11. Numerical modelling of the ocean

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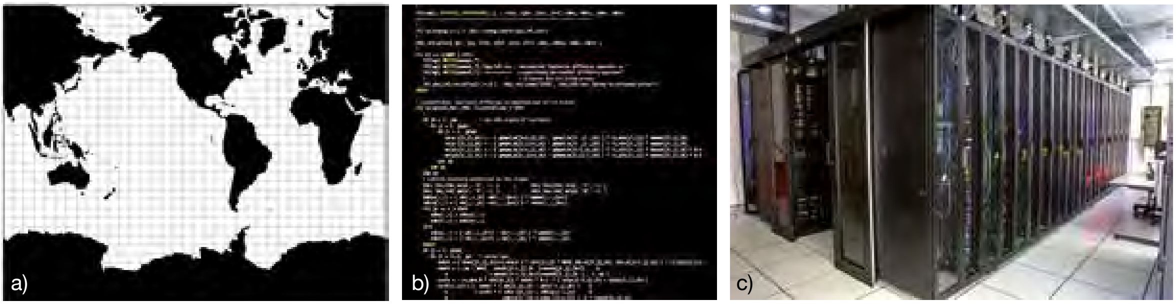
The numerical modelling of the ocean involves simulating observable characteristics of the ocean based on physical, biological and chemical hypotheses about the relationships between these variables. These characteristics can describe water masses and their movements (temperature, salinity, marine currents...), sea ice (expansion, thickness, age...) or the ocean's biogeochemical properties (quantity of dissolved organic and inorganic carbon, pH...). The observa-tions of these characteristics (by satellite, cf. III.3, or by *in situ* measurement, cf. III.2) are indispensable for producing, validating and interpreting the simulations generated by modelling. In return, these simulations are useful for recon-structing the spatio-temporal context of spot observations, and for analysing the role of the different processes at play. Furthermore, because of the ocean's key role in the climate system (cf. I.3), numerical modelling of the ocean is an essential element for reconstructing the past climate, understanding the current climate, and predicting the future climate.

The history of numerical modelling

In the early days of oceanography, geophysical fluid physicists tried to theorize the characteristics and movements of water masses, based on the fundamental principles of mechanics and thermodynamics. These attempts, conducted from the early 20th century, in parallel with the improvement and multiplication of oceanic observations, focused on estab-lishing and then solving the fundamental equations of physical oceanography. The analytical resolution of these equa-tions (by hand) was therefore consistent with the very limited number of observations of the ocean. However, the growing number of observations and the failures of theory to reproduce these observations have revealed the importance of complex phenomena (non-linear processes, factoring in the relief of the seabed, deep stratification), which make the system of equations too complex to solve on paper. Moreover, solving these equations numerically provided a response to the emerging interest in future climate projection. This is how numerical modelling of the ocean began, around the end of the 1970s.



a) Horizontal grid of the NEMO eORCA1 configuration (global ocean at a 1°×1° resolution). Each grey square contains 100 cells of the model. **b) Example of Fortran 90 code from the NEMO model. c) ESPRI IPSL mesocentre at the École Polytechnique.** © École Polytechnique / J. BARANDE. ■

Marine biogeochemistry is very closely connected to ocean dynamics. The development of the first numerical models of the ocean allowed the emergence of numerical modelling of the oceanic carbon cycle in the late 1980s. Before, there were only theoretical models of phytoplankton and of phytoplankton-zooplankton interactions.

In the 1990s, about ten global oceanic models were developed. Using these, it was possible to simulate the general circu-lation of the oceans and, for some of them, the oceanic carbon cycle. These models were distributed freely within user communities, which allowed their usage to spread, and made inter-comparison exercises between these different models possible. Then, in the 2000s, a fully integrated vision of the climate system emerged. This led to the appearance of the first models of the Earth system, of which the 'blue-white-green' ocean (dynamics, sea ice and marine biogeochemistry) is a major component. Currently, these models are used for future climate projection exercises, which provide information for IPCC reports.

Principles of modelling

There are three major stages in the construction of oceanic models. Firstly, it is necessary to define the system to be represented. This could be the global ocean, a region, or a specific structure such as an eddy. During this stage, the theoretical (mathematical) formalism is chosen. For ocean dynamics, the researchers use equations from geophysical fluid dynamics. For marine biogeochemistry, the modelling is based on physical equations for describing transport of chemical species and plankton, and on empirical formulations for representing biological processes. The second stage is the spatial and temporal discretization of the selected equation systems. For this, a grid of the represented domain must be defined. Decisions must be made on aspects like the spatial resolution and the cell geometry. Processes that are impossi-ble to represent explicitly, either because they are characterized by a spatial and temporal scale which is finer than the chosen resolution, or because they are too complex to describe precisely, must be parameterized often using empirical relationships. Finally, the boundary conditions must be prescribed, including, for example, the oceanic conditions at the boundaries of the domain and the interactions with the atmosphere. The third and final stage is the translation of the model into computer code, and its execution on computers. During this stage, questions regarding performance, repro-ducibility and results archiving are posed. Since oceanic models are often very expensive in terms of computer calcula-tion, the simulations are primarily done on massively parallel supercalculators with thousands of processors, located in dedicated regional or national calculation centres (Fig.).

Taking into account all the possible choices at each stage in the creation of an oceanic model, in theory, the number of possible models is infinite. In practice, the international oceanographic community pools its development efforts. Cur-rently, around twenty models of ocean dynamics, sea ice, and/or marine biogeochemistry are used. These models are developed by researchers and engineers, to meet the needs of one or more applications: academic research on oceanic processes, climate projections or operational oceanography (cf. III.12). When comparing the simulations produced by these models to corresponding observations of the ocean, it is necessary to take into account the uncertainty about both the observations and the models. Although the models are primarily based on deterministic equations, the simulated variables contain a significant portion of random signals. The finer the spatial resolution of the grid, the greater this portion. The random component of the simulations can be evaluated and eliminated by the production of an ensemble of simulations, very close to each other, similar to the sets of predictions used for meteorological forecasting. However, this requires massive computer calculation resources.

In conclusion, there is no universal model of the blue-white-green ocean which meets all the needs of scientific and non-scientific users. The numerical modelling of the ocean is an oceanographic discipline which interacts strongly with many other scientific disciplines, including observational oceanography, marine biology, applied mathematics and computing.

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