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Multi-scale modeling: nested-grid and unstructured-mesh approaches

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In 1969, the *Journal of Computational Physics* published a seminal article by K. Bryan presenting the first ocean general circulation model. Since then, many numerical studies of the World Ocean, as well as regional or coastal flows, used models directly or indirectly inspired by the work of Bryan and his colleagues. A number of these models have evolved into highly modular and versatile computational systems, including multiple physical modules and options as well as varied biogeochemical, ecosystem and acoustics modeling capabilities. Several modeling systems are now well-documented tools, which are widely used in research institutions and various organizations around the world. The list of such modeling systems is large and too long to be summarized in this editorial.

Over the last three decades, significant progress has been made in the parameterization of subgrid-scale processes, in data assimilation methodologies and in boundary condition schemes, as well as in the efficient implementation of algorithms on fast vector and subsequently parallel computers, allowing higher and higher resolution in space and time. However, many of today's popular modeling systems can still be regarded as members of the first generation of ocean models: at their core, rather similar geophysical fluid dynamics equations are solved numerically using a conservative finite-difference method on a structured grid.

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Today, several aspects of structured-grid models could benefit from significant upgrades, learning from major advances in computational fluid dynamics. In particular, the use of a structured grid limits the flexibility in the spatial resolution and does not allow one to take full advantage of numerical algorithms such as finite volumes and finite elements, which can achieve their best performance when implemented on unstructured meshes.

Even though many of today's complex marine modeling and data assimilation systems have evolved significantly since Bryan's prototype, it would be challenging to modify them step-by-step from a structured-grid approach to an unstructured-grid one. Therefore, novel marine model design research is underway, paving the way for the second generation of ocean modeling systems. It is difficult to predict today if this new generation of ocean models will achieve its chief objective: widening the range of resolved scales of motion with increased efficiencies and accuracies, possibly allowing multi-resolution, multi-scale, and multi-dynamics numerical simulations of marine flows, all occurring seamlessly within distributed computing environments. In fact, hybrid approaches merging the advantages of structured and unstructured-grid modeling may be the way forward.

Whether or not unstructured mesh approaches will prevail is all the more difficult to predict now that structured mesh modelers have developed powerful solutions for increasing the resolution when and where needed. For instance, grid embedding is still a popular and useful method for enhancing model resolution. It can involve multiply nested domains and allows the relatively straightforward use of different dynamics or models in each domain. Research is also underway for developing multi-grid, wavelet, and other multi-scale decompositions for the numerical solution of dynamical equations but also for the study of results, model evaluation or data assimilation.

This special issue presents a number of examples of the abovementioned developments. Ringler et al. examine the potential of spherical centroidal Voronoi tessellations for performing multi-resolution simulations; they apply this method to the Greenland ice sheet and the North Atlantic Ocean. Lambrechts et al. present a triangular mesh generation system and its applications to the World Ocean and various shelf seas, including the Great Barrier Reef, Australia. Finite element models on unstructured grids are described and utilized in several manuscripts. Bellafiore et al. study the Adriatic Sea and the Lagoon of Venice, while Jones and Davies simulate tides and storm surges along the western coast of Britain. Danilov et al. assess two finite element discretizations, i.e., a continuous element and a non-conforming one, and compare the results of these discretizations with those of a finite-difference model. In Harig et al., the tsunami generated by the great Sumatra–Andaman earthquake of 26 December 2004 is simulated by means of a finite element model. Comparisons are carried out with various types of data as well as with the results of a structured mesh model using a nested structured-grid system. A nested-grid ocean circulation model is also employed by Yang and Sheng to carry out a process study on the Inner Scotian Shelf, Canada, focusing on the circulation induced by a tropical storm. Debreu and Blayo present a detailed review of two-way embedding algorithms for structured-grid models. Finally, Logutov develops a multi-scale assimilation scheme for tidal data within the framework of a multiply nested structured-grid barotropic tidal modeling approach.

As illustrated by these manuscripts, the next generation of ocean modelers is motivated by a wide range of research opportunities over a rich spectrum of needs. Future progress will involve fundamental and applied numerical and computational research as well as new multi-scale geophysical fluid modeling. Domains of ongoing interest range from estuaries to the global ocean, including coastal regions and shelf seas. New multi-scale modeling of physical as well as biological, chemical or interdisciplinary processes will flourish in the coming decades.

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