NESTED INTERDISCIPLINARY THREE-DIMENSIONAL MODELS OF THE MARINE SYSTEM

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Summary

The construction of interdisciplinary three-dimensional models of the marine system is discussed emphasizing (i) the natural variability of the ocean where physical and biogeochemical processes of all time and length scales cohabit and interact, (ii) the existence of spectral windows corresponding to scales of external forcings, eigenmodes of oscillations and information channels and to hierarchical levels of ecological and biochemical organization, (iii) the necessity of developing an assemblage of nested models, each of which is focused on a definite spectral window and takes advantage of larger scale models to determine the initial and boundary conditions set by the long term trend and reach and of smaller scale models to parameterize the non-linear residual effect of the sub-window scale fluctuations. Operant state variables are defined by their nature but also by their length scale, time scale and hierarchical position in the biogeochemical/ecological web. Appropriate evolution equations are established and the formulation of flows, fluxes and local production/destruction rates are discussed. The perspective of applying 3D nested interdisciplinary models for the evaluation of sustainable development scenarios is stressed and their present and essential role in focusing sets of fuzzy data and clearing the data base which will be needed for model forecasts is emphasized.

1. Introduction

All Sustainable Development programs emphasize the need of the acquisition of more data and the constitution of better equipped and more convivial data bases, of a more thorough understanding of the confronting environmental and socio-economical problems and of *the necessity of disposing of management policy tools in the form of interdisciplinary mathematical models* able to simulate the system's behavior for different scenarios of global and regional environmental changes, socio-economic constraints or political decisions.

No-one disputes the fact that a well-validated three-dimensional model of the Ocean's hydrodynamics and ecodynamics, including both the pelagic and benthic food-webs, biogeochemical interactions and atmospheric and coastal in- and outputs (with a special attention to anthropogenic disturbances) would constitute the ideal tool for sustainable development policy assessments. The model could be run for different scenarios of environmental protection or socio-economic development policies and model forecasts would provide valuable bases for decision-making and policy planning.

One may argue that a reliable model of this size, however, can only be a long term goal. However one must keep it in view to define and organize our present efforts towards sustainable management of the Sea.

The International *Globec* Program has identified two main characteristics as desirable attributes of the model to be progressively constructed and of the efforts directed to achieve this aim.

1. *The model must be a nested model.*

   Physical processes of all scales can occur in the sea. Certain well-defined domains of length- and time-scales however dominate the dynamics of the marine system. These « *spectral windows* » correspond to the scales of external forcings (energy inputs) or of intrinsic mechanisms (eigenmodes ...). Similarly, marine ecosystems show a hierarchical organization resulting from the different rates of ecological processes confronted to the multi-scale physical environment. Processes with similar time-scales constitute distinct *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 « ultimate goal » model needed to simulate different scenarios of sustainable development will not be able to represent - in a single modeling edifice - all scales of motions and all hierarchical levels from microturbulence to synoptic eddies and climatic anomalies, from individual organisms to populations and their seasonal or year-to-year variations. The model to be developed for interdisciplinary research and sustainable development scenarios will inevitably be an **assemblage** of **nested models**.

   Models can be nested: i) spatially, ii) temporally, and iii) trophically.
   Spatial nesting includes embedding of finer-scale regional models in coarser-scale basin-wide or global models. This embedding allows the large-scale phenomena to impact the regional physics. Temporal nesting includes using time-averaged quantities from a short time-scale model in a long time-scale model. More generally, one may use the results of a short time-scale model to aid parameterization of those

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processes which cannot be modeled explicitly in the long time-scale model. This is akin to using fine grid circulation models to aid the development of better subgrid-scale mixing parameterizations in coarse grid circulation models.
Trophic nesting refers to the use of detailed (e.g. multispecies, physiological, behavioral …) models within any particular trophic level of a highly aggregated multi-trophic-level model.

2. *The model must have a strong reliable hydrodynamic component.*

   Hydrodynamic/physical processes control, to a large extent, the transport, diffusion and accumulation/removal of dissolved and suspended constituents. Moreover, the persistent hydrodynamic constraints exerted by physical processes on the lower trophic levels, unprovided with strong competitive means of intrinsic motions, tend to impress on biological populations much of the spatial organization of the *resonant* physical processes, i.e. the physical processes having characteristic time-scales of the same order of magnitude as one or the other hierarchical level of the ecosystem.

   A good understanding of the current, temperature, salinity and sediments fields and of their seasonal variability is prerequisite to the understanding and modeling of such important phenomena as coastal eutrophication, transports in the sea and translocation through the food chain of pollutants, stresses on biological communities and changes in species' diversity and habitats.

2. Operant State Variables and Evolution Equations of a 3D Interdisciplinary Ocean Model

If one leaves aside boundary processes (surface waves, for instance), and the overpresent 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 rotation which, in axes fixed with the Earth, tends to return a particle to its point of departure in a circular trajectory ; the last one is an effect of the earth's sphericity which generates wave motions of large horizontal scales, the so-called Rossby waves, involving, in many cases, the whole water column. Time scales associated with these waves can be, for the sake of comparison set at 10^2 s for internal waves, 10^4 s for inertial motion, 10^6 s for curvature-dominated Rossby waves.

The external forcings on the ocean system may be, in first approximation, separated into a few well understood signals: astrophysical forcings 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.

However, even if one can define clear-cut forcing mechanisms and well-delimited channels through which waves can propagate energy and information and which are

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typical of the geofluid, the **basic non-linearities** of the equations describing the system generate an enormous dispersion of both energy and information over a vastness of harmonics or sub-harmonics and, as a result, physical processes of all scales can occur in the ocean and no model can address the whole spectrum simultaneously. Still, this spectrum is a succession of peaks and valleys with the main peaks associated with external forcings (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. These spectral domains are called "*spectral windows*".

Marine ecosystems, down to bacteria (or viral) populations deeply involved in the most basic geochemical regenerating mechanisms, show a hierarchical organization resulting form the different rates of physiological, behavioral, ecological, … processes confronted to 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 spectral window of auscultation (i.e. 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 … over any characteristic time of the spectral window, have some of the attributes of a background "noise" largely canceling out in the mean and affecting the processes at window-scale through the residue of non-linear interactions.

At the first stage of constructing models for explorations of sustainable developments' scenarios, one had perhaps a simple view of the physics (one needs to know the water velocity, temperature, pressure and that's it) 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 ?) but this early appreciation was wrong. There is nothing like the velocity or the temperature of the 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.

But there are spectral windows where the most important processes occur and the same is true for biogeochemical/ecological and socio-economic processes. These spectral window might not fall in the same range of scales for the different disciplines but the Ocean is a strongly non-linear system which does not only couple physical mechanisms of different scales but also physical, biological, chemical processes in such a way that the whole system becomes only viable if it cooperates within a limited number of spectral windows where a truly *resonant* inter-fertilization is made possible.

Developing models for long-term sustainable development assessments, one cannot define the variables only by their *nature* (velocity, temperature, biomass, …) but one must also specify them by their time scales and length scales and by the level they

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occupy in the natural hierarchy of life. The new variables, anchored in scales and hierarchical levels, are the *operant* variables of the model. One can see that this leads to different types of models, differing by their subjects and objectives but also by their spectral windows and capable of answering different management interrogations.

The *operant* state variables (denoted in the following by the generic letter y) are thus *mean values* representative of a specific spectral window. One emphasizes that the choice of a spectral window is one defining feature of a model and, obviously, all the state variables of the model must correspond to the same spectral window, i.e. are similarly defined averages.

One is thus lead to make a distinction between the *flow* of y defined as the *transport* of y by the mean velocity **v** (as defined above) and the *flux* of y defined as the *diffusion* by the multiple and diversified displacements at scales not resolved by the model and viewed, on that account, as disordered fluctuations.

The equations describing the evolution in space and time of the state variables are then all particular expressions of a unique basic equations. This equations sets forth that the variation in time of any state variable (momentum, biomass, energy …), at any given point, is the result of (i) local production or destruction, (ii) transport by the fluid (flow), (iii) diffusion by sub-window scale processes (flux), i.e.

$$\frac{\partial y}{\partial t} = Q^{y} - \nabla \cdot \left(\varphi_0^{y} + \varphi_u^{y} \right) \qquad (1)$$

where Q^y is the rate of production (destruction), φ_0^y is the flow, φ_u^y is the flux and ∇ is the vector-operator

$$\nabla = \mathrm{e}_1 \frac{\partial}{\partial x_1} + \mathrm{e}_2 \frac{\partial}{\partial x_2} + \mathrm{e}_3 \frac{\partial}{\partial x_3} = \hat{\nabla} + \mathrm{e} \frac{\partial}{\partial x_3} \qquad (2)$$

$\mathbf{e}_1$,$\mathbf{e}_2$,$\mathbf{e}_3$ denoting respectively the unit vectors along the axes of coordinates ($\mathbf{e}_3$ pointing vertically upwards), $\hat{\nabla}$ being the horizontal part of ∇.

3. The Hydrodynamic Component

In the sea, the density ρ never varies much from a constant reference value ρ_0 and one can, with a very good approximation, replace ρ by ρ_0 everywhere except in the gravity force where small variations of ρ are multiplied by the acceleration of gravity which is considerably larger than typical fluid accelerations (the so-called "Boussinesq approximation").

In the scope of the Boussinesq approximation, the sea may be treated as an incompressible fluid ($\rho=\rho_0$, $\nabla \cdot \mathbf{v} = 0$, y can be defined indifferently per unit mass or per unit volume) submitted to an additional force, called "buoyancy", i.e. (per unit mass)

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$$\mathrm{b} = b\mathrm{e}_3 = -g\,\frac{\rho - \rho_0}{\rho_0}\,\mathrm{e}_3 \tag{3}$$

where g is the acceleration of gravity. $\nabla\cdot\mathbf{v}$ is the divergence of the velocity vector, i.e.

$$\nabla\cdot\mathrm{v} = \frac{\partial v_1}{\partial x_1} + \frac{\partial v_2}{\partial x_2} + \frac{\partial v_3}{\partial x_3} \tag{4}$$

The bulk of the gravity force $\rho\mathbf{g}$ is hydrostatically balanced by a vertical pressure gradient. This is taken into account by introducing a "reduced" pressure (per unit mass)

$$q = \frac{p}{\rho_0} + \mathbf{g}x_3 + \omega \tag{5}$$

where the hydrostatic pressure of a fluid of constant density ρ_0 has been substracted from the acting pressure and where ω denotes the potential of astronomical forces (responsible for lunar and solar tides).

If y, in equation (1), is the velocity vector $\mathbf{v}$, (i.e. the momentum per unit mass), by virtue of Newton's law, Q^y is the total force $\mathbf{F}$ (per unit mass). This force includes the pressure gradient, gravity, astronomical forces and the *fictitious* force of Coriolis which is nothing but a correction one must make to the law of Newton when the axes of reference are in motion (in this case, rotating with the Earth). In the scope of the Boussinesq approximation, taking into account eqs (3) and (4), one may write

$$\mathrm{F} = -\nabla q + b\mathrm{e}_3 - 2\Omega\wedge\mathrm{v} \tag{6}$$

where Ω is the Earth's rotation vector. The essential contribution of the Coriolis force, $-2\Omega\wedge\mathbf{v}$, is at most latitudes, due to the vertical component of Ω i.e. $f = 2\Omega_3$ and

$$2\Omega\wedge\mathrm{v} \sim f\mathrm{e}_3\wedge\mathrm{v} \tag{7}$$

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* The text of this article has been adapted from the references indicated by * and follows closely the rational of those publications. Sections of general character have been used in the Topic Overview.

Biographical Sketch

Jacques C.J. Nihoul Born in Ans, Belgium, on June 6, 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). 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 and of the Academia Europaea. Author of some 200 papers in international journals, he was awarded the Francqui Prize for Medical and Natural Sciences in 1978.

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