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Evaluation of SIFOM-FVCOM system for high-fidelity simulation of small-scale coastal ocean flows*

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Abstract: This paper evaluates the SIFOM-FVCOM system recently developed by the authors to simulate multiphysics coastal ocean flow phenomena, especially those at small scales. First, its formulation for buoyancy is examined with regard to solution accuracy and computational efficiency. Then, the system is used to track particles in circulations in the Jamaica Bay, demonstrating that large-scale patterns of trajectories of fluid particles are sensitive to small-scales flows from which they are released. Finally, a simulation is presented to illustrate the SIFOM-FVCOM system's capability, which is beyond the reach of other existing models, to directly and simultaneously model large-scale storm surges as well as small-scale flow structures around bridge piers within the Hudson River during the Hurricane Sandy.

Key words: coastal ocean flow, multiscale, multiphysics, hybrid method, domain decomposition, SIFOM-FVCOM system

Introduction

In the past few decades, a number of geophysical fluid dynamics (GFD) models have been developed for large-scale coastal ocean flows. For example, circulation models, such as the Princeton Ocean Model (POM)[1], the Finite Volume Coastal Ocean Model (FVCOM)[2], the Hybrid Coordinate Ocean Model (HYCOM)[3], the Regional Ocean Modeling System (ROMS)[4], the Advanced Circulation Model (ADCIRC)[5], and Geophysical Conservation Law (GeoClaw)[6], were designed to predict ocean currents for periods as long as months and over regions with horizontal sizes roughly $O(10)\ \mathrm{km}$ - $O(10\,000)\ \mathrm{km}$. Other large-scale models have targeted specific coastal processes, such as the Simulating WAves Nearshore (SWAN) model for surface waves[7]. These models have been greatly successful but strictly speaking, until now, are limited to currents and waves at large scales, although occasionally numerical simulations provide limited dynamics at scales as small as $O(100)\ \mathrm{m}$. In addition, these models, including their non-hydrostatic versions, were designed to deal with singly-connected domains, and thus they cannot handle at all multiply-connected domains such as a hole in a seamount at bottom of an ocean. At the same time, numerous fully 3D fluid dynamics (F3DFD) approaches have been developed, and they can satisfactorily predict many fully 3D, small-scale flows in hydraulic, mechanical, chemical, and aerospace engineering with high-fidelity. In recent years, F3DFD models have been extended to flows of larger scales ($O(1)\ \mathrm{m}$ - $O(10)\ \mathrm{km}$), with local mesh resolution as small as $O(0.01)\ \mathrm{m}$ [8,9]. In principle, these small-scale approaches, including direct numerical simulation (DNS), do not have the aforementioned limitations of large-scale GFD models. However, the F3DFD models are prohibitively expensive with regard to computational time and storage and also ineffective in view of their governing equations and computational techniques[10]. It should be pointed out that, generally speaking, these small-scale F3DFD models and those large-scale GFD models are based on different governing equations, numerical

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techniques, turbulence closure, and parameterization.

Now it is becoming more and more important to develop our capabilities to simulate multiphysics phenomena, especially those at small scales, and efforts with this regard have been made using GFD approaches. For instance, nested grids in ROMS have been proposed to capture small-scale, local flows[11,12]. In order to take non-hydrostatic effects into account, it was proposed to nest SUNTANS and GCCOM into ROMS[13,14]. A few more similar attempts can be found in Refs.[15,16]. However, until now, in general, these hybrid systems are primarily implemented via simple methods such as straightforward interpolation, one-way coupling (e.g., solution of a model is transferred as boundary condition into another but not vice visa) or weakly two-way coupling, and nested structured grids.

In order to advance our modeling capabilities to directly simulate in high-fidelity many emerging multiscale and multiphysics coastal ocean flow problems, especially those at small scales, such as initial mixing in oil spill of the 2010 Gulf of Mexico and hydrodynamic impact of storm surges on coastal bridges during the 2005 Hurricane Katrina, since 2010, the authors and co-workers have developed a modeling system that is hybrid of the Solver for Incompressible Flow on Overset Meshes (SIFOM) and the Finite Volume Coastal Ocean Model (FVCOM)[17-20]. SIFOM is a F3DFD model designed for fully 3D, small-scale flows[21-23], while FVCOM is a GFD model made for large-scale ocean currents[24,25]. In the SIFOM-FVOCM system, SIFOM is applied to small-scale, local flows that FVCOM cannot handle, such as a flow passing a hole in a seamount, and FVCOM is employed for large-scale background tidal currents, which cannot be dealt with by SIFOM due to its limitations. The two models are strongly coupled in two-way as a single modeling system, and they march in time simultaneously. The SIFOM-FVCOM system is the first of its kind, and it can model various coastal ocean flows involving multiple physical phenomena at distinct scales that are beyond the reach of any other existing models. Indeed, development of such hybrid system is challenging in view it involves heterogeneous domain decomposition (DD) that couples different partial differential equations (including those for turbulence closure), computational grids, and numerical methods, and such heterogeneous DD for coastal ocean flows is essentially an untapped area with regard to rigorous theories, methods, and algorithms. For details of the SIFOM-FVCOM system, the reader is referred to [19].

This paper makes an evaluation of the SIFOM-FVCOM system. First, it justifies a method in the system to treat buoyancy from aspects of computational accuracy and efficiency. Second, particle tracking is implemented into the system, and it is applied to circulations in the Jamaica Bay. Third, the software package of the system is modified for SIFOM to simulate local flows at multiple sites, and it is employed to model storm surges during the Hurricane Sandy. All of these will clearly demonstrate capabilities and potentials of the proposed SIFOM-FVCOM system to simulate a variety of emerging flow problems in coastal and oceanic waters that cannot be handled by other exiting models.

1. Outline of SIFOM-FVCOM system

In the SIFOM-FVCOM system, SIFOM is used to resolve small-scale, local flow phenomena, and FVCOM is applied to capture large-scale background flows. The computational domains of SIFOM and FVCOM overlap with each other, as shown in Fig.1. Since 20 years ago, SIFOM started to merge as a solver for the fully 3D, Navier-Stokes equations in conjunction with another few equations for turbulence closure[21-23]. Its governing equations are discretized on curvilinear coordinates and non-staggered, structured grids using a second-order accurate finite difference method. The resulting algebraic system is solved by an artificial compressible method enhanced with a local-time-stepping, V-cycle multigrid method to accelerate convergence. In order to deal with complicated geometry, a domain decomposition approach is implemented with Chimera grids and the Schwarz iteration. SIFOM has been intensively tested and successfully applied in many problems with various backgrounds, e.g., chaotic behavior of vortex, coherent structure dynamics, flow around artificial heart, thermal effluent flow, and flow past bridge piers, and a brief history of the model is presented in Ref.[19].

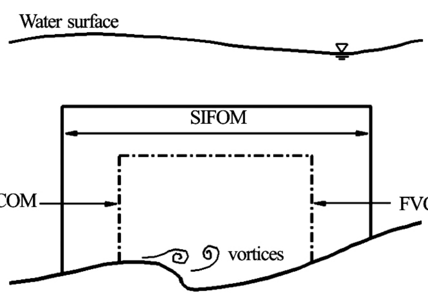

Fig.1 Computational subdomains of the SIFOM-FVCOM system[19]

In FVCOM, a finite volume method is adopted on a triangular mesh in the horizontal plane and a σ-grid in the vertical direction. The model has an external mode and an internal mode, their convection terms are approximated using upwind schemes, and the time derivative terms are discretized by Runge-Kutta methods. The external and internal mode may use different time steps. In FVCOM, pressure is not in presence, but it can be recovered by the hydrostatic assumption.

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