LONG-TERM GOALS

The long-term goal of the project is to develop and enhance the research and educational capabilities in the area of coastal engineering and science at Louisiana State University (LSU) while simultaneously supporting the Navy’s research goals in the areas of Coastal Geosciences. The focus of the present study is to develop a new modeling framework for simulations of coastal processes in deltaic environments using advanced numerical methods and high performance computing technology.

OBJECTIVES

The specific objectives of this project are to:

- Develop the capability of modeling coastal circulation and nearshore surface waves in deltaic sedimentary and hydrodynamic environments in an integrated modeling framework by extending the Boussinesq theory for nearshore hydrodynamics to muddy coasts and non-hydrostatic three-dimensional (3D) flow regimes with stratifications.

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1 Dynamics of Potential Vorticity in the Swash and Surf Zones, PI: Q. Jim Chen
• Complement the Office of Naval Research recent research initiatives on Tidal Flats and Wave-Mud Interactions by integrating the new modeling system with the field data collected in those programs.

• Simulate large-scale, long-term problems in the deltaic environment by integrating the application-oriented modeling system with massive-processor computing facilities and technologies available at LSU and in Louisiana.

• Quantify the generation, transport and dissipation of potential vorticity in the surf and swash zones, as well as the momentum exchange between the two dynamical regions.

**APPROACH**

The three-year research project consists of theoretical formulation and analysis, development and verification of an advanced modeling system using the spectral-element methods and high-performance computing technologies, and the utilization of the new model as a research tool to advance knowledge and understanding of coastal circulation and nearshore waves in deltaic sedimentary and hydrodynamic environments. Relevant methodologies in three disciplines: civil engineering, physical oceanography and computational science, will be utilized. Interdisciplinary interactions are taking place among the PIs in different fields and through recruiting a post-doctoral researcher and graduate students from the three disciplines.

A new approach is taken to meet the objectives of this project: 1) Use the Boussinesq theory to improve the efficiency of non-hydrostatic 3D Navier-Stokes equation solvers as well as to extend the applicability of the modeling system to deltaic environments, and 2) utilize spectral-element methods with unstructured grids to solve the partial differential equations (PDE) under realistic deltaic conditions on high-performance, massive-processor computers available at LSU.

The theoretical derivation will follow closely the approach of Dalrymple and Liu (1978) for the treatment of soft mud, and the procedure of Chen et al. (2003) and Chen (2006) for the treatment of surface waves. We will establish a system of Boussinesq-type models capable of simulating nearshore surface waves and surf-zone currents in heterogeneous sedimentary environments ranging from permeable sandy beaches to soft mud bottoms. The fully nonlinear Boussinesq-type equations for waves and currents will be solved numerically.

The Boussinesq approach is not just limited to the modeling of nonlinear surface waves and breaking-generated currents over porous or muddy seabed. An efficient hydrodynamic model for density-stratified flow with a free-surface in the weakly non-hydrostatic regime has been developed by Shen (2001) and Shen and Evans (2004). This formulation allows for applying the weakly non-hydrostatic approximation, similar to the Boussinesq approach to nonlinear surface gravity waves, to strongly nonlinear internal waves in the coastal ocean where the horizontal scale of the density-stratified wave/current motion exceeds the local water depth. The approximation eliminates the vertical dimension of the elliptic equation that is normally required for the fully non-hydrostatic modeling, and as a result the model’s computation efficiency is greatly increased by a factor proportional to the number of grid points used for vertical resolution. Using the methodology of Shen (2001), we shall incorporate the horizontal vorticity components into the Boussinesq-type equations for waves and
currents over muddy bottoms. This will allow for the simulation of waves on shear currents or coastal circulation with stratification.

Instead of using finite-difference methods to solve the new set of model equations, the research team will utilize spectral-element methods for numerical solution (Canuto et al., 1987, and Deville et al., 2002). One of the challenges of solving Boussinesq-type equations using finite-difference methods is the elimination of the truncation errors that are mathematically similar to the dispersive terms in the equations. Higher-order numerical methods, such as the spectral-element method, completely eliminate such problems (Eskilsson and Sherwin, 2004; Eskilsson et al., 2006). The new modeling framework will solve the four sets of fully nonlinear Boussinesq-type equations for coastal waves and currents for solid beds, porous seabed, muddy bottoms and strong stratifications using the same numerical schemes, same data structures, same parallelization strategies, and same input and output formats for coupling with coastal sediment transport models.

Boussinesq models for wave-driven currents are computationally demanding. Taking seabed conditions into account by the new Boussinesq model will increase the computational effort by a factor of two. It is therefore desired to speed up Boussinesq models for practical applications, in particular for morphological and ecological simulations. The solution to the growing demand of computing power by Boussinesq coastal models is the use of high-performance computing (HPC) technologies. The Co-PIs, Drs. Gabriel Allen and Mayank Tyagi are responsible for the HPC and CFD-Toolkit tasks.

Figure 1 illustrates the structure of the CFD Toolkit being developed at LSU. The CFD Toolkit uses a collection of state-of-the-art numerical solvers that scale well on parallel computers. It provides user the ability to “compose” his/her favorite solver. It is also extending the capability of the Cactus framework (Goodale et al., 2003) by developing multi-block structured as well as unstructured mesh infrastructure in it. Boussinesq equations and shallow water equations will also be implemented to augment the current capabilities that have Navier-Stokes equations in its physics module.

WORK COMPLETED

The project started in June, 2007. As the first step, Boussinesq equations using the finite difference numerical discretization on structured computational domains have been implemented into the Cactus computational framework. It provides several verification and validation cases for the implementations of other Boussinesq-type equations within the CFD Toolkit using spectral element methods. Extensive
tests on the performance and scalability of the parallelized Boussinesq model are being carried out. Secondly, structural and un-structural grids have been developed for the deltaic environment east of Mississippi River, including the Mississippi Sound and Mobile Bay. The computational grids will be used by a shallow water equation (SWE) solver based on the discontinuous Galerkin spectral element/p-h method being implemented into the CFD-Toolkit to simulate wind and wave-driven circulation. Moreover, the structural curvilinear grid has been used by the parallelized spectral wave model SWAN to model waves in the northeastern Gulf of Mexico, which provides Boussinesq wave models with offshore boundary conditions along the 10 m water depth contour. Thirdly, numerical experiments based on the Boussinesq model have been carried out to examine the momentum mixing and particle dispersion statistics in the surf zone. Last, but not least, we have successfully recruited Dr. Claes Eskilsson from Sweden, Mr. Yaakoub El-Khamra and a Ph.D. student to join our research team.

RESULTS

The major results obtained so far are: 1) the implementation of the Boussinesq model (FUNWAVE) for waves and currents on a solid bed into the Cactus computational framework, 2) the development of computational grids for the modeling of waves and currents in a deltaic environment, and 3) the computation of momentum mixing and particle statistics in the surf zone.

To demonstrate a few capabilities and features of the Cactus computational framework implementation of FUNWAVE, some preliminary results are presented in Figure 2. Cactus provides web interfaces to the users with multitudes of interactive functionality such as steering the simulation parameters as well as retrieving a run-time snapshot of the simulation as a .jpeg image of some relevant simulation variables. The HTTPD (Hyper Text Transfer Protocol Daemon) thorn provides an interface, which allows a web-browser to connect to a running simulation. Interactive control of the simulation as well as the time-bin information can help the user explore the parameter space in a logical fashion. The Cactus framework also provides the interfaces to a large number of data format, including HDF5, netCDF, PETSc, HyPRE, Amira and OpenDX. One of the primary goals of this research project is to utilize state-of-the-art I/O methods, numerical solvers as well as visualization capabilities. For more details about the Cactus framework, readers are referred to the URL (www.cactuscode.org).

Single processor runs of FUNWAVE implementation in the Cactus framework have been successfully verified against the standalone runs. The parallelization work is currently in progress. Since there are several obsolete programming features in the serial legacy code, the parallel version is currently under careful development to ensure that all such changes to adopt the latest standards should reproduce the same numerical results. It is expected that portability of the FUNWAVE code with the underlying framework on a variety of high-performance computing platforms should not only help reduce the simulation time through the use of multiple processors but also provide platform independence.

One of the numerical problems associated with the simulation of coastal circulation in an estuary or river mouth with tidal flats is the requirement of fine spatial resolution near shorelines to resolve large hydrodynamic, topographic and geometric gradients. A conventional rectangular grid mesh covering a littoral or river mouth area usually has difficulty to provide enough resolution in the nearshore region because of the computational restraint. We have developed structured and unstructured grids with varying grid spacing to give fine enough resolution in the area of large gradients and avoid over-resolving the flow field in the area with smooth solution. Figure 3 illustrates an unstructured and a structured grid for the modeling of coastal processes in deltaic environments under the proposed
modeling framework. The common feature of the two grids is the high resolution for the barrier islands and the shorelines. Both grids have been used to model Hurricanes Katrina (2005) and Ivan (2004).

Figure 2: Web interfaces for the cactus computational framework that can: a) retrieve time-bin information, b) check & modify parameters, c) steer the parameters during the run-time, d) download output files to local machines, and e) provide viewports as a run-time snapshot of the simulations on a web-page at users’ local machines.
Notice that the computational grids were designed based on the availability of field measurements of tides and waves. For circulation modeling, the southwest and east boundaries of the unstructured grid are located near the coast where there are tide gauging stations that provide water levels for specifying the offshore boundary conditions. For wave modeling, the south boundary of the structured grid is curved to accommodate the two offshore buoys that provide the offshore boundary conditions. Figure 4 shows the comparison of the modeled and measured significant wave heights, mean wave directions, and peak wave periods at the wave gage AL001 near Orange Beach, Alabama, during Hurricane Isidore (2002). Good agreement has been found. SWAN will provide offshore wave boundary conditions at the 10-meter water depth for the spectral-element Boussinesq wave model.
As part of the study on the vorticity dynamics and momentum mixing in the surf zone using the Boussinesq model, we have extended the work of Briganti et al. (2006) from a single cluster of weightless particles to multiple clusters and launching locations in a longshore current. As shown in Figure 5, particles clusters were launched at different cross shore locations simultaneously and their trajectories were tracked continuously. Particle statistics were computed and the information on the particle dispersion and momentum mixing was extracted. It is seen from Figure 5 that most of the particles launched inside the surf zone were transported out of the surf zone by “jets” owing to shear instabilities of the longshore current over a longshore uniform barred beach with a SandyDuck averaged cross shore beach profile. The model result is consistent with the field observation of Smith (2007) who reports that wave-driven longshore currents generated considerable offshore surface flow that likely flushed the in-shore region in Duck, NC. We are documenting the modeling result in a manuscript for possible journal publication.

Figure 4: Comparison of measured and modeled significant wave heights (meters, top), mean wave directions (degrees, middle) and peak wave periods (seconds, bottom) during Hurricane Isidore.
Figure 5: Lagrangian particles at different time in an unstable longshore current. Particle clusters have been marked red, blue and black to distinguish their cross shore initial positions.
IMPACT/APPLICATIONS

The proposed research is expected to improve the Navy’s capability of modeling nearshore surface waves and coastal processes in heterogeneous sedimentary environments. First, the study will extend the applicability of Boussinesq models (Chen et al., 1999, and Chen et al., 2003) to the porous and soft mud seabed. This will provide sediment transport models with more realistic estimates of cross-shore and alongshore velocities in coastal regions with substantial variation in seabed properties. Therefore, improvements in predicting littoral sediment transport will be anticipated. A better prediction of turbidity in coastal regions is of importance to naval deployments of unmanned underwater vehicles (UUV) and divers for inshore countermine warfare. The modeling framework integrated with the CFD Toolkits developed at LSU will allow us to couple the hydrodynamic models with sediment transport models for coastal morphodynamic studies. It is anticipated that the proposed project will also complement the new research initiatives on Tidal-Flats and Wave-Mud Interactions.

In addition to supporting the Navy’s research goals, the proposed project will lead to contributions to the Louisiana State University’s mission on research and graduate education. A survey conducted by the National Research Council has shown that the north Gulf Coast, where the Naval Research Laboratory and other naval facilities are located, is in need of research and education in coastal engineering. Thus, the proposed training of the post-doctoral fellow and graduate students will enhance the graduate program in coastal engineering at LSU to meet the need for graduate education on the Gulf Coast in support of national defense.

TRANSITIONS

None

RELATED PROJECTS

Our project is leveraging and coordinating with activities in several other ongoing activities:

XiRel: This NSF funded project is optimizing and extending an Adaptive Mesh Refinement layer for the Cactus framework, which will be used for our structured grid codes. (http://www.cactuscode.org/Development/xirel)

ALPACA: This NSF funded project is developing debugging and profiling tools for the Cactus framework which will support the Coastal Modeling Framework developed in this project. (http://www.cactuscode.org/Development/alpaca)

CyberTools: This NSF/BOR funded project is developing a cyberinfrastructure across the 100 TFlop machines of the Louisiana Optical Network Initiative. Our project is providing one of the application drivers for this infrastructure. (http://cybertools.loni.org)

CFD IGERT: An NSF graduate training and education program at LSU in training students in computational fluid dynamics and high performance computing. Several research projects are building on the CFD Toolkit which is contributing to our project.
SCOOP: Where appropriate, our models will be integrated into the community infrastructure of the NOAA/ONR funded SURA Coastal Ocean and Observing Program. SCOOP maintains a coastal archive at LSU with realtime forcing and simulation data for storm events.

NSF-CAREER: The five-year research project is focused on simulations of nonlinear coastal waves and air-sea momentum fluxes, which will complement the present research project. [http://www.nsf.gov/eng/cbet/nuggets/1443/1443_chen.htm](http://www.nsf.gov/eng/cbet/nuggets/1443/1443_chen.htm)

The Office of Naval Research new research initiatives of Tidal Flats and Wave-Mud Interactions are closely related to the present study. These provide the project with an excellent, timely opportunity to combine the modeling efforts with the field studies.

REFERENCES


