# OCEANOGRAPHY

**Jacques C. J. Nihoul**
*University of Liège, GHER, B5 Sart Tilman, B-4000 Liège, Belgium*

**Chen-Tung Arthur Chen**
*Institute of Marine Geology and Chemistry, National Sun Yat-sen University, Taiwan, R.O.C.*

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## Summary

The geographical and geodynamical importance of the ocean, in a global perspective of sustainable development, is emphasized. Historical, recent, and ongoing progress 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 timescales, 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 blue and white planet. The ocean gives the blue color and the clouds the white. 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.

*High-energy physics (almost perished)* was one of the hottest sciences in the twentieth 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.

*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.

*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.

*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 fifty 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.

*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 socio-economic 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 inter-disciplinary overviews, novel equipment and techniques of observational surveys, and worldwide co-operation.

In addition, human activities are fundamentally affecting marine ecosystems at the global scale via fisheries, aquaculture, introduction of non-native species, modification or destruction of critical habitats, and through the addition of nutrients and pollutants. The stress is particularly severe in coastal zones which occupy just 10 percent of the ocean surface, but on which 50 percent of the world's population depend, extracting resources and disposing of waste. 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, 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 intricate interactions of processes belonging to different disciplines: physics, biogeochemistry, ecology, economics, and sociology that have different levels of hierarchical organization and different (time and length) scales.

Perhaps the notion of *timescale* 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 timescale 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 timescales 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 inter-disciplinary 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, socio-economic, 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 timescale 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 forcing.

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

For instance, solar radiation is 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 forcings have well-defined frequencies and generate wave motions in a band of timescales 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 timescales 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 "*internal 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 $10^{-4}$ to $10^{-2}$ $s^{-1}$. One may thus associate with the vertical stable stratification an *eigenmode* of the marine system with timescales 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 timescales, 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-forcing 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 (very nearly) 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 timescales 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 timescales 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 forcings may seem to have similar functions, imposing the timescales of energy transfers from astronomical and atmospheric sources to the ocean (what better example of this hypothesis than the lunar tides?). 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 battlefield: 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 forcings 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 a means of first, separating a targeted set of processes belonging to a well-defined range of (time and length) scales, i.e. a "*spectral window*"; second, appraising

the long-term, long-range trend laid upon these processes by larger scale phenomena; and third, 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 timescales where, in terms of biogeochemical and ecological processes, "things are bound to happen." Similarly, socio-economic 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 socio-economic processes.

The non-linear interactions that one has identified between physical processes happen, in exactly the same way, between physical processes and biogeochemical/ecological/socio-economic processes and between the latter. Any inert or living particle in the sea is transported by currents of all timescales 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 socio-economic 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, and harvesting at all levels of the food chain up to the final exploitation of the ocean's (living and non-living) 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 timescales). 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/socio-economic processes tuned to the same scales of global forcings. 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.

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**Bibliography**

Bethoux, J. P.; Gentili, B.; Morin, P.; Nicolas, E.; Pierre, C.; Ruiz-Pino, D. 1999. The Mediterranean Sea: A Miniature Ocean for Climatic and Environmental Studies and a Key for the Climatic Functioning of the North Atlantic. *Progress in Oceanography*, No. 44, pp. 131–46. [The Mediterranean Sea provides a case study not only for dense water formation and climatic functioning at a basin scale, but also as a body of water evolving in response to the effects of environmental changes. Temperature and salinity changes have taken place since the 1960s in response to changes in heat and water budgets across the sea surface.]

Couper, A. 1983. *The Times Atlas of the Oceans,* New York, Van Nostrand Reinhold. 272 pp. [Ocean environment from life at the sea-bottom to the ocean–atmosphere system; sea use from naval warfare to merchant shipping; ocean resources from offshore oil to fish catches; ocean management from pollution control to transoceanic yacht races are briefly described.]

Denman, K. L. 1994. Scale-Determining Biological–Physical Interactions in Oceanic Food Webs. In: P. S. Giller; A. G. Hildrew; D. G. Raffaelli (eds.) *Aquatic Ecology: scale, Pattern and Processes,* San Diego, Academic Press. pp. 377–402.

Denman, K. L.; Gargett, A. E. 1983. Time and Space Scales of Vertical Mixing and Advections of Phytoplankton in the Upper Ocean. *Limnol. Oceanogr.*, Vol. 28, No. 5, pp. 801–15.

Denman, K. L.; Powell T. M. 1984. Effects of Physical Processes on Planktonic Ecosystems in the Coastal Ocean. *Oceanogr. Mar. Biol. Annu. Rev.*, No. 22, pp. 125–68.

Denman, K. L.; Freeland, H. J.; Mackas, D. L. 1989. Comparisons of Time Scales for Biomass Transfer up the Marine Food Web and Coastal Transport Processes. *Can. Spec. Publ. Fish. Aquat. Sci.*, No. 108, pp. 255–64.

Dickey, T. D. 1991. The Emergence of Concurrent High-Resolution Physical and Bio-Optical Measurements in the Upper Ocean and their Applications. *Review of Geophys.*, No**.** 29, pp. 383–413.

Globec. 1988. Global Ocean Ecosystems Dynamics. In: V. Cullen *Report of a Workshop Held at Wintergreen, Virginia, May 1988*, Joint Oceanographic Institutions, Washington, D.C. 131 pp.

Horne, J. K.; Schneider, D. C. 1994. Analysis of Scale-Dependent Processes with Dimensionless Ratios. *Oikos*, No. 70, pp. 201–11.

Intergovernmental Oceanographic Commission. 1984. *Ocean Science for the Year 2000,* Paris, UNESCO. 99 pp. [This is a report on an inquiry by the Scientific Committee on Oceanic Research and the Advisory Committee on Marine Resources Research for the Intergovernmental Oceanographic Commission and UNESCO.]

Jumars, P.; Hay, M. 1999. *Ocean Ecology: Understanding and Vision for Research*, Report of the OEUVRE Workshop, Keystone Colo., March 1–6 1998.

Monin, A. S.; Kamenkovich, V. M.; Kort, V. G. 1977. *Variability of the Oceans,* New York, Wiley. 24 pp.

Morgan, J. R.; Valencia, M. J. (eds.) 1983. *Atlas for Marine Policy in Southeast Asian Seas*, Berkeley, University of California Press. 144 pp. [Topics on the natural environment, scientific research, valuable and vulnerable resources, marine jurisdictions and boundaries, fisheries, shipping, oil, gas, and pollution are covered.]

National Geographic Society. 1995. *Atlas of the World*, 134 pp. [An atlas with 150,000 entries covering 191 nations. "The Oceans" is one of the chapters.]

National Research Council. 2000. *50 years of Ocean Discovery*. Washington, D.C., National Academy Press. 270 pp. [This is a monograph summarizing the major achievements on marine sciences funded by the US National Science Foundation.]

Nihoul, J. C. J. 1993. Applications of Mathematical Modeling to the Marine Environment. In: P. Zannetti, *Environmental Modeling*, Vol. 1, Ashurst, England, Computational Mechanics Publications. pp. 75–140.

Nihoul, J. C. J.; Djenidi, S. 1991. Hierarchy and Scales in Marine Ecohydrodynamics. *Earth Sci. Rev.*, No. 31, pp. 255–77.

Nihoul, J. C .J.; Adam, P.; Brasseur, P. 1994. Mathematical Visualization of the Northern Bering Sea's Summer Ecohydrodynamics. In: P. Brasseur; J. C. J. Nihoul, *Data Assimilation: Tools for Modeling the Ocean in a Global Change Perspective*, NATO ASI Series, No. 119, New York, Springer-Verlag. 239 pp.

Nihoul, J. C. J.; Djenidi, S.; Hecq, J. H. 1989. Modeling of Coastal/Shelf Systems with Emphasis on Long Term Trends. *Int. J. Numerical Methods Eng.*, No. 27, pp. 113–27.

O'Neill, R. V. 1989. Perspectives in hierarchy and scales. In: J. Roughgarden; R. M. May; S. A. Levin, *Perspectives in Ecological Theory*, pp. 140–56. Princeton, New Jersey, Princeton University Press.

Rui Xin Huang, 1999. The Future of Physical Oceanography: a Personal View. In: Th. Roger; W. Young, *The Future of Physical Oceanography*, pp. 115–23. Report of the APROPOS Workshop, Monterey, California, December 15–17, 1997.

Steele, J. H. 1985. A Comparison of Terrestrial and Marine Ecological Systems. *Nature*, No. 313, pp. 355–8.

United Nations Convention on the Law of the Sea 1982. [This is the official text of the United Nations Convention on the Law of the Sea with annexes and index. The Convention represents not only the codification of customary norms, but also, and more significantly, the progressive development of international law establishing a comprehensive framework for the regulation of all oceanic space. It is divided into seventeen parts and nine annexes, and contains provisions governing, inter alia, the limits of national and preservation of the marine environment, exploitation of living resources and conservation, scientific research, sea-bed mining and other exploitation of non-living resources, and the settlement of disputes. In addition, it establishes new international bodies to carry out functions for the realization of specific objectives.]

**Biographical Sketches**

Born in Changhwa, Taiwan, on April 22 1949, **Professor 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, Professor 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 1984–5. 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.Professor 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 and 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. Professor 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 June 6 1937, **Professor Jacques C. J. Nihoul** and his wife are currently residing in St. Severin, Belgium. His son, 36, an architect-engineer is in charge of the maintenance and renovation of the University of Louvain's Campus Infrastructure; his daughter, 30, a D.Phil. in Political and Social Science, works at the European Commission (Directorate of Education, AudioVisual, Culture

and Sports). 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 1964–5 at the Royal Military College of Belgium and was elected to full Professorships in Liège and Louvain Universities in 1966.Professor 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, Professor Nihoul is a Member of the Academia Europaea and 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.