmosphere and influences the climate. These interactions have been exemplified recently by developments in equatorial oceanography and its linkage with meteorology, or by studies of sea-ice formation and drifting and their role in modulating air–sea exchanges. The economic benefits of understanding the role of the ocean in the climate systems are obviously enormous. Long-term forecasting of the coupled atmosphere–ocean system is one significant path for future research in oceanography.

The best way to visualize the physical processes in the ocean is perhaps to take advantage of the multiplicity of scales to characterize them: (i) at time scales from years to decades, the ocean is strongly coupled with the atmosphere and their interactions are part of the so-called short-term climate variations; (ii) at seasonal and annual scales, large-scale ocean currents fostered by atmospheric and solar forces, winds, and heat fluxes, the so-called "general circulation," re-deploy heat and water within the ocean and, in turn, affect the atmospheric dynamics and climate; (iii) the instabilities of such large-scale currents as the Gulf Stream and the Kiroshio give rise to very energetic synoptic/mesoscale eddies, with life-times of the order of a month, which co-exist with the wave motions and waves packets associated with the effect of the Earth's curvature'; (iv) currents and eddies are responsible for the cohabitation of large water masses of very different properties and thus separated by fronts where these properties vary over short distances; (v) frontal instabilities generate vortices, interleaving layers and other mesoscale features, transferring energy to smaller scales (contributing in an important way to transport and mixing): the smallest of these scales overlap in the range of scales of days to hours, with another type of oscillations associated with the Earth's rotation, tidal forces, and wind-induced surges; (vi) at smaller scales (hours to minutes), the vertical stratification is responsible for "internal" wave motions and simultaneously the inhibition of turbulent mixing by the restoring force exerted on vertical excursions, and the generation of it by the breaking and non-linear interactions of the waves; (vii) at scales of minutes to seconds, no restoring force like stratification, Earth's rotation or Earth's curvature is felt and microscale turbulence and mixing dominate.

Although necessarily schematic, this description provides a reasonably good picture of the ocean's dynamics but ignores processes which are, one way or another, related to the existence of ocean boundaries: (i) the ocean is vertically bounded by the bottom and the air–sea interface, and ocean hydrodynamics must satisfy there boundary conditions. The adjustment to the boundary conditions may be effected over rather thin boundary layers with quite specific characteristics: bottom friction in the bottom layer and wind-induced turbulence in the upper layer (mediated eventually by the presence of sea-ice) tend to homogenize heat, salt, and other constituents' contents, while the fluid velocity constrained by bottom or wind stresses varies in amplitude and also in direction under the effect of the Coriolis force, associated with the Earth's rotation, which tends to deflect the velocity vector (more and more as one goes away from the boundary) in what is universally referred to as the Ekman Spiral; (ii) lateral boundaries of the ocean are not truly coasts but rather the shelf break where abrupt variations of the bathymetry separate the open ocean from the relatively shallow continental shelfs and the so-called "coastal zones."

Traditional oceanography has often made a distinction between the open ocean and the coastal zone, although they are confronted with the same problems: transport of water masses by currents, mixing, biogeochemical cycles, marine ecology, sediment deposition, reprocessing and erosion, and so on. The distinction is to some extent justified because coastal zones are shallow, influenced by bathymetry and coastal geometry, directly exposed to fresh water and particulate matter discharges from rivers or wind-born rain and aerosols, subjected, for the best or the worst, to pervasive human management policies and to the stress of a rapidly increasing population. Hence, although processes are similar, orders of magnitudes (of tidal velocities, particle concentrations, etc.) may be very different and, although the study of the open-sea and the coastal zone do not require oceanographers of different skills, they may benefit from research specialists of different field experience.

The problem of assessing the processes occurring at the shelf-breaks and the exchanges occurring between the open-ocean, shelf seas, and coastal zones is an essential challenge that will require sustained research efforts in the future.

4. Chemistry of the Oceans

Chemical oceanography deals with the chemical composition of seawater, sea ice, and sediments, with distribution of ions, dissolved gases, particulate and dissolved biogenic elements, radionuclides and other pollutants, and with their chemical interactions, against a background of physical and biological processes. In short, it studies the properties and interactions of substances present in the marine environment.

Measurement of the chemical composition of the ocean can be traced back to the 1770s when Antoine Lavoisier and Torbern Bergman made their analyses of the composition of seawater. In 1819, A. M. Marcet pointed out that the major components of seawater remain in constant ratios everywhere. By 1873, the *HMS Challenger* expedition had a chemical laboratory equipped to map out many constituents on a worldwide scale. However, because of the complexity of the chemical composition of seawater, including not only the multitude of interactions that occur between the chemicals themselves but also those involving air–sea exchanges, marine biota, and bottom sediments, the main activity in chemical oceanography from this time to the middle of the twentieth century was primarily descriptive. This was limited, by today's standards, by the rather weak capability for analyzing seawater. As a result, aside from the pioneering work of determining elemental distributions in the oceans and insights gained on nutrient chemistry, the field of chemical oceanography was principally playing a supportive role to physical and biological oceanography.

During the past several decades, however, this field has matured to become a major component of the marine sciences and to the point where questions can be asked about how the oceans, including their interfaces, are acting as chemical systems, and at what rate. This has resulted mainly from the introduction of increasingly more sensitive and selective measurement techniques and from the ideas and perspectives advanced by non-marine scientists, such as those in solution chemistry. A remarkable advance in the chemical investigation of the marine environment began when Lars Gunnar Sillen presented his thoughts on the chemistry of seawater at the International Oceanographic Congress held in New York in 1959. The field has since progressed to a point where modern chemical oceanographers encompass many chemical disciplines. They are armed with powerful analytical tools that can not only be applied to studying the processes and mechanisms that give rise to the chemical properties of the ocean, but also can often provide capabilities and information that find use in the other oceanographic disciplines. For example, laboratory studies of the carbonate equilibria have greatly increased our understanding of how these minerals behave in the sea, and refined techniques for analyzing low-level radioactivity (e.g. tritium, ^{14}C, ^{39}Ar, ^{35}Kr, ^{134}Cs, ^{137}Cs as well as the chlorofluorocarbons (freons) and the tritium/helium ratio) have given insight into the study of mixing processes in the deep oceans. A major objective of workers in the field of chemical oceanography is to understand the mechanisms that control the composition of seawater. A useful consequence of this understanding has been an ability to predict the effects of natural or anthropogenic perturbations in a quantitative manner.

The various sub-disciplines comprising chemical oceanography find themselves in different stages of development. For example, advances in our understanding of the physical chemistry of seawater have permitted the formulation of a new equation of state for seawater and ways to calculate the speciation of chemicals. On the other hand, marine organic chemists are still faced with an overwhelming number of dissolved compounds present in seawater and require the help of microbiologists for gaining a better understanding of the controlling biochemical mechanisms involved in numerous chemical (and biogeological) processes (e.g. the degradation of detrital material and the dissolution of carbonate and silicious testas and skeletons).

An enormous mass of the dissolved organic carbon is present in the oceans, which is about 10^3 times more than all living marine organisms combined. The total amount, at about 700 Gt C is almost the same as all the CO_2 in the atmosphere. In the oceans, photosynthesis of organic matters is possible only in the euphotic layer, which is less than 100 m thick, whereas decomposition of organic matter is not light-dependent and may go on at arbitrary depths. The share of oceanic production eaten up by the microconsumers amounts to about only 10 percent. The major part of particulate organic carbon produced is converted to dissolved organic matter or forms organic detritus such as fecal pellets or dead particles, which are then eaten by zooplankton, bacteria, and other heterotrophs. To address questions of the cycling of organic matter in the oceans, it is necessary to determine chemically the products of primary production and also to investigate low levels of bioactive substances that are vital to communication within and among species.

Today, the framework of chemical oceanography encompasses the identification of the major pathways of both natural and anthropogenic substances, which in some cases are also pollutants. The essential mass balance concept has been applied in the field, and the chemical processes involved in the transfer of matter from one region to another have now begun to be understood in order to achieve a quantitative chemical description of the ocean. The origin and nature of river-borne and aeolian matter has been studied, as well as the processes that occur in coastal zones, especially in the upwelling regions and in the mixing zones between river water and seawater. An equally important interface exists between the air and the ocean surface, where important mass transfers take place and some rates are now known. The processes occurring at the sediment–seawater interface determine to a large extent the composition of the sediment, as well as the overlying seawater, and are intimately related to the formation of certain mineral resources (e.g. manganese nodules and metal sulfide deposits). The addition and release of matter in coastal seafloors is also of particular importance.

In addition to the phenomena that are occurring at these boundaries, chemical processes occurring within the ocean are also important. These include the interactions between particulate (both inorganic and biological) and dissolved constituents of seawater. But by far the most chemically important system in the oceans, with the exception only of the chemistry of water itself, is the CO_2^- system, a buffering system that helps to maintain the pH of seawater to within a narrow range. CO_2 hydrates with water rather rapidly (in milliseconds) to form carbonic acid. Once CO_2 is hydrated, it is involved in a series of even more rapid proton transfer steps (submicroseconds) to form bicarbonate (HCO_3) and carbonate (CO_3^2): CO_2 (gas) $+ H_2O = H_2CO_3$, $H_2CO_3 = H^+ + H_2CO_3$, $H_2CO_3 = H^+ + CO_3^2$. Because of the large buffer factor of seawater, a 10 percent change in the partial CO_2 pressure results in only an approximately 1 percent change in TCO_2. At the current pH of seawater (about 8), the anthropogenic CO_2 added to the oceans reacts with the carbonate ion to form the bicarbonate ion without a change in pH: $CO_2 + CO_3^{2-} + H_2O = 2H\ CO_3$.

The concentration of the carbonate ion is limited by the solubility of calcium carbonate as follows: $Ca^{2+} + CO_3^{2-} = CaCO_3$. In this reaction the solubility of $CaCO_3$ increases with pressure but decreases with temperature. The surface layer is usually saturated with $CaCO_3$, but except for isolated regions such as the Bahama Banks, spontaneous precipitation does not occur because organic material and magnesium in seawater retard $CaCO_3$ formation. Many marine organisms, however, utilize calcium and carbonate ions to form $CaCO_3$ skeletons and shells. This process occurs mainly in the surface layer. As the organisms die, their shells and skeletons sink to a level where the temperature becomes low enough or the pressure becomes high enough, and the water becomes undersaturated with respect to $CaCO_3$, at which point they start to dissolve. Accumulation of undissolved $CaCO_3$ in the sediments over millions of years, however, makes the sediments a major sink of carbon.

Inorganic carbon, along with nutrients, is also used by marine organisms to grow soft tissue. Soft tissue decomposes quickly in the water column. Both soft and hard parts of the marine organisms act as a "biological pump," thus removing CO_2 and nutrients from the surface ocean and transferring these into the deep ocean and ocean bottom. With the knowledge gained, naturally occurring chemical constituents (e.g. nutrients, total CO_2, and oxygen) as well as pollutants in the marine environment (e.g. tritium, excess CO_2) have been used to study physical mixing as well as biological processes. It is now well established that the marine organisms have an average C/N/P ratio (the Redfield ratio) of 106/16/1 and the N/P ratio is also 16/1 in seawater. The C/N/P ratio in seawater, however, is close to 80/16/1. As a result, carbon is never in short supply but whether N or P is the limiting nutrient is less certain. Since nitrogen fixation occurs in the oceans even when N is exhausted, it seems that P may be the limiting factor.

Another limiting micronutrient is iron, which is in short supply in the high-nutrient, low-chlorophyll regions such as the Southern Ocean.

Rivers supply far more dissolved and particulate material to the ocean than do all other sources combined. The influence of rivers on the geochemical budgets of many elements relays a major role in the cycling of materials through the ocean, especially in the continental marginal zones. Estimates of the composition and rates of fluvial and atmospheric inputs to the ocean are important boundary conditions for chemical budgets in the ocean and have been used to ascertain the impact of human activities in changing the ocean environment.

A focus has been placed on major rivers, for some of which there is already a background of information (e.g. Amazon, Mississippi, Yangtze). Riverine study areas have extended from terrestrial drainage basins to the outer limit of plumes in the ocean. Long-term effects of river-transported sediment to the oceanic shelf, and chemical alteration in open ocean water, have already been included.

Rivers commonly pass through estuaries on their way to the coastal oceans. Dams and irrigation schemes affect the chemical structure of an estuary, which traps significant quantities of material and thus acts as a filter between land and the oceans. Biological processes may also play an important role in the trapping and mobilization of material carried by rivers and land runoff.

Coastal sediments are subject to erosion, bioturbation, transport or accumulation. In general, most particulate matter from land is deposited in areas of accumulation such as estuaries, continental shelves, and slopes. The leakage from such sediments may be considerable, especially if the sediment has a high content of organic matter and thus has a rich fauna. Ammonia, urea, amino acids, phosphate, carbonate, silica, trace metals, and trace organics are released to the coastal water in such instances.

Some nineteenth-century river water analyses may be of interest when establishing the impact of man. Comparison of data for the upper Elbe from 1892 to 1976 indicates that nitrate concentrations have increased fortyfold (among other ions). Since nitrate is considered to be the limiting nutrient in some ocean surface waters, increased nitrate levels in rivers and land runoff have caused coastal eutrophication and low oxygen levels below the ventilated surface water. Recent observations in the Chespeake Bay, off the Mississippi river mouth, and in the North Sea and the adjacent Skagerrak and Kattegat waters indicate an over-fertilization. Thus coastal waters can be greatly influenced by land management (e.g. the use of fertilizers).

The sediment-water interface can introduce a chain of reactions both chemical and biotic, which serve to modify particulate matter drastically before the material enters the bulk geochemical cycles. Spreading centers in general are of particular interest and the discovery, since the early 1970s, of active hydrothermal vents in the ocean may be the most significant finding in the field of oceanography since the refinement of theories on sea-floor spreading. These vents are active seafloor areas where seawater circulates through hot, newly-formed oceanic crust and is discharged into oceanic bottom waters. For instance, near the mouth of the Gulf of California, copper, zinc, and iron sulfide chimneys have been observed forming around discharge vents when the >350°C waters encounter cold seawater. The discharging waters contain high concentrations of hydrogen sulfide, potassium, calcium, silicate, barium, manganese, iron, and zinc, but are low in magnesium. These observations confirm earlier suggestions that such discharging waters are important in controlling seawater chemistry.

Lower temperature vents in the Gulf of California and in a vent field northeast of the Galapagos Islands are characterized by extensive communities of organisms including giant clams, 30 cm long mussels, crabs, and forests of meter-long tube worms. Organisms living around the vents have highly-specialized physiological systems suited to their unique chemical environment. Sulfur-reducing bacteria play a major role in the vent food web, and the morphology and enzyme systems of the giant tube worms may also be specialized to derive food energy from similar symbiotic bacteria. Such specialized physiological pathways lend support to geological and chemical data that suggest vents have existed on the seafloor for millions of years. It has even been speculated that the unique vent environments may have provided the proper physical and chemical conditions for the origin of life on Earth.

Several dozens more vent areas in the Pacific have been located using unmanned systems with sonars and cameras towed near the seafloor. Photographs and sonar records show rocky pinnacles rising from the sediment-covered floor, several with dense clusters of tube worms and clams.

Sulfidic basin waters, such as those found in the fjords of Norway, the Black Sea, and the Cariaco Trench, are yet the other areas of special chemical oceanographic interest, since life in such basins is restricted to a few species of bacteria; increased trace-metal concentrations are found which have been explained by the formation of soluble disulphide complexes (e.g. HgS_2H^-).

Another area of research that has gained attention is ocean-atmosphere exchanges, including specific efforts to study the chemistry of the sea surface microlayer. Such investigations have included not only the determinations of aeolian transport, but also chemical phenomena which could play a role in such transport (e.g. methylation as a mechanism in trace-metal mobilization).

The sea surface microlayer is the boundary between the oceans and the atmosphere. It is also a source of contaminant accumulation and can cause modification of biological processes and air–sea exchanges. Natural surface-active substances are often enriched in the sea surface compared with subsurface water. Amino acids, proteins, fatty acids, lipids, phenols, surfactants, and many other organic compounds accumulate at the surface. The biota of the water column below is the source for most of the enrichment of natural chemicals. Marine organisms and sea birds produce dissolved compounds as products of their metabolism. Air bubbles, rising through the water column, scavenge these organic materials and bring them to the surface, and sometimes into the air. Also, as plankton die and disintegrate, some particles and many of the breakdown products such as oils, fats, and proteins, float to the surface.

The accumulation of natural organic chemicals modifies the physical and optical properties of the sea surface. Thin organic films, invisible to the naked eye, are ubiquitous in aquatic systems. In areas where currents converge, thicker films accumulate. Under light to moderate wind conditions, areas of accumulated film dampen small waves and become visible as "surface slicks." Strong surface tension forces exist, creating a boundary region where turbulent mixing is much reduced.

In areas contaminated by petroleum hydrocarbons, the films may be dominated by hydrocarbons, and heavily-esterified compounds; in contrast, natural films are for the most part complex polymeric components with a high degree of hydroxylation, carboxylation, and proteinaceous content. These types of films differ significantly in their thicknesses, pressures and spreading characteristics, and they retard the transfer of gases and elements to varying degrees.

The air–sea interface acts not only as a "membrane" between the aqueous phase and the atmosphere but, like the sediment–water interface, presents a discontinuity where significant chemical reactions may occur. Certain chemicals are photodegradable. On the other hand, photo-active species in the upper illuminated layers of the sea are generated. Some of the postulated marine photo-chemical phenomena include: the degradation and transformation of xenobiotic materials (and hence would have consequences on considerations of the toxicities of parent and daughter compounds); mechanisms of solubilization of surface films including hydrocarbon slicks; metal-organic photo-interactions; and the production of gaseous components from primary metabolites.

Present-day biogeochemical cycles are often based on assumption of a steady state, but anthropogenic inputs can upset such assumptions. Coastal eutrophication and the adsorption of excess CO_2 in the oceans are capital. Transport of marine aerosols is important for the cycling of several elements and terrestrial life. Bubbles act as both gas exchangers and producers of aerosols. The transfer of carbon through the air–sea interface has drawn great attention because of the critical role it plays in the fate of human-mobilized CO_2 and its effects on the oceans and climate. Carbon dioxide is receiving still increasing interdisciplinary attention, and research into the transport, effects, and outcomes on the environment is now underway in major programs such as the Global Ocean Flux Study and the Global Ocean Observation System programs.

Despite international conventions limiting the release of potentially harmful substances, point introductions of pollutants such as blow-outs of production wells, tankers damaged at sea, chemical dump-sites, heavily polluted rivers, etc., will continue to occur in the future. In addition to their consequences being of interest, their ubiquitous presence has been used to forecast the pathways of substances in the ocean. Similarly, as new compounds continue to be synthesized on a large scale, they and their by-products may appear as future pollutants.

Upwelling areas are interesting because of marked impact of the material transport and mixing on some of the seawater constituents, notably nutrients. A characterization of the components removed in particulate matter (e.g. carbohydrates, lipid proteins), or fecal material leaving the system, is essential to an understanding of the depletion of the essential nutrient elements in these systems. These areas of advection and recirculation of essential elements via major ocean mixing processes may be better described by the movements of chemical tracers, including those compounds (such as the halogenated hydrocarbons DDT and PCBs) originally measured only because of their detrimental effects on marine life.

Warm and relatively calm areas are often more accessible for study than cold, hostile regions. The Arctic Ocean is of special interest since it is important for the climate of the northern hemisphere. Also, it connects the Pacific and Atlantic Oceans and is markedly influenced by the input of river-water and ice. Formation of deep water is a process of considerable interest that takes place in the cold regions in the Arctic and Antarctic. In addition to learning more about the composition of this water (C/N ratios, nutrient content, ^{14}C, and tritium) before it is exported from these regions, one needs additional tracers to follow its outflow and reappearance, and to determine its age. Mixing processes in various regions of the world require the use of multiple tracers for their elucidation. Measurements of tritium, helium-3, carbon-14, freons and other halo-carbons, strontium-90, and cesium-134 and 137 are valuable aids in such studies. For example, radioactive effluents from the British Sellafield plant are well-regulated and monitored (e.g. the Cs-137/Sr-90 and Cs-134), and have been used to study the flow of Atlantic water through the Irish Sea around Scotland into the North Sea, and along the coast of Norway into the Arctic Ocean.

The levels of some trace metals are considerably lower than reported previously. Biological systems may therefore be more sensitive to heavy-metal inputs than had been thought. Of the 80 elements known to occur in seawater, a number are concentrated by marine organisms in a process known as bioaccumulation. For example, vanadium concentration in some filter-feeding animals has been found to be 10^5 times greater than that of the surrounding seawater. Fortunately, vanadium is not very toxic, but many trace metals are. Take zinc and copper as examples. These are essential for the growth of many organisms, but when oysters accumulate too much zinc and copper they become toxic to humans. Oysters themselves can turn green with too much copper, although they do not necessarily die. In most cases, however, the affected organisms don't show any warning. For instance, several hundred people died after eating mercury-laden shellfish in Minamata, Japan. Copper, zinc, and lead are of special interest since they are produced and used in huge quantities. Mercury is intriguing since humankind has considerably increased the pool of this element circulating in nature. Tributyl tin-based paints have been banned in several countries because of toxicity to marine organisms.

5. Biology of the Ocean

Major biogeochemical cycles must be studied at the global scale and this implies reliable assessments of chemical fluxes between the ocean and neighboring Earth compartments (e.g. land, sediments, atmosphere). However, the transit and internal cycling of materials within the ocean, in relation with the physical and biological processes, is also of the uppermost importance. One still discovers new fundamental geological phenomena which act on biogeochemical cycles: for instance, hydrothermal processes where seawater, circulating in the ocean crust and the sediments, becomes heated in the vicinity of magmatic chambers and spurts up at high temperature at the ocean's bottom. Such processes play a crucial role in chemical budgets and the same is true of the very dynamic biological and geological phenomena found in rift zones. Hydrothermal ecosystems have been found in the deep ocean where the primary source of energy is bacteria-mediated geochemical reactions, and not the familiar solar energy used by plants on continents and in the upper layers of the sea.

In the ocean, chemical elements are transported by the currents in dissolved or particulate forms in suspension as well as by living organisms. Inputs from rivers and winds, in the form of alluvia and aerosols, constitute important sources, but seawater has its own chemistry and discharged material and chemical compounds may undergo complex transformations in the sea that participate in the internal biogeochemical cycles. Similarly, material deposited on the bottom is not definitely removed from the water column. Biological activity inside the sediments and physico-chemical reactions between the sediments and the interstitial waters, associated to their migration, contribute to the reinserting of a large amount of elements into the water column.

The biological activity of the ocean has often been described as a long hierarchical chain of consecutive, not quite closed, loops where (mineral and organic) materials are partly recycled and partly exported (consumed as food) to higher levels. At the outset of the chain, nutrients (such as carbon, nitrogen, phosphorus, silicon and other minor, but sometimes limiting, constituents like iron) are synthesized, with the help of appropriate energy supplied, to organic forms constitutive of living organisms. Part of this material (dead cells, excretions, exudations) is returned by various mechanisms to the nutrient pool; part of it is consumed as food by higher-level organisms, which in turn feed larger living species up to fish and marine mammals which may be harvested by man.

Research on marine biodiversity has evolved from an inventory of species to the study of the dynamics of ecosystems, the role of diversity in the stability of marine populations, and the health of the marine system as a whole when confronted to natural or man-made severe perturbations. Perhaps the best example of the dramatic changes which have occurred in the last two decades in our understanding of ocean ecology is the expanding vision of the food-web structure in the marine water column. As described in the OEUVRE Workshop Report, "recognition of the roles of microbes has added a suite of new trophic levels to the classic 'diatom–zooplankton–fish' food-chain. Major advances include: the discovery of large populations of bacteria growing on dissolved organic carbon partly exuded by autotrophs; a large fraction of primary production originating from very small autotrophs; and a significant role of flagellate and ciliate predators. Recent findings also point to the importance of viral-induced lysis of bacteria, and the complex role of mixotrophic nutrition. This new view of the food-web has improved understanding of the transfer efficiency of primary production to higher trophic levels and the role of nutrient regeneration within the photic zone."

This is just one example of the remarkable advances made in our understanding of marine biology and ecology within the last 20 or 30 years, but it is indicative of the speed at which these sciences have developed and must continue to evolve to acquire the mastership necessary to deal effectively with the accelerating pace of environmental change and the challenge of sustainable development. As stated in the "Critical Issues and Promising Opportunities" section of the OEUVRE Workshop Report:

> Ocean ecologists must provide for better stewardship of marine resources and ecosystems by: understanding and predicting which perturbations and food-web alterations will cause collapses of marine communities and the ecosystem services that they provide; predicting and mitigating the effects of harmful algal blooms; understanding and predicting interactions among global climate, marine geochemical processes and marine biota; and, understanding and mitigating outbreaks of microbial pathogens that can decimate important marine populations. Meeting these challenges will require better understanding and resolution of the causes and consequences of changes on scales from hours to millennia.

6. Geology of the Oceans

Geological oceanography, or marine geology, investigates the ocean bed, which is no longer considered just as "land covered by water." On the contrary, the highly-complex measuring instruments of oceanographers have established an underwater landscape with gorges much deeper than the Grand Canyon and mountains greater than Mt. Everest, making anything on land seem minuscule. (After all, the average depth of the oceans is 3 729 m compared with an average land height of only 840 m). Although only a fraction of the bottom of the sea has been explored and mapped, it is known that it consists of a thin layer of sediments overlying heavy basaltic rocks and that it was probably formed and processed at different times from the land. Thus, the domain of geological oceanography includes the subjects of shape and topography of continental shelves, slopes, margins and deep ocean, basins, ridges, plate tectonics, and classification and distribution of marine sediments.

Since the human race began to interact with the sea, a knowledge of seafloor structure and composition has accumulated. At first a minimum set of intuitive knowledge was obtained to allow boatman and sailors to find food, avoid hazardous rocks and reefs, and return back to the shore. Later, some seagoing trips went further offshore and perhaps started explorations in which simple, preliminary charts for mapping the distribution of shoals and deeps were produced. Later, with the advance of technology, weighted lines were used to measure depth. When numerous measurements along the cruise trajectories were recorded, bathymetric surveying was born. These early seagoing efforts may be seen as the parent of modern marine geological exploration.

The Chinese were one of first leading explorers of the ocean. Between 1405 and 1433, in the early stage of the Ming Dynasty, the Chinese organized many cruises to the Indian and Pacific Oceans. There were the largest peacetime voyages ever undertaken, involving approximately 37 000 men and 300 ships. Magnetic compasses and detailed navigation charts were used in these expeditions, demonstrating the maturity of maritime technology developed then by the Chinese, although the cruises were not necessarily designed to accumulate scientific data.

Marine geology is a young branch of geology. Tracing back through the early literature of geology, it can found that in the eighteenth century James Hutton reported his studies of marine rocks on land. In his "Theory of the Earth," Hutton accepted that changes of sea level are important agents for shaping the rock formations on the Earth. Earlier, a famous chemist, Antoine Laurent Lavoisier, had already been able to distinguish two categories of rock layers of marine origins: "pelagic beds," which are formed in the open sea at great depth, and "littoral beds," which are deposited along the coast. In the early period of exploration, marine geologists who wanted to go to sea and gather more information about the processes of marine rock formations were constrained by navigation techniques. It was even believed that the deep sea did not circulate but lay stagnant at the ocean bottom, and that consequently, no incoming oxygen would be available to support life there. Hypotheses such as these were not refuted until the 1860s, when the bottoms of the ocean basins were sounded during the laying of transoceanic telegraph cables. Living animals such as corals were found on a cable from 2 000 m depth when the cable was raised for repairing.

As marine geological exploration progressed and moved further out to open sea, there was a gradual change of emphasis from straightforward descriptions of marine sediments and environments to looking for a better understanding of the origin and evolution of the seafloor and its relationship to the history of the Earth. The *HMS Challenger* expedition (1872–1876) represents such an effort; systematic investigations were made of the general morphology of the seafloor and the type of sediments distributed globally. By the 1860s, the scientific oceanography community had recognized the need for large-scale, global investigations of the deep sea. Funded by the RSL, the expedition aboard *HMS Challenger* established a tradition of large-scale research projects that has been an important component of oceanographic research ever since. The *Challenger* was remodeled for scientific purposes from a sailing warship. The scientific party onboard was assigned to investigate "everything about the sea." The mission included the study of all physical and biological conditions in every ocean. The track of the *Challenger* during the first comprehensive scientific study of the ocean in 1872–1876 spread over the Atlantic, the southern Indian, and the western and southern Pacific oceans. The shipboard scientists took water samples and made measurements of the temperatures of surface and deep oceans, observing currents, and also collecting sediment samples. Along a journey of approximately 109 000 km, numerous rock and sediment samples were dredged; soundings of water depth from ocean basins that the ship passed through were taken by using a weighted hemp line. Data from the expedition filled 50 large volumes. The cruise reports, written over 23 years, were a watershed in the development of oceanography, and signaled the beginning of modern marine geology. The reports gave a foundation that established the general morphology of the deep-sea floor and the types of sediments covering it.

Marine geological exploration on sediments has stimulated a variety of interests in oceanic history. To obtain marine geological records for revealing the past variability of oceans, technology must be developed for taking or drilling "cores" of marine sediments from the deep sea. Pioneer expeditions taking or drilling marine sedimentary cores were made by the German vessel *Meteor* and the Swedish vessel *Albatross* in the years 1925–1948. Marine sedimentary cores taken during *Meteor* cruises were used to develop and estimate the concept and magnitude of sedimentation rates. The *Albatross* cruises, led by Hans Pettersons, discovered and presented the first evidence of cyclic sedimentation patterns in deep sea cores which may be related to climate fluctuations of ice-ages in the past million years.

The saga of the plate tectonic revolution has its roots in the meteorologist Alfred Wegener's theory of continental drift in the 1920s. With data such as magnetic anomalies in the ocean basins resulting from seafloor spreading, combined with aperiodic reversals of Earth's magnetic field, the theory of plate tectonics received recognition in the 1960s. Observation of the magnetic lineations across fracture zones and the nearly perfect symmetry in these lineations confirmed the theory in the 1970s. Subsequently, second-order effects, such as the existence of propagating ridges and microplates, were observed from detailed surveys and found to be important mechanisms for accommodating changes in the direction of relative plate motion.

A hypothesis and theory for explaining satisfactorily the overall morphology of ocean basins and various types of continental margins and sedimentations were first proposed by Wegener in his debated book, *The Origin of Continents and Oceans*. Wegener was first interested in the parallelism of the coastlines bordering the Atlantic Ocean, a phenomenon noted early in eighteenth century by the famous naturalist Alexander von Humboldt. Wegener thought that the continents over the two sides of the Atlantic Ocean looked like puzzle pieces which belonged together. Later, he was impressed by evidence provided by paleontologists regarding the existence of "land-bridges" in the remote past between Europe and North America to explain the similarity of fossil faunas and floras. These convinced him to propose a concept of "continental drift," in which he imagined granitic continents floating in basaltic mantle magma like icebergs in water. The driving forces or mechanisms responsible for the continental "drifting" were unknown at that time. Wegener envisioned that the forces could come from the rotation of the Earth.

A revolutionary theory in marine geology and also in earth sciences, "plate tectonics" needed more critical evidence collected by marine geophysicists. These pioneer efforts of marine geophysical explorations included earth magnetism, heat flow, and seismic surveying by E. C. Bullard and M. Ewing, and gravity anomaly patterns of deep-sea trenches and the detailed structure of continental margins by H. Hess. Among much accumulated evidence pertaining to the concept of plate tectonics, Hess's publication "A History of the Ocean Basin" was critical. As a naval officer, Hess had discovered and mapped a great number of flat-topped seamounts, and investigated geophysically the properties of deep-sea trenches. Combining all evidence from geophysical surveying on the rift morphology and heat flow of the mid-ocean ridge, Hess proposed his model of the seafloor being generated at the center of the mid-ocean ridge, moving away and downward into the continental margins, finally disappearing into trenches. A theory of "sea-floor spreading" was used to describe the whole convection process happening in the upper layers of oceanic and continental crusts. The sea-floor spreading theory, with lately added observations on marine geology and geophysics, transformed into a theory of plate tectonics which has since become the basic framework within which most of the data in geological oceanography are interpretable.

The vertical motion of the seafloor was predicted from conductive cooling relations and compared with the depth data. The archives of heat flow observations were compared with the predictions based on the thermal cooling model that fitted the subsidence of the seafloor away from the mid-ocean ridges, but were found lacking. The conductive heat flow was less than predicted near the ridges and on the flanks, leading to the proposal that hydrothermal circulation was appreciable in young crust. Later expeditions to the East Pacific Rise in 1979, found the "smoking gun" for hydrothermal circulation near mid-ocean ridges in the form of hot vents and the completely unexpected chemosynthetic food chain associated with them.

Hotspots, although not a natural component of the plate tectonic paradigm, proved to be a useful indicator of direction and speed of absolute plate motion. Observations of the flexure of the lithosphere beneath the weight of the hotspot islands and seamounts, and seaward of subduction zones, were used to calibrate the strength of the oceanic plates. These studies led to unprecedented abilities to predict the horizontal and vertical history of the seafloor in all of the world's oceans.

The impact of the reconstruction of the paleoclimates on society has been no less important than the plate tectonic revolution. Whereas the time scales for plate tectonics are measured in millions of years, the deep sea record from sediment cores has taught us that the Earth's climate vacillates on hundred-year time scales, and possibly even less. There is every reason to believe that natural climate cycles enhanced by human degradation of air, water, and land could result in a planet unable to support the present population in a matter of centuries, or sooner.

The climate story partly started with cores demonstrating that the carbonate compensation depth in the oceans has varied over time, as had sea level. Furthermore, the microfossils indicated that there had been sudden swings of climate from warm-loving to cold-loving marine planktonic microfossils and back again at rates too fast to have been caused by plates drifting into different climate zones.

High-resolution mass spectrometers were used to analyze the down-core oscillations in the ratio of the heavy oxygen isotope, ^{18}O, to the light oxygen isotope, ^{16}O. Based on the correlation with the biostratigraphy, these variations were clearly correlated with changing climate, but it was unclear whether the isotopic variations were caused by changes in ocean temperature or in terrestrial ice volume. Another core containing well-preserved benthic and planktonic foraminifera showed the same oxygen isotopic signal. Whereas surface waters are very prone to temperature changes, the deep sea is roughly isothermal. Therefore, the fact that the signal was the same in the surface waters as in the deep sea suggested that the ultimate cause was climate-related changes in ice volume, not temperature directly.

The impact of the development of the stable isotope proxy on paleoceanography was substantial. The oscillations in the stable isotopes have been the paleoclimate equivalent of the magnetic reversals for plate tectonics. The pattern was used for global correlation and spectral peaks matched the predictions of the Milankovitch hypothesis. According to this theory, variations in the Earth's orbital parameters (eccentricity, tilt, and precession of the equinoxes) caused variations in solar insulation that resulted in changes in climate. The deep sea has provided a well-calibrated record of the Earth's natural climate changes that can be used to help assess the future impact of human's activities, such as the greenhouse effect.

7. Coral Reef Studies

Shallow coastal areas support a greater variety of habitat and are of vital importance to the life cycles of a high proportion of the animal life in the world's oceans. One of the most important of these habitats is a coral reef. Biologically-rich coral ridges form in warm shallow seas by the accumulation of the skeletons of certain colonial marine invertebrates, coral polyps being the most significant. The gradual accumulation of calcareous material results in the growth of permanent coral fringing reefs, rings or islands. Coral polyps repeatedly divide themselves into daughter polyps, such that colonies are formed with a common skeleton. Coral reefs are attached to the ocean floor and may become so large and so heavy that only an excessively violent storm could disturb them. Coral reefs provide habitat, food, and shelter for a vast array of forms of marine life, perhaps equal to tropical rainforests in terms of biodiversity, or the variety of living things. They are of great importance not just in their own right from bone graft material to the development of pesticides, but also as breeding areas of a large proportion of the ocean's fish resources, including commercially valuable species, like lobster, sea cucumber, and grouper. They also affect coastal life, serving as natural breakwaters which safeguard land from typhoons and soil erosion. Unfortunately, coral reefs are under severe threat today, with a large proportion of them being damaged or threatened by over-exploitation, tourism, climate change, overfishing or other destructive forms of fishing, pollution, and even the discarding of fishing nets by unwitting fishermen.

There are four principal forms of coral reefs: fringing reefs, barrier reefs, atolls, and patch reefs. Coral islands are comprised of low land, generally only a few feet above sea level. They may be created by accretion or accumulation, such as through storms, or more gradually through sedimentation in combination with the action of currents and waves. Beaches develop around shoals and reefs near the surface of the sea, and dunes may develop over them, providing conditions for terrestrial vegetation.

Many coral islands in the Central and South Pacific, for example, came into existence in this manner. Reef islands, particularly those close to sea level, are often not very stable. The storms that help create them may also destroy them. However, these reef islands are home to many people in the Pacific. Waves may attack one side and redeposit the material on the other. As precarious as reef islands are, they have nevertheless long been the homes of peoples dependent on the oceans for their livelihood. The extent to which human activities contribute to the destruction of reef islands is a major concern today, as is the threat to reefs and coral islands from rising sea levels.

8. Human Uses of Oceans

Humans have settled in the coastal zone in search of the many amenities that it provides. A century ago, the presence of humans caused little harm to the coastal environment. Fishing and other forms of use of the marine and coastal resources indeed caused local environmental changes, but did not threaten biodiversity on sustainability. Today, technological advancement, coupled with the growing resources demands of the ever-increasing population, has led to the use of numerous resources from the marine and coastal zone. We are now extracting hydrocarbons, mining coral reefs, cutting mangroves, and in some cases promoting coastal tourism, marine transportation, and the exploitation of fisheries. In addition, we have beach erosion and a rise in sea levels. Further, the last decades have seen a significant increase in pollution from human by-products and wastes into the marine environment.

In the past, oceans and coastal seas have been regarded as inexhaustible sinks where waste and other pollutants could safely be dumped without any significant adverse effects. However, it is now realized that environmentally-irresponsible actions and activities can cause potential public health hazards through exposure to contaminated seafood and water. In recent years, another threat to living marine resources has been identified as resulting from global environmental change. Global warming may raise the temperature of the oceans, reducing upwelling of nutrient-rich subsurface waters, and having catastrophic effects on phytoplankton and heat-sensitive corals. In addition, the depletion of the atmospheric ozone layer is causing more ultraviolet radiation to reach the Earth's surface, affecting the plankton in the oceans.

Environmental effects on the coastal zone caused by human activities fall broadly into four categories: nutrient input, sedimentation, contamination, and habitat modification. Some of these impacts are mere amplifications of natural environmental conditions. One such case is increased sedimentation. Increases in both suspended sediments and seafloor sedimentation have direct adverse effects on plants and on suspension-feeding organisms such as bivalve mollusks and polychaete worms. Research and monitoring of the related impacts have increased with public awareness and media coverage. However, basic research on the complex interactions is still insufficient to provide an adequate scientific basis for pollution-management decisions.

Examples of ocean research topics that are important to the maintenance of environmental quality include: the evaluation of useful biological indicators to assist in distinguishing anthropogenic from natural fluctuations; studies of the bacterial transformation of compounds exotic to the marine environment; assessment of the mechanisms of transport and dispersion; evaluation of the sublethal effects of various pollutants on marine communities, stuffy of the effects of non-toxic substances (e.g. silt or sludge) on biota, and the effects of excess nutrients on the structure and functioning of marine communities. In each case, the research will prove highly relevant to the problems of natural and cultivated fisheries as well as studies of environmental quality.

9. Ocean Engineering

Ocean science is in large part an observational science, which requires technology ranging from ships, satellites, underwater vehicles, and buoys, to sophisticated tools and instrumentation such as SWATH bathymetric sonar, global positioning system devices, ocean bottom seismometers, field magnetometers, Acoustic Doppler Current meters, bioluminescence sensors, and long-term mooring technologies. Developing this technology calls for the assistance of ocean engineering.

At the scientific level, ocean engineering includes the fields of fluid and solid mechanics of oceans, marine systems, and ships. Much support comes from industry. For instance, the dramatic recovery of oil and natural gas prices in the year 2000 buoyed offshore exploration and field development activity around the globe. The offshore technology industry bounced back after a near-record low in 1999 of US $10 per barrel crude to more than US $30 per barrel in the first quarter of 2000. Oilfields 2 km below the surface of the ocean can now be exploited. Remotely-operated vehicles (ROV) equipped with tools, cameras, and navigational equipment can reach almost any depth now to construct and maintain oil wells on the ocean floor, and, of course, for scientific studies as well.

Rather than causing environmental hazards, old oil rigs are now put in good use. There are, for instance, over 3 900 oil- and gas-production platforms off the coasts of Alabama, Mississippi, Louisiana, and Texas in the Gulf of Mexico. The operation started in 1947. After reaching their 25–30 year lifespan, some 100–150 rigs cease operation and require decommissioning each year. All offshore leases granted by the U.S. federal government call for eventual site clearance and the restoration of the seafloor to predrilling conditions— a difficult job. Now, abandoned rigs are only partially removed, whereby only the deck and superstructure are dismantled. The submerged structure is left on-site as an artificial reef, in order to create a fish habitat on the otherwise featureless floor of the Gulf.

Ocean engineering refers to the application of engineering, planning, and management to the state-of-the-art in the field of oceanography. Oceanography is dictionary-defined as a science dealing with the oceans and includes the delimitation of their extent and depth, the physics and chemistry of their waters, marine biology, and the exploitation of their resources. Thus, ocean engineering can be explained in terms of the practical implementation of science and mathematics by which the physical and chemical properties of ocean water and the sources of energy in the ocean are made useful to people. Ideally, the quality of having utility and practical worth or applicability for human beings should be the essential issue; therefore, a qualified ocean engineer requires not only a firm foundation in general education, but also a strong knowledge of ocean environment and its relationship to other sciences and engineering. Such background equips an ocean engineer to handle ocean engineering data processing– -the engineering design of components and systems for usage in the ocean, and the application of these elements to the solution of engineering problems concerned with developing the resources of the oceans.

Should there be any potential for a significant adverse effect to any environmental quality, alternatives for avoiding or mitigating that possible adverse effect should be included to fulfill environmental equilibrium as well as economy benefits. As a result, a deliberate strategy should conduct a multidisciplinary appraisal of the total impact of a given development project. The necessity for this appraisal at the planning and design stage is apparent and regulated by law in most countries. Currently, emphasis is placed on the solution of engineering problems related to the marine environment through consideration of ecological and esthetic perspectives. Further requirements include the accumulation of additional baseline data and knowledge of the quantitative ecological physical relationships. This information can be developed by monitoring before, during, and after construction effects on any ocean engineering projects.

In recent years new literature has developed rapidly, so much so that scientists and engineers of all disciplines attempt to keep up with mushrooming knowledge without becoming too narrowly specialized. Collections of review articles covering broad sectors of science and engineering are still the best way of sifting incoming commentaries critically. In this regard, the following seven areas broadly illustrate the interrelationships among many types of problems encountered in ocean engineering: field measurement and remote sensing; marine structures and materials; naval architecture; ocean energy; mariculture engineering; underwater acoustics; and harbor and navigation.

Field Measurement and Remote Sensing. A field measurement is termed *in situ* if the sensor or instrument has a direct contact with, or a very close proximity to, the medium being measured. Often, measurement is made from a distance and is usually conducted using electromagnetic waves and remote-sensing methods. Generally speaking, *in situ* measurements can provide continuous and long-term data at a single location whereas remote-sensing measurements can supply data for a wide range. Applications with direct impact in the ocean engineering areas are: wave, ocean current, and wind, problems associated with natural or man-made damage, data accuracy, and gauge and fixture durability.

Marine Structures and Materials. In the sea, various engineering facilities are constructed for the exploitation of marine resources and the continuity of economic development. The classification of marine structures may depend on mobility, function, or located terrain. At present, modern ocean technology is calling for a sophisticated and practical approach to the structural design of deep ocean exploitation, from concept to completion.

Naval Architecture. The practice of designing and building watercraft can be classified by the various means of physical supporting force and their intended purposes. Three kinds of water lift are aerostatic, hydrodynamic, and hydrostatic. Merchant ships, naval vessels, working craft, and pleasure craft are assorted by intended purposes.

Ocean Energy. When viewing the world's future energy supply, there is the demand to exploit alternative energy in order to sustain and further develop the activities of mankind. Greater attention has come to be focused on ocean energy, and expectations have been understandably high since the ocean provides a vast energy resource, theoretically capable of meeting all our needs if only we could discover effective extraction methods. The oceans are the world's largest solar energy collector and storage system, and a great deal of usable power could be generated, not only via the dynamic exertion of currents, waves, and tides, but also via oceanic thermal energy conversion. These means of supply are possible with the requisite technology; however, more research is necessary to provide greater confidence in technical and economic feasibility.

Underwater Acoustics. The sound velocity profiles are important factors for acoustic wave propagation at sea and for the measurement of the speed of sound in water and the study of acoustic phenomena in the ocean. Three sophisticated wave propagation models are the acoustic ray model, the normal mode model and the PE (parabolic wave equation) model.

Mariculture Engineering or "sea farming" technology can be stated as the cultivation of marine organisms in their natural environment. Today, hefty research efforts to produce some fish species under artificial conditions have given significant results when it comes to volume. The technological progress towards a sustainable industry has mainly been focused at two areas: artificial reef and cage technology, and feeding technology. Reasons for the success of the sea farming industry include the fact that coastlines are often well-suited for the growing of general water-fish species, and the well-developed coastal infrastructure. In addition to general research on biological matters, studies have produced large steps forward in terms of vaccine development, feed development, farm technology development, and farming strategy.

Harbor and Navigation. Harbors afford a place of safety for vessels in a protected water area where vessels may discharge or receive cargo. Harbor activities include approaches, anchorage, and the commercial aspects of quays, wharves, facilities for transfer of cargo, docks, and repair ships. Methods of navigation involving determining position, course, and distance traveled.

10. Ocean Modeling

Mathematical models of the ocean, and of the coupled ocean–atmosphere system have become essential components of ocean studies. In addition to their capacity of forecasting natural or human-induced evolution of the marine system, such models provide a convenient framework for organizing the results of theoretical studies and observational data. Data-assimilation, on the one hand, and process-model explorations of theoretical ideas, on the other, are clear examples of the cross-fertilization of mathematical modeling, theoretical investigations, and field observations.

The development of marine hydrodynamic models, before anything else, has been considerably stimulated by simultaneous advances in weather prediction and by their immediate application to coastal and offshore engineering. The prevailing idea was, more or less, that hydrodynamic models are "self-contained." Although transport and dispersion of non-living or living material in the sea are determinant factors of biogeochemical processes, the feedback of these processes on hydrodynamic phenomena is not significant (and, if needed, could easily be taken into account in some parametric form). Some socio-economic undertakings of course could have considerable effects but they were easy to transcribe in purely hydrodynamic terms, as for instance dredging simply changes the depth distribution.

It is understandable that the physics may have seemed more easily tractable. For instance, if one leaves aside boundary processes (surface waves, for instance), and the ever-present acoustic and electromagnetic waves, the ocean body has only three canals to propagate information and energy: one is associated with the stable stratification and is globally referred to as "internal waves" (because they appear in the core of the ocean column where stratification is not eroded by mixing); the other one is related to the Earth's rotation which, in axes fixed with the Earth, tends to return a particle to its point of departure in a circular trajectory; the last is an effect of the Earth's sphericity which generates wave motions of large horizontal space scales, the so-called Rossby waves, involving, in many cases, the whole water column.

For the sake of comparison, time scales associated with these waves can be set at 10^2 s for internal waves, 10^4 s for inertial motion, and 10^6 s for curvature-dominated Rossby waves.

The external forces on the ocean system may be, in first approximation, separated into a few well-understood signals: astrophysical forces generate (solar and lunar) tides of well-defined frequency crenels; solar thermal energy has well-known peaks of activity at diurnal and seasonal time-scales; air–sea (and sea–ice) interactions have more variable ranges of activity but each ocean region has learned to know the regime it is subjected to.

The question arises, then: "Why is modeling the physics of the ocean so complicated?" The answer lies in the fact that the problem is fundamentally *non-linear*. One can identify clear-cut forcing mechanisms and well-delimited channels through which waves can propagate energy and information and which are typical of the geofluid. However, the basic non-linearities of the equations describing the system will not allow this to proceed without an enormous dispersion of both energy and information. As a result of the non-linearity of the geohydrodynamic equations, physical processes of all scales can occur in the ocean and no model can address the whole spectrum simultaneously.

However, this spectrum is a succession of peaks and valleys, with the main peaks associated with external forces (energy inputs) or intrinsic mechanisms (eigenmodes of oscillations), and it is possible to distinguish cogent bands of length-scales and time-scales which contain most of the energy and information one needs to apprehend, understand, and possibly forecast the system's behavior.

At the first stage of constructing models for the exploration of sustainable development scenarios, one had perhaps a simple view of the physics (one needed to know the water velocity, temperature, and pressure), and a completely discouraging vision of the other disciplines (how many chemicals, living species of all sizes and specificities, not taking into account anthropogenic intruders, shall one have to include). This early appreciation was wrong. There is nothing like the velocity or the temperature of marine water. There is a whole distribution of these properties over time scales and length scales spanning as many orders of magnitude as one wishes to consider.

Everything that has been said for the hydrodynamics may be repeated for the other disciplines of ocean science. Marine ecosystems, down to bacteria (or viral) populations deeply involved in the most basic biogeochemical regenerating mechanisms, show a hierarchical organization resulting from the different rates of physiological, behavioral, and ecological processes in the multi-scale physical environment. Processes with similar time-scales constitute levels in the hierarchy. Phenomena, on a particular level, are to a large extent dissociated from lower level "fluctuations" or higher level "global trend," and may be relatively easily singled out of the total complexity of the ecosystem.

The word "fluctuations" emphasizes the fact that, given the range of time-scales and length-scales of the hierarchical level of the ecosystem which is being studied and of the hydrodynamic processes in which it is embedded, all physical and biological processes of smaller scales (undergoing multiple variations, bifurcations, reversals, etc.), have some of the attributes of a background "noise" largely canceling out in the mean. This small-scale background affects the model forecast through the residue of the non-linear interactions expressed in the model in theory-guided semi-empirical parametric formulations.

A completely realistic model would describe an infinite number of variables, but that model would be the real world itself. Computing facilities, of course, impose limitations on the number of variables but, independently of such restrictions, there are reliability and clarity constraints: a model with many variables incorporates as many different processes and interactions and involves a correspondently large number of parameters and boundary/initial conditions which cannot be evaluated from existing databases within an inevitable margin of error. On the other hand, the results of such a model can become impossible to interpret in terms of scientific diagnosis and management recommendations.

Trying to reduce the overall dimensions of a model, it is tempting—and this approach has prevailed for a long time—to separate the model into disciplinary sectors and to consider separately hydrodynamical, chemical, biological, and economic models.

Of these, the hydrodynamic models are for historical reasons by far the most advanced. In a sense, this is rather fortunate because the understanding of hydrodynamic processes is prerequisite to any form of chemical, biological, or economic modeling and, indeed, constitutes, in the present state of development of marine models, the most reliable contribution to the explanation and anticipation of ecological processes and to the management of marine resources.

This discipline-oriented approach, however, while naturally consistent with the early stages of model development, cannot be extended to models intended to conduct investigations into sustainable development scenarios. These require global vision and long-term perspectives. The wider and the longer one looks at the Earth system, the more one needs the understanding of all the disciplines of knowledge, and of their intricated interactions, to appraise all the consequences of environmental or human-induced activity.

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Biographical Sketches

Born in Changhwa, Taiwan, on 22 April 1949, **Prof. Chen-Tung Arthur Chen**, his wife and two daughters are currently residing in Kaohsiung, where he has been Professor at the Institute of Marine Geology and Chemistry since 1986. After receiving his B.Sc. degree in Chemical Engineering from National Taiwan University in 1970, Prof. Chen was awarded his Ph.D. degree in Chemical Oceanography from the University of Miami in 1977. In the same year, he was appointed Assistant Professor in the College of Marine Sciences of Oregon State University, where he was later promoted to Associate Professor in 1981. He served as visiting professor at National Sun Yat-Sen University (NSYSU) in Kaohsiung, Taiwan, and as Chargé de recherche (CNRS), Université Pierre et Marie Curie in Paris during 1984–1985. During this period, he founded the Institute of Marine Geology at NSYSU, and served as its director until 1989 when he was made Dean of the College of Marine Sciences, a position he held until 1992.

Prof. Chen has sat on numerous international committees, including the Scientific Committee on Oceanic Research and the World Ocean Circulation Experiment. He also served as one of the executives of the Scientific Steering Committee of the Joint Global Ocean Flux Study (JGOFS) between 1992–1995. Just prior to that, he had helped to form the Joint JGOFS/LOICZ Marginal Seas Task Team in 1991, and served as its chairman until 1995. Prof. Chen is at present one of the editors of *Oceanography Journal* and associate editor of *Marine Chemistry*. Besides having more than 150 of his own scientific papers published, Professor Chen was awarded the highly-coveted Biowako Prize for Ecology from Japan in 1997.

Born in Ans, Belgium, on 6 June 1937, **Prof. Jacques C. J. Nihoul** and his wife are currently residing in St. Severin, Belgium. His son, 34, an architect-engineer is in charge of the maintenance and renovation of the University of Louvain's Campus Infrastructure; his daughter, 28, a D.Phil. in Political and Social Science, is a Cabinet Adviser for European Affairs in the Belgian Government. He has been Professor of Geophysical Fluid Dynamics in the University of Liège and Louvain since 1965. After receiving his Engineering Degree from Liège University in 1960, Prof. Nihoul was awarded his M.Sc. Degree in Mathematics from MIT University (USA) in 1961 and his Ph.D. in Applied Mathematics and Theoretical Physics from the University of Cambridge (UK) in 1965. He served as an Air Force Officer during his National Service in 1964–1965 at the Royal Military College of Belgium and was elected to full Professorships in Liège and Louvain Universities in 1966.

Prof. Nihoul has sat on numerous international committees including SCOR, IAPSO, and GLOBEC. He is at present editor of the *Journal of Marine Systems*, *Earth Science Reviews*, Oceanography Section and one of the Editors of *Mathematical and Computer Modelling*. President of the National Committee of Oceanography of the Royal Academy of Belgium, Prof. Nihoul is a Member of the Russian Academy of Natural Sciences. Author of some 200 papers in international journals, he was awarded the Francqui Prize for Medical and Natural Sciences in 1978.