Finite Element-Based Coastal Ocean Modeling: Today and Tomorrow

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Introduction: The continued necessity of military special forces operations in riverine and coastal environments along with increasing civilian concerns related to sediment transport, search and rescue, pollutant dispersal, and coastal restoration, have resulted in the need for detailed knowledge of currents and water levels in coastal, estuarine, and riverine environments. This demand for information at highly resolved spatial and temporal scales and the availability of massively parallel computer resources has brought to the forefront the capabilities of finite element (FE)-based coastal ocean circulation models. The use by these models of unstructured triangular meshes permits a large degree of flexibility in representing the complexities of coastal environments associated with convoluted shorelines, and steep gradients in currents or bathymetry. Ultimately this flexibility results in model predictions over periods of hours or less at spatial scales that range from meters to kilometers.

A Model for Coastal Mississippi and Louisiana: Unstructured meshes containing upwards of 281,800 computational points and 540,000 triangular elements are constructed to represent riverine and coastal currents off the shores of southeast Louisiana and Mississippi (Fig. 1). Spatial resolution is 50 m in rivers and decreases to 100 to 200 m offshore. The need for remote boundary forcing is accomodated by including the Gulf of Mexico and extending the mesh into the north Atlantic ocean. The applied forcing includes tides, wind stress at the water surface and river discharge from the Atchafalaya and Mississippi Rivers.

Connecting Mississippi River Currents and Observed Optical Properties: The underlying physical processes that influence observed optical distributions as derived from remotely-sensed ocean color data are often too complex and are manifest at space and time scales that preclude full understanding from imagery alone. But when coupled with highly resolved, dynamically advanced numerical models, understanding increases and the prediction of dynamical processes and optical patterns in coastal waters is possible. During March 2004, magnitudes of the depth-averaged currents computed at the mouth of the

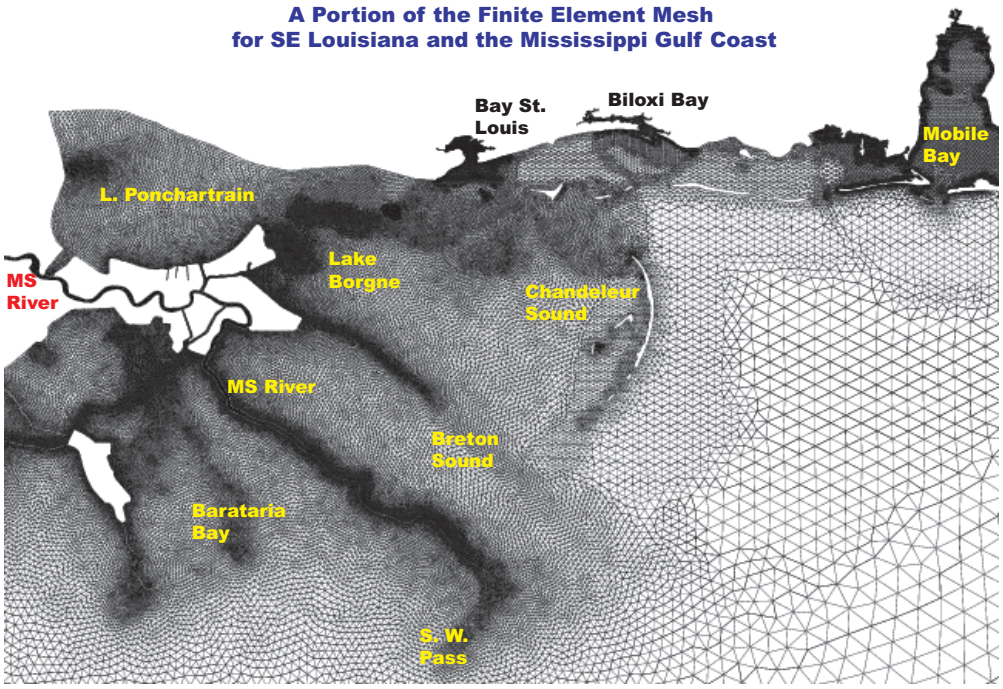

FIGURE 1
Detail of the unstructured computational mesh constructed for Louisiana and Mississippi coastal waters. The mesh, containing 281,528 computational points and 455,203 triangular elements, has 50-m resolution of the Mississippi and Atchafalaya rivers, 100-m resolution of nearshore areas, and includes the entire Gulf of Mexico extending to 60 deg W in the north Atlantic ocean to accommodate remote tidal forcing from a global tide model.

Mississippi River and westward are correlated to the spatial distribution of the beam attenuation coefficient (a sum of the total absorption and scattering) derived from the MODIS 250-m ocean color data.[1] The plume of high beam attenutation (an indication of more sediment particles in the water) found westward of the Mississippi River outflow is a response to the stronger, undulating westward moving coastal currents (Fig. 2). Comparisons of the same currents with observed chlorophyll are not as striking; this is expected since many unmodeled biological and optical processes contribute to the distribution of chlorophyll in coastal waters. Remotely sensed ocean color data are often the only observational window on ocean processes in denied areas of military interest, making the coupling of satellite imagery with numerical models imperative for developing a preditive capability in such regions.

Predicting Hurricane Katrina Storm Surge: Tidal variability combined with the best available NOAA reanalyzed surface winds representing the evolution of Hurricane Katrina force the FE-based coastal model in a hindcast of the surge elevation experienced along the Mississippi Gulf coast. Model predictions (Fig. 3, top) at landfall on August 29, 2005, 5:30Z indicate maximum surges are in the range of 9 m and occur several hours after the peak winds (Fig. 3, lower panels). The unstructured mesh includes such features as levees along the Mississippi River, channels, inland topography, and a capability for surge overtopping of barrier islands.

A New Approach for the Future: While the current FE methodology leads to robust computations of tide and surge dynamics, limitations on local conservation properties are motivating development of the next generation of FE-based coastal models. NRL is implementing a new and promising class of FE methods, the discontinuous Galerkin (DG) methods, which have seen very rapid development over the last several years. The primary advantage of DG methods is their local (element by element) enforcement of the conservation laws, which pave the way for accurate transport of temperature and salinity, or other conservative tracers. Findings from comparisons between the existing FE-based model and a model using the new DG methodology[2] show that the DG formulation is able to retain the robustness of existing model solutions while more sharply resolving gradients and other small-scale circulation features. Furthermore, the local nature of the DG method is advantageous in permitting 1) elemental specification of the order

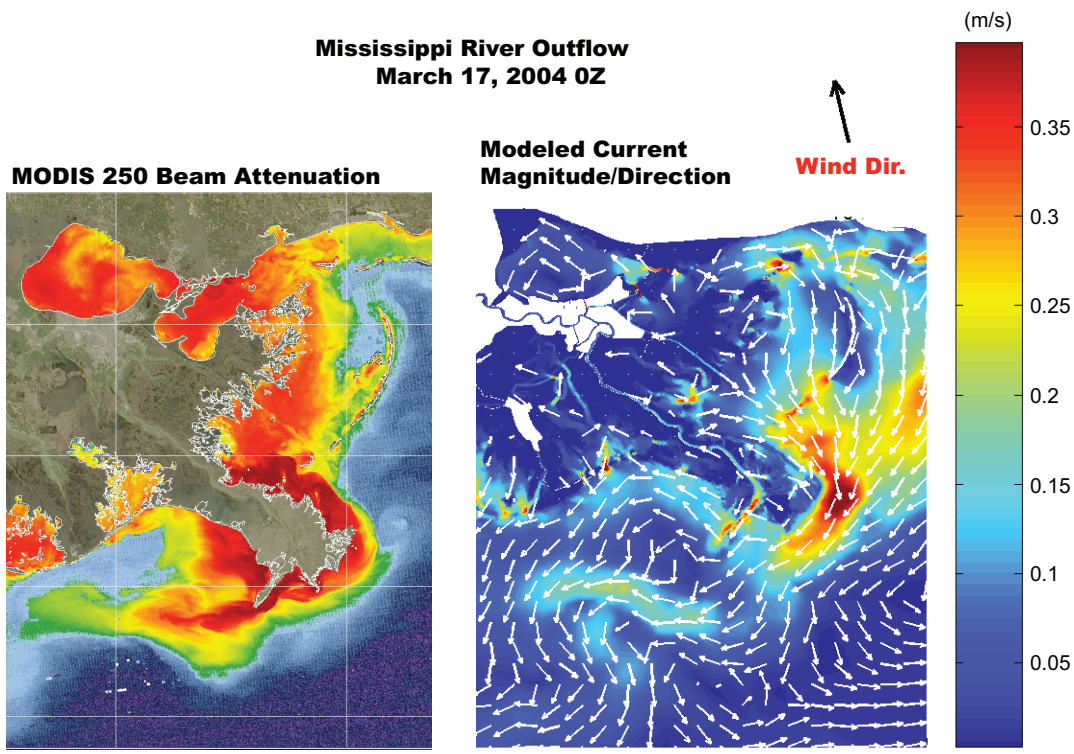

FIGURE 2
The beam attenuation coefficient derived from the MODIS 250-m ocean color data (left) is well correlated to 2D finite element model-predicted barotropic currents (right) on March 17, 2004. The westward movement of the sediment plume (high beam attenuation/high particle concentration) from the Mississippi River can be attributed in part to the underlying westward movement and undulation of the currents.

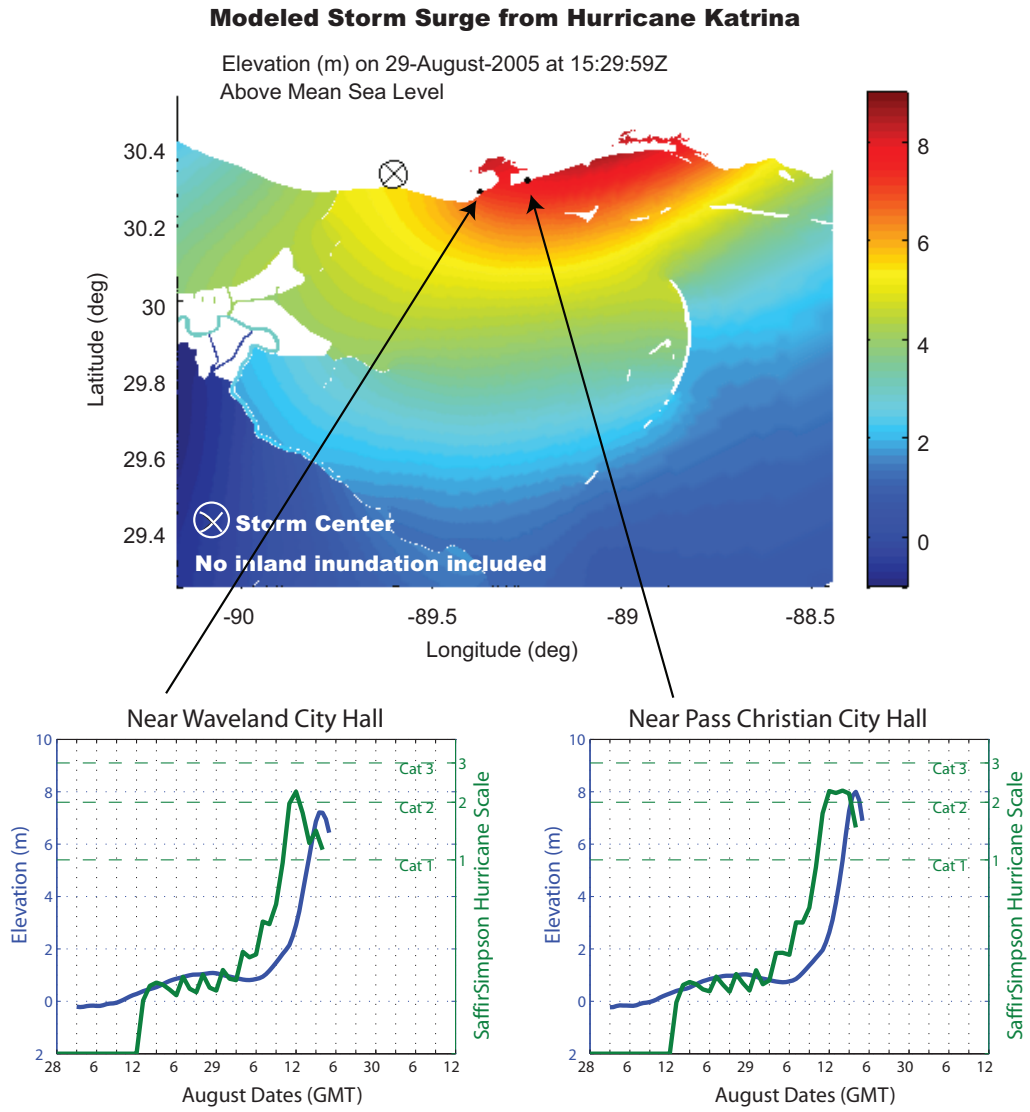

FIGURE 3
Hindcast of Hurricane Katrina storm surge elevations near the time of landfall August 29, 2005, 5:30Z. Time series evolutions of the wind and surge at Waveland, MS and Pass Christian, MS.

of approximation, thereby allowing for the capture of frontal and sharp gradient regions, 2) nonconforming unstructured meshes that simplify development of adaptive meshing strategies, and 3) a reduction in the computational footprint to an element and immediate neighbor elements, a necessity for efficient parallel processing on distributed memory machines. The potential of this new methodology to revolutionize coastal ocean modeling is significant and NRL is leading the way in its development and application to complex ocean dynamics problems.

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[2] C.A. Blain and T. C. Massey, "Application of a Coupled Discontinuous-Continuous Galerkin Finite Element Shallow Water Model to Coastal Ocean Dynamics," *Ocean Modeling* **10**, 283-315, 2005.