A New Generation Hurricane Storm Surge Model for Southern Louisiana

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Summary

We have developed a basin scale, unstructured grid, high resolution hydrodynamic model for computing dynamically correct storm surge in intricate coastal floodplains.

Abstract

We have developed a large domain–unstructured grid strategy to compute hurricane storm surge over Southern Louisiana's geometrically intricate and feature-dominated coastal floodplain. The large domain allows full dynamic coupling between ocean basins, coastal shelves, and the coastal floodplain, and greatly improves the accuracy of the boundary conditions. The application of an unstructured grid resolves the energetic scales of motion on a localized basis, accurately solving the governing equations while minimizing the number of discretization points and making the computations feasible from a cost perspective. A hindcast of Hurricane Betsy captures detailed flow features such as the surge that propagates up the Mississippi River, demonstrating the effectiveness of the modeling strategy. The U.S. Army Corps of Engineers will apply the resulting model as their design tool to optimize levee construction in Southern Louisiana.

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Flooding due to hurricane storm surge in coastal regions risks large loss of life and enormous environmental and economic damage. Southern Louisiana in particular is extremely vulnerable to hurricane-induced flooding with 60% of its topography lying less than 1 m above the geoid. New Orleans, for example, lies largely below the geoid and is almost entirely surrounded by water. In order to prevent inundation, a complex system of ring and river levees has been constructed and is actively being improved. A modeling capability is needed to design levee systems that offer the best possible protection, to forecast the flooding potential of an incoming hurricane, to assess the environmental impact of organic and inorganic pollutants spread during a storm surge event, and to evaluate the effects of long term geomorphological change of the region.

Developing predictive models of hurricane storm surge in Southern Louisiana is difficult due to the complexity of the domain, the range of spatial scales involved and the long term change in the physical system. Specifically, the evolution and propagation of storm surge is influenced by the hydrodynamic coupling of the Atlantic Ocean, the Gulf of Mexico, the continental shelf, and the low lying coastal floodplain which defines Southern Louisiana. In addition, the geometric complexity of the region results in energetic short flow scales. Geometric intricacies include the Mississippi and Atchafalaya Rivers; numerous dredged manmade navigation canals; lakes and bays interconnected by deep naturally scoured channels; widespread wetlands; and an extensive system of river banks, levees and raised roadways. Finally, geometry and topography change significantly in time due to both natural morphological evolution and substantial man-induced changes. The latter includes the development of levee systems and channels, leading to a sediment-starved delta which is slowly subsiding. This geometrically and hydrodynamically complex region presents one of the most challenging areas in the world to correctly model hurricane flooding.

Traditional storm surge models have applied structured computational grids with regularly spaced discretization points placed such that the domain is limited to the continental shelf. Due to the domain boundary location, these traditional models do not capture the basin to shelf dynamics, which is critical to accurately force the surge event. It has been shown that shelf-sized domains appear to under-predict the surge at the adjacent coast (1). Shelf-sized domains also do not capture the basin to basin dynamics which can influence the prediction of storm surge forerunner. Furthermore, traditional structured grid models provide a relatively coarse computational discretization of the governing shallow water equations (SWE). Coarse grids lead to storm surge over-prediction adjacent to the coast while being unable to resolve critical features which control flood wave propagation inland (2). Thus the use of a shelf-sized domain with a relatively coarse grid suggests using either a high level of parameterization of the missing physics or data assimilation. However, due to the low frequency of hurricane events and the significant geomorphic evolution in the physical system, neither strategy will work. This then implies the need for computational models that can establish accurate boundary conditions and resolve the energetic scales of the pertinent physics. Particularly in Southern Louisiana, where flood wave amplitude and propagation are controlled by topographic details and features such as channels and levees, it is critical to define a sufficiently fine numerical discretization such that these features and the associated flow scales are well resolved.

Large domain–localized grid resolution strategy

We have developed a modeling strategy that defines very large computational domains and applies unstructured discretizations refined such that the flow is correctly resolved on a local basis. The computational domain, shown in Figure 1, incorporates a large portion of the western North Atlantic, the entire Gulf of Mexico, and the entire Caribbean Sea. The open ocean boundary lies along the 60 degree west meridian between Nova Scotia, Canada, and eastern Venezuela and is predominantly located in deep water with depths between 1000 m and 6000 m. This computational domain has numerous advantages for computing both tides and hurricane storm surge for U.S. coastal regions.

Accurate tidal boundary conditions on the deep Atlantic open ocean boundary can be obtained from global tide models which are based on solutions to the governing SWE, global satellite altimetry, or SWE solutions coupled with assimilated satellite data (3-9). Tides on this boundary tend to vary slowly in space and are dominated by astronomical tidal constituents. Conversely, open ocean boundaries that are situated within shallow coastal waters, on the continental shelf, in the vicinity of tidal features known as amphidromes where tidal amplitudes cancel, or within resonant basins such as the Gulf of Mexico and the Caribbean Sea can have complicated tidal structures that vary much more quickly in space and may include non-negligible nonlinearly-generated overtides and compound tides.

Accurate hurricane storm surge boundary conditions on the model's deep Atlantic Ocean boundary can be simply specified as a water surface perturbation computed as the inverted barometer associated with the atmospheric pressure deficit (1). If the open ocean boundary was situated on the continental shelf, a sizable primary surge exists at that boundary which is virtually impossible to estimate accurately as a boundary condition. Furthermore, it is not feasible to define accurate open ocean boundary conditions for boundaries located within resonant basins, even when those boundaries are located in deep water.

We note that hydrodynamic response within our large domain will be solved simultaneously using a single computational mesh. This is an important feature since significant two-way coupling occurs between the various regions. Thus our large domain allows for much more accurate fully-coupled modeling of basin to basin, basin to shelf, and shelf to adjacent coastal floodplain dynamics. Furthermore, the large domain open ocean boundary location leads to significantly simpler and more accurate boundary conditions.

In order for any computational model to be accurate, the energetic scales of motion must be accurately resolved locally. Fortunately, for tidal and hurricane storm surgeinduced flows, the scales of motion that exist within the domain are fairly well sorted. We have studied discretization requirements for both tides and hurricane storm surge response (2, 10-14). The longest scales of motion exist in the deep ocean; intermediate scales exist on the shelf; while the smallest scales of motion exist in the intricate and feature-dominated coastal floodplain.

The grid shown in Figure 2 applies an unstructured finite element mesh that sufficiently resolves the energetic hydrodynamics on a local basis. Figures 3 through 6 show more detailed views of the model features and grid in Southern Louisiana. Note that the levees and raised roads are represented by red lines, while topographic and bathymetric values define land heights and water depths with respect to the geoid. Deep ocean grid size is approximately 25 to 50 km; continental shelf resolution is between 5 and 20 km; and in Southern Louisiana nodal spacing ranges from 100 m to 2000 m. We note that grid size varies smoothly and slowly in order to maintain computational second order spatial accuracy (13). This computational mesh contains 85% of the nodes within Southern Louisiana and its adjacent shelf. Thus from a computational cost perspective (which for our SWE code is linearly proportional to the number of nodes), we are only adding 15% overhead by defining the very large basin-scale computational domain thereby achieving a tremendous improvement in boundary condition accuracy and full dynamic coupling of all pertinent regions. This grid contains 314,442 computational nodes, while a structured grid that covers the same computational domain at a resolution of 100 m would include more than 750,000,000 nodes. A correctly resolved, unstructured, variably-graded mesh will give the same solution as a very fine structured mesh for a fraction of the computational cost.

Description of the ADCIRC SWE Model

The flow physics for tides and hurricane storm surge on the shelf and adjacent coastal floodplain as well as within estuaries and rivers is well described by the SWE. These equations describe conservation of water volume and momentum with depth-averaged variables. They were first developed by Laplace in 1776 in order to compute tides in a global ocean (15). In our ADCIRC SWE code, we formulate the equations in spherical coordinates due to the large size of our computational domains (16). We include internal barriers to handle levees so that flow can propagate correctly across any defined levee using a weir formula (17). We also allow wetting and drying of regions as flow propagates onshore and then recedes.

The model is forced at boundaries with a combination of surface elevation specified, flow specified, and flow-radiation specified boundary values. Tidal elevations are prescribed at the open ocean boundary in the Atlantic. Flow-radiation boundary conditions are prescribed on the rivers, forcing the defined river flow to enter the river but allowing tides and surges to propagate out of the system. Land boundaries are prescribed using no-normal flow conditions.

Within the interior of the domain, we specify tide-generating lateral forces that originate from the sun and moon's gravitational pull and the earth's wobble. Hurricane wind models or data assimilation codes provide marine wind and atmospheric pressure data. The wind boundary layer is dynamically adjusted within the hydrodynamic computations to account for upwind land roughness as well as the level of local inundation. Winds are adjusted to 10 minute averages to be consistent with the application of Garrat's wind drag coefficient formula used to compute the applied wind stress (18).

Numerical solutions to the SWE on unstructured grids using finite element methods have been under development for the past three decades (19, 20). Finite element methods are widely used in structural analysis and solid mechanics due to their ability to specify fine computational discretizations in regions with rapidly varying stress or deformation. A significant problem for unstructured SWE solutions has been avoiding non-physical spurious modes with wavelengths near twice the grid size without requiring adding artificial damping. Developing noise-free and accurate SWE solutions on structured grids has been significantly easier since this can be achieved by simply staggering the variables. Four finite element-based unstructured SWE algorithms have emerged which are at least second order accurate in space; have noise free solutions without requiring artificial damping; and are sufficiently robust to be applied to the wide range of scales of motion and wide range of hydrodynamic balances that exist when computing flows in the deep ocean, on continental shelves, in inlets, floodplains, and rivers (21-24). The two best developed of these algorithms are the Generalized Wave Continuity Equation (GWCE) and the Quasi-Bubble formulations, which are functionally almost identical despite entirely different derivations (21, 22, 25). We have selected the GWCE solution as the current base algorithm in our SWE code, ADCIRC (26, 27). Unstructured finite element based methods permit SWE solutions that can localize resolution, leading to globally and locally more accurate solutions within the realm of feasible computational expense.

Specific advances in computer sciences such as conjugate gradient (CG) linear system of equation solvers and parallel computing paradigms have made it possible to apply unstructured grid algorithms to problems with a very high number of discretization points. The use of the CG solver allows the ADCIRC code to achieve run times that are linearly proportional to the number of time steps taken and to the number of discretization points in space for both single thread and parallel implementations. The application of a domain decomposition strategy using the Message Passing Interface (MPI) library achieves linear or even super-linear speedup for up to 256 processors depending on the platform and the size of the unstructured grid. For the Southern Louisiana grid with 314,442 discretization points using 2 second time steps, the wall clock time is 2.14 hours per day of simulation time on a CRAY T3E with 128 processors and 0.57 hours per day of simulation time on a Beowulf-class machine using 128 1.8 GHz Intel Xeon processors.

Hindcasting Hurricane Betsy

Hurricane Betsy represents an ideal storm to illustrate the advantages of a large domain-locally refined unstructured grid model for Southern Louisiana. Hurricane Betsy was a fast moving Category 5 hurricane that made landfall on September 10, 1965 near Grand Isle, tracking between the Atchafalaya and Mississippi Rivers and causing extensive flooding throughout southeastern Louisiana. Hurricane Betsy was in fact an impetus to redesign the levees throughout Southern Louisiana.

Geometry, hydrodynamic forcing, and meteorological forcing are all defined to replicate the prevailing conditions during the storm. All levee heights are defined using the 1965 values. A steric adjustment of 0.37 m above the geoid is applied to account for the expansion of warmer Gulf of Mexico waters in September. Tides are forced both on the Atlantic open ocean boundary as well as within the interior domain with lateral body forces. The Mississippi and Atchafalaya rivers are forced with steady flows of 1900 m^3/s and 630 m^3/s respectively, which represent flow averages during the storm event. Marine wind fields are generated by the H*Wind system from NOAA's Hurricane Research Division using data assimilated values (28-31). Atmospheric pressure fields are based on minimum pressures, track and estimated radius to maximum winds (32). Viscous hydrodynamic parameters are globally specified for bottom friction and lateral viscosity using standard physically relevant values. We emphasize that no tuning or optimization was performed with respect to the selected values. In fact, selective grid refinement to improve the definition of important hydraulic features was the only thing done to improve matches between measured and modeled water surface elevation gauge readings.

Figure 7 shows the time evolution of surface elevation during the event with the forcing wind and illustrates the rapid buildup of storm surge. A more detailed AVI formatted movie of surface response and forcing winds is available online (Movie S1, www.sciencemag.org). Peak surge during the storm event is summarized in Figure 8. It is clear that storm response is dominated by physical features such as levees, river berms, raised roads, inlets, channels, and rivers. Storm surge over Southern Louisiana is highly localized and varies rapidly over even a few kilometers. We note that water is predominantly being blown from the east and then stopped by obstructions, resulting in strong storm surge buildup. This happens on the west side of Lake Pontchartrain where the railroad berm holds the water and the surge builds up to more than 4.1 m; in New Orleans at the confluence of the Intracoastal Waterway (ICW) and the Mississippi River Gulf Outlet (MRGO) where surge builds up against the levee on the west side of the Inner Harbor Navigation Canal (IHNC) up to 3.7 m; against the concave-shaped portion of the east Mississippi River levee near English Turn where surge is amplified by a focusing effect up to 3.3 m; against the east and west Mississippi River levees between Pointe a la Hache and Port Sulphur where surge builds up to 4.3 m; and east and west of Grand Isle where a combination of levees and low-lying islands and banks results in surge build up to 3.3 m.

Of particular interest is the surge that develops between Pointe a la Hache and Port Sulphur. The Mississippi River has a west and an east levee for all locations upriver from Scocola, while only a west levee exists downriver from Scocola. During the event, winds blow across Breton Sound, inundate the wetlands between the Mississippi River and Breton Sound, and then cause water to pile up against the exposed (either east or west) river levee between Pointe a la Hache and Port Sulphur. Locally the surge builds up to 3.9 m and subsequently propagates up the Mississippi River as a flood wave, passing New Orleans at 2.4 m above the normal river flow height and Baton Rouge at 1.6 m above normal river flow height. Hydrographs of water level at South Pass, Pointe a la Hache, Algiers Lock, and Carrollton in Figure 9 show the rapid progression of this flood wave (it takes only 2 hours to reach New Orleans) and compare our ADCIRC prediction to measured surface water values during the event. The model simulates both tides and surge well.

Betsy occurred during a period of low river flow and the 6 m to 8 m river levees protecting New Orleans were more than adequate to protect the city from the almost 3.5 m surge coming up the river. However, for a similar hurricane event occurring earlier in the year during a high river stage scenario, the same flood wave generated against the west levee south of Scocola could possibly endanger New Orleans depending on how the flood wave interacts with the high flow river current. We do note that the peak of the wave generated between Pointe a la Hache and Port Sulphur will likely be limited by the height of the local Mississippi levees, and thus a larger storm may not greatly increase the height of the actual surge relative to the background river level.

Conclusions

It is clear in hindcasting surge for Hurricane Betsy that accurate predictions of flow over an intricate coastal floodplain are only possible with high resolution and the inclusion of detailed physical features. The large domain-unstructured grid modeling strategy allows the scales of motion to be resolved on a localized basis so that the governing equations are solved accurately; includes flow controls directly in the computations; leads to full dynamic coupling between ocean basins, coastal shelves, and the coastal floodplain; and greatly improves the accuracy of the boundary conditions. This is all achieved while minimizing the number of discretization points for a given accuracy, which makes these computations feasible from a cost perspective.

The model will be used by the U.S. Army Corps of Engineers to redesign the levees in Southern Louisiana and by the State of Louisiana to study the environmental impact of hurricane floods. The unstructured grid and massively parallel capabilities of the ADCIRC hydrodynamics code will allow us to continue adding geometric and feature detail, include more physics such as wind wave current interaction, and more carefully study parameterized processes such as air-sea momentum transfer.

References and Notes

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34. **Supporting Online Material**

www.sciencemag.org

Movie S1

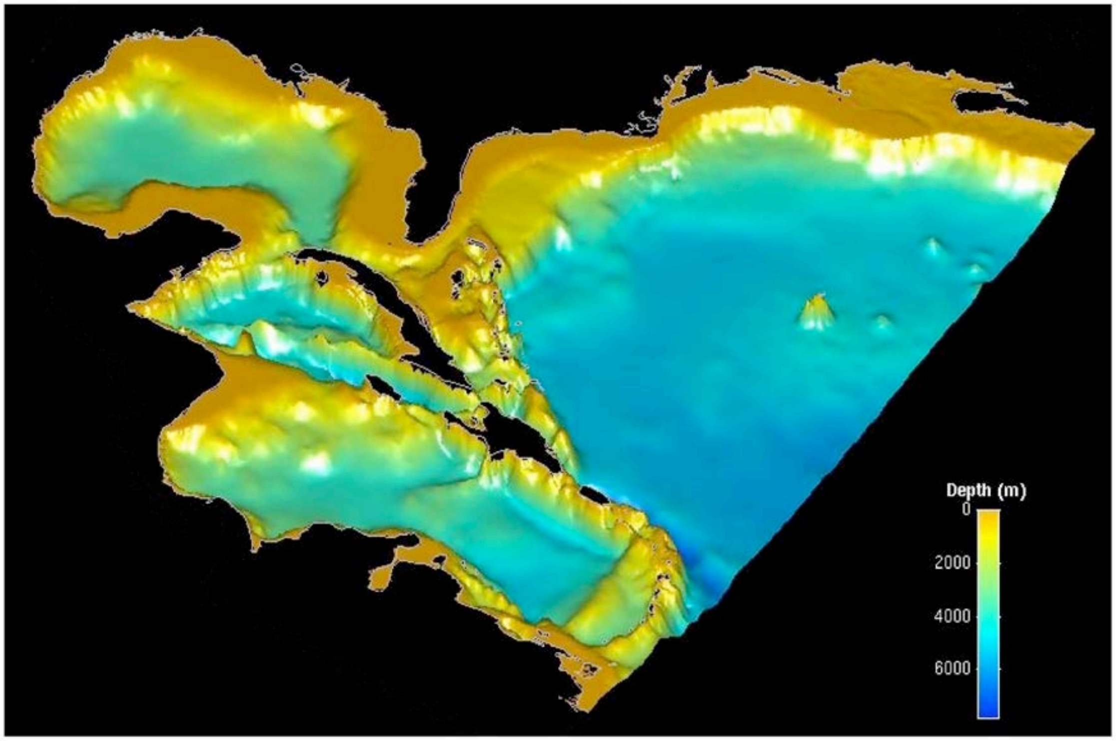

Figure 1. Computational domain with bathymetry (m).

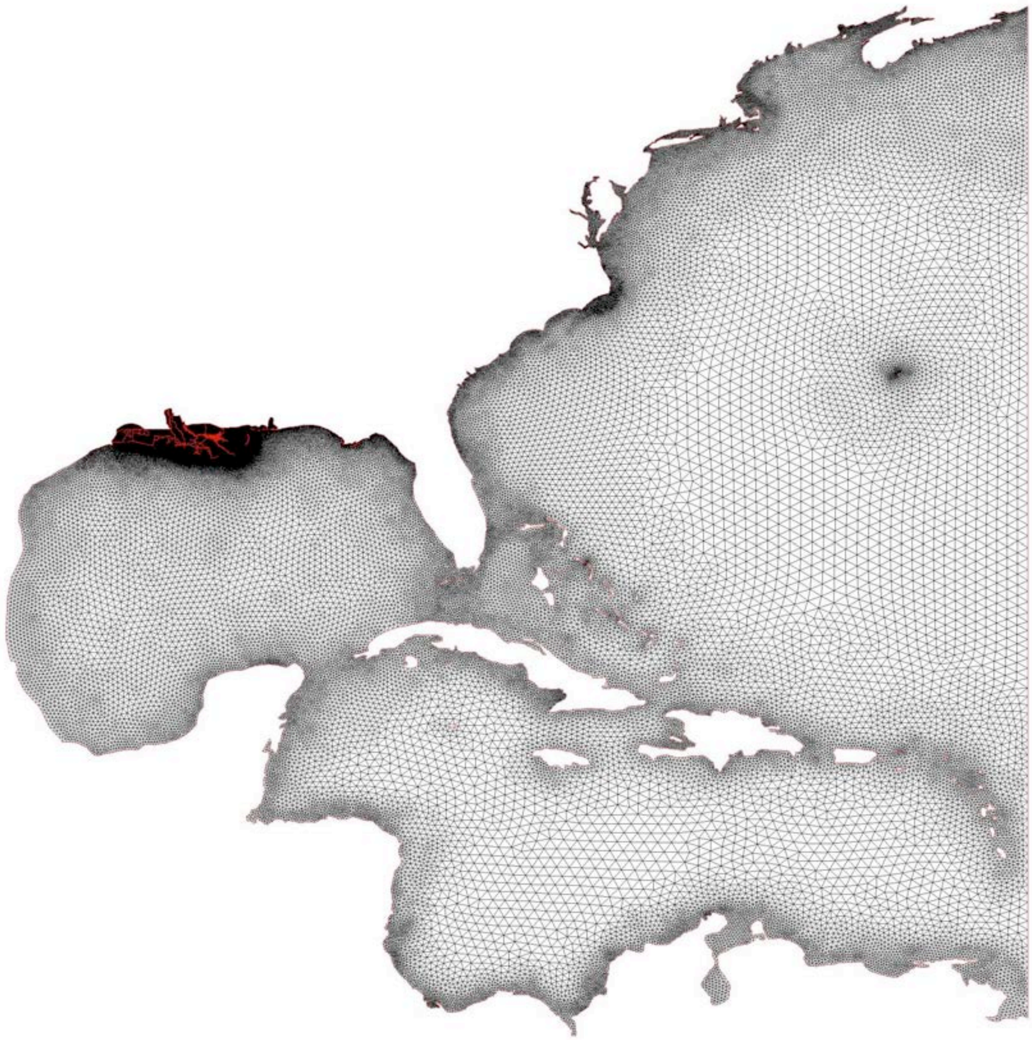

Figure 2. Unstructured grid of the entire domain.

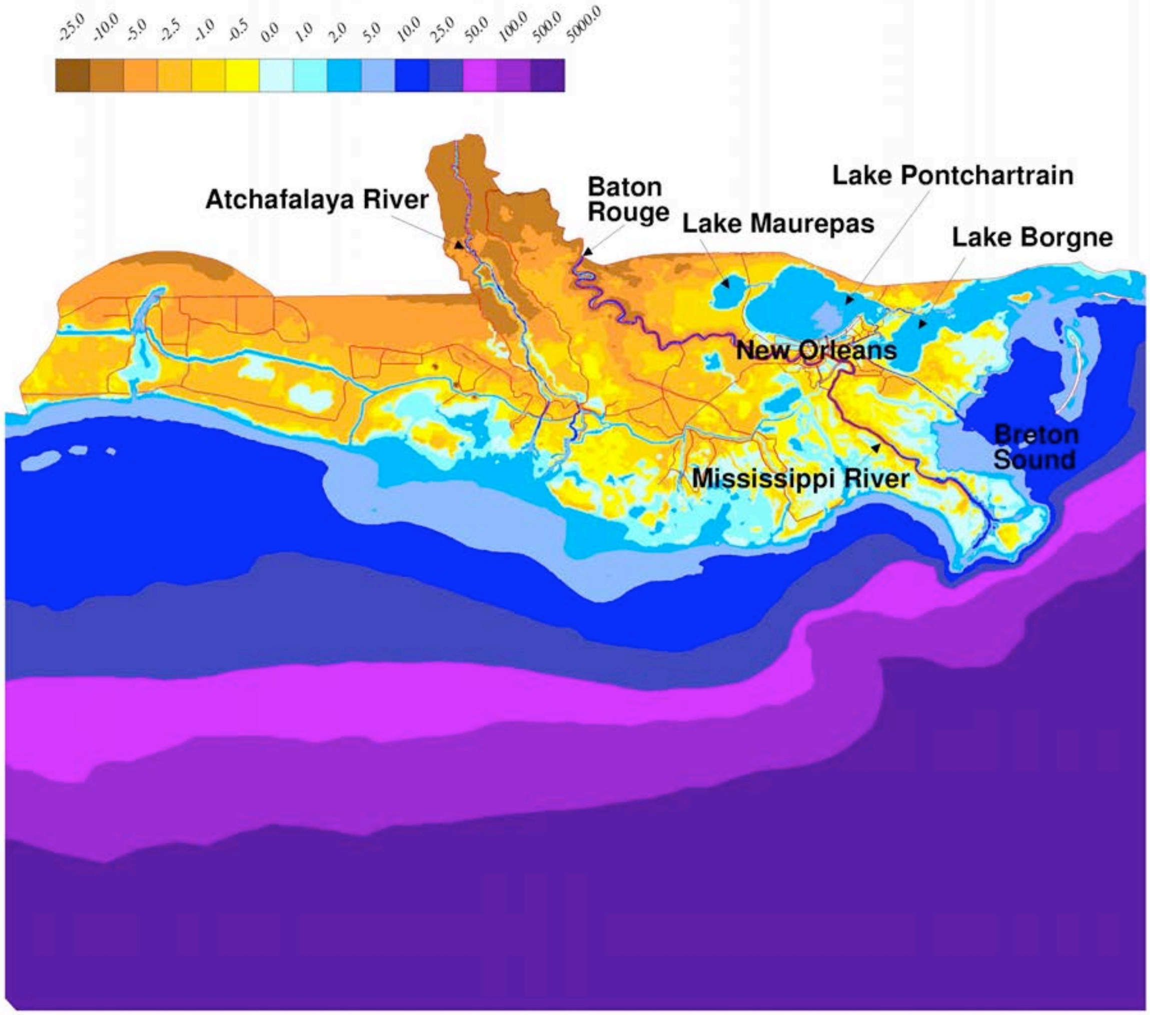

Figure 3. Detail of bathymetry and topography across Southern Louisiana (m).

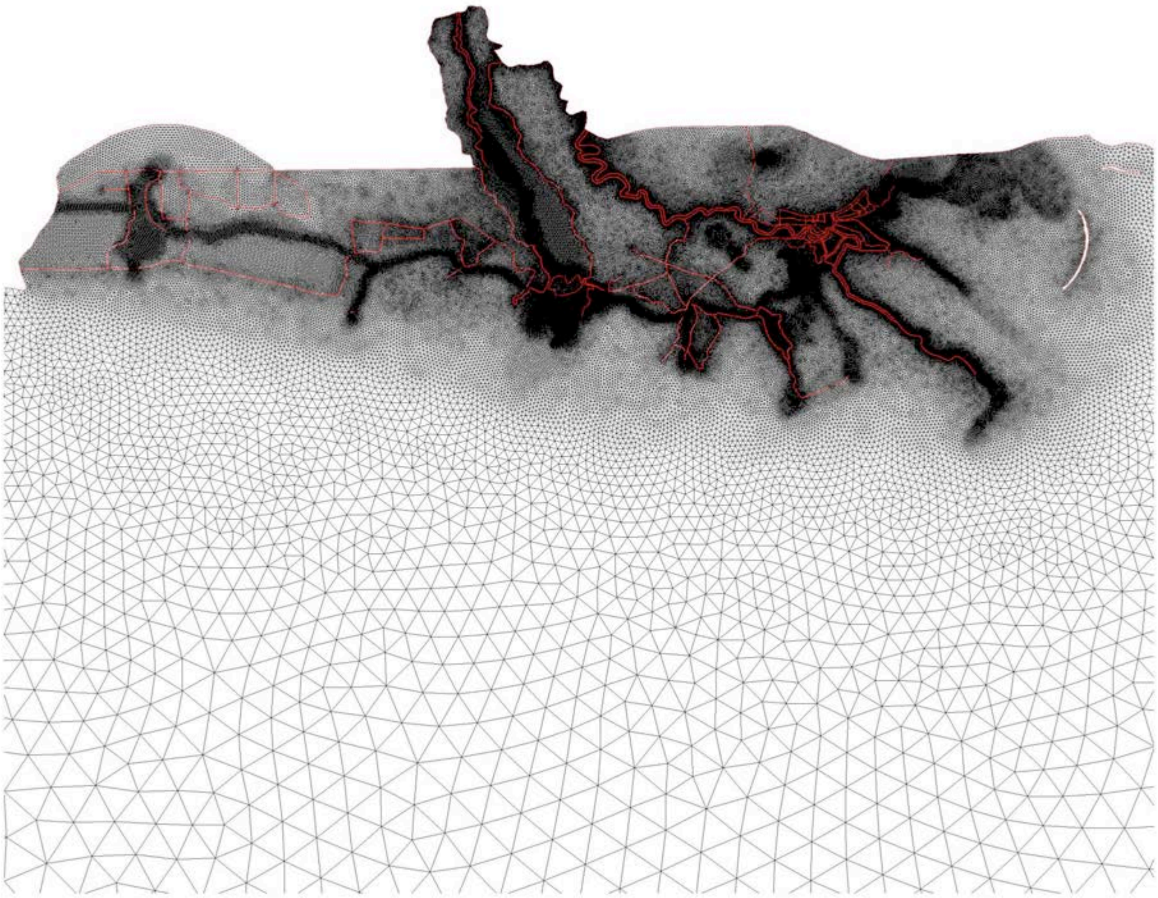

Figure 4. Detail of the unstructured grid in Southern Louisiana.

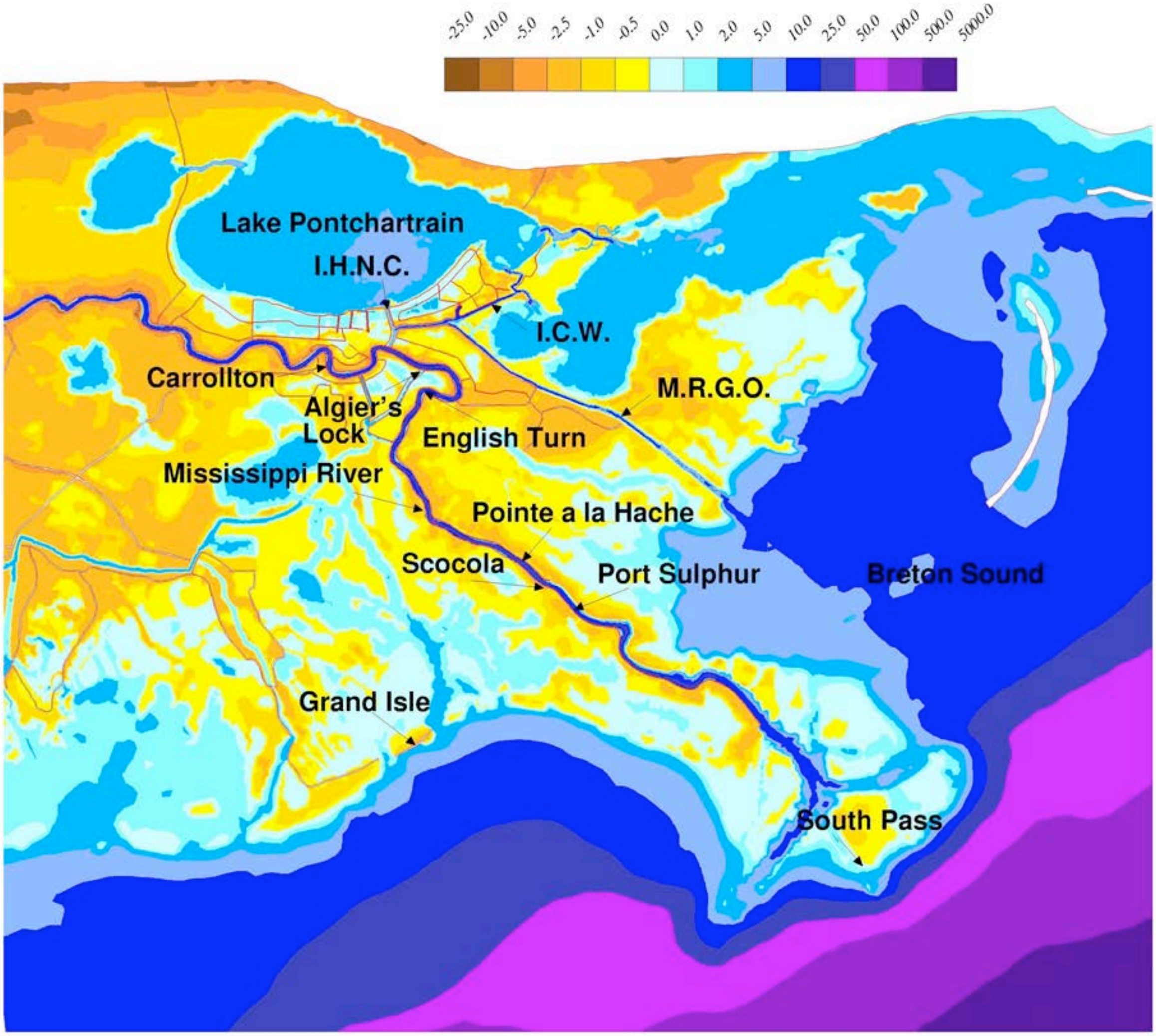

Figure 5. Detail of bathymetry and topography across eastern Southern Louisiana (m).

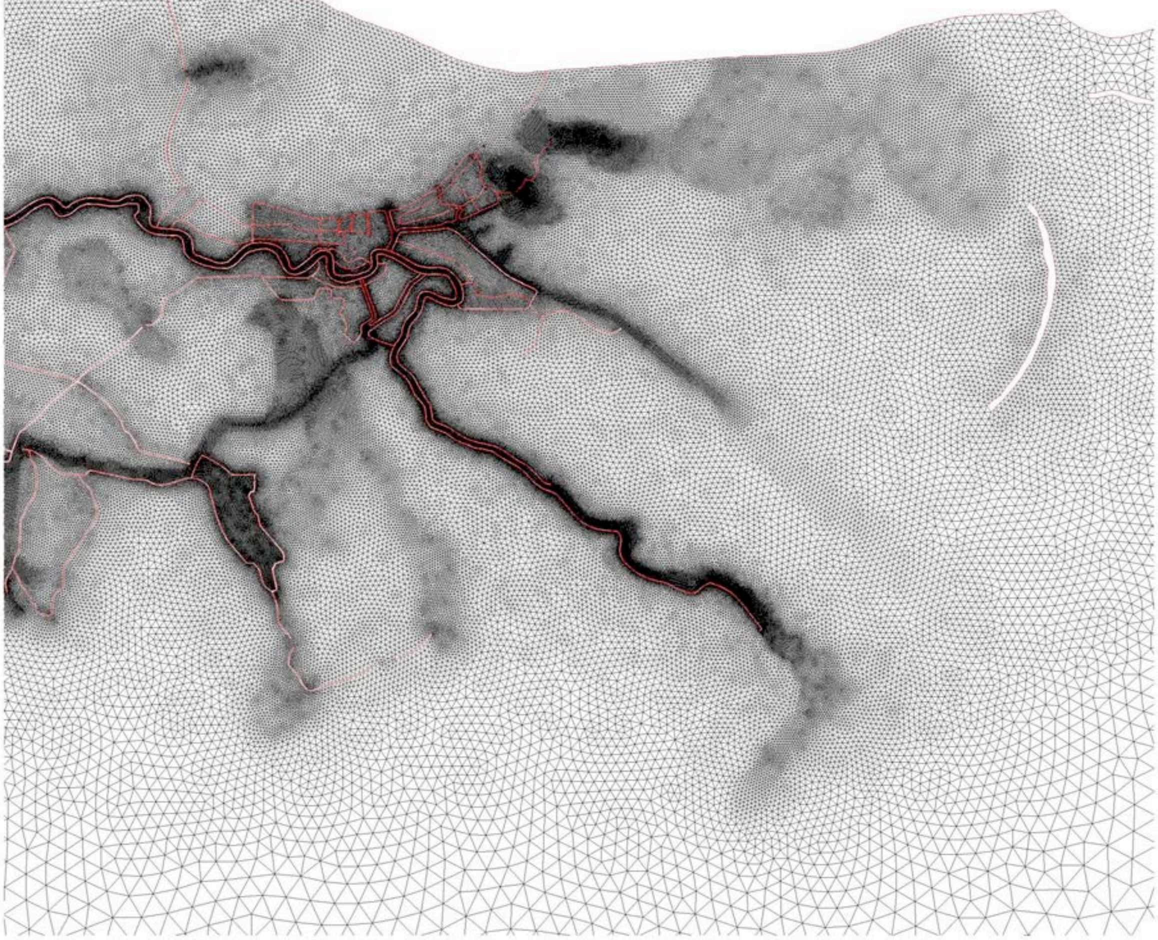

Figure 6. Detail of the unstructured grid in eastern Southern Louisiana.

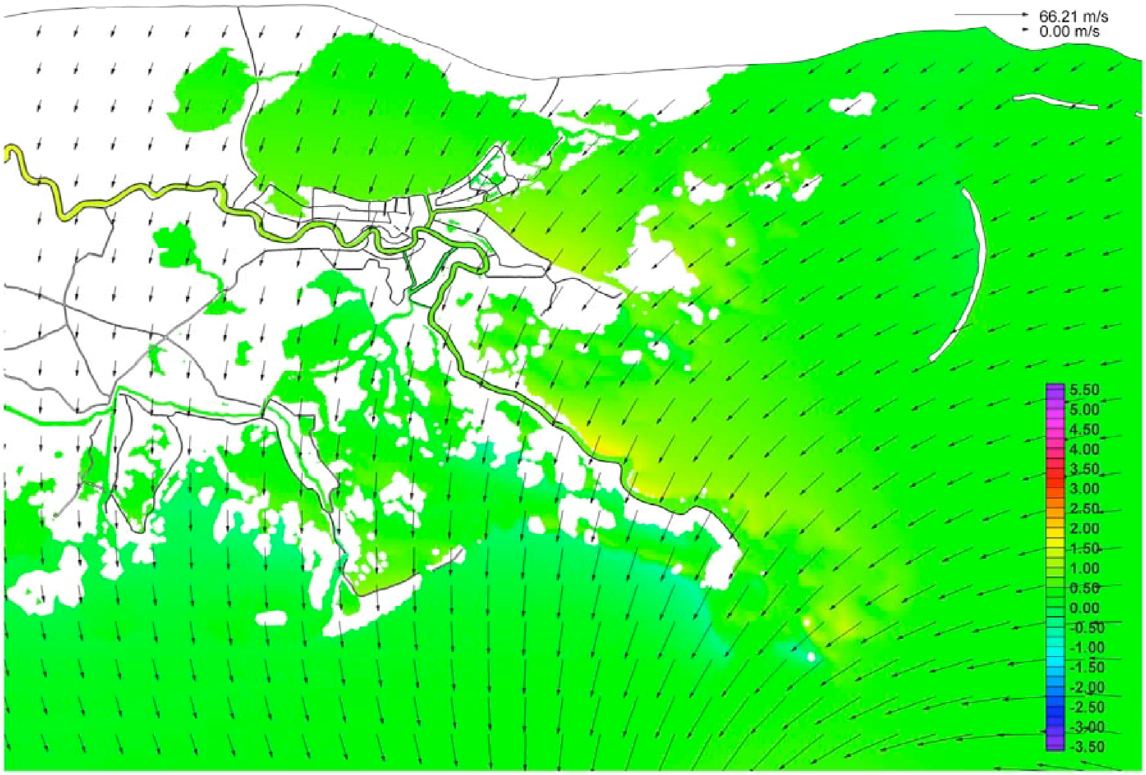

Figure 7a. Water surface elevation with respect to the geoid (m) with marine wind velocity vectors (m/s) during Hurricane Betsy on September 10, 1965 at 0000UTC.

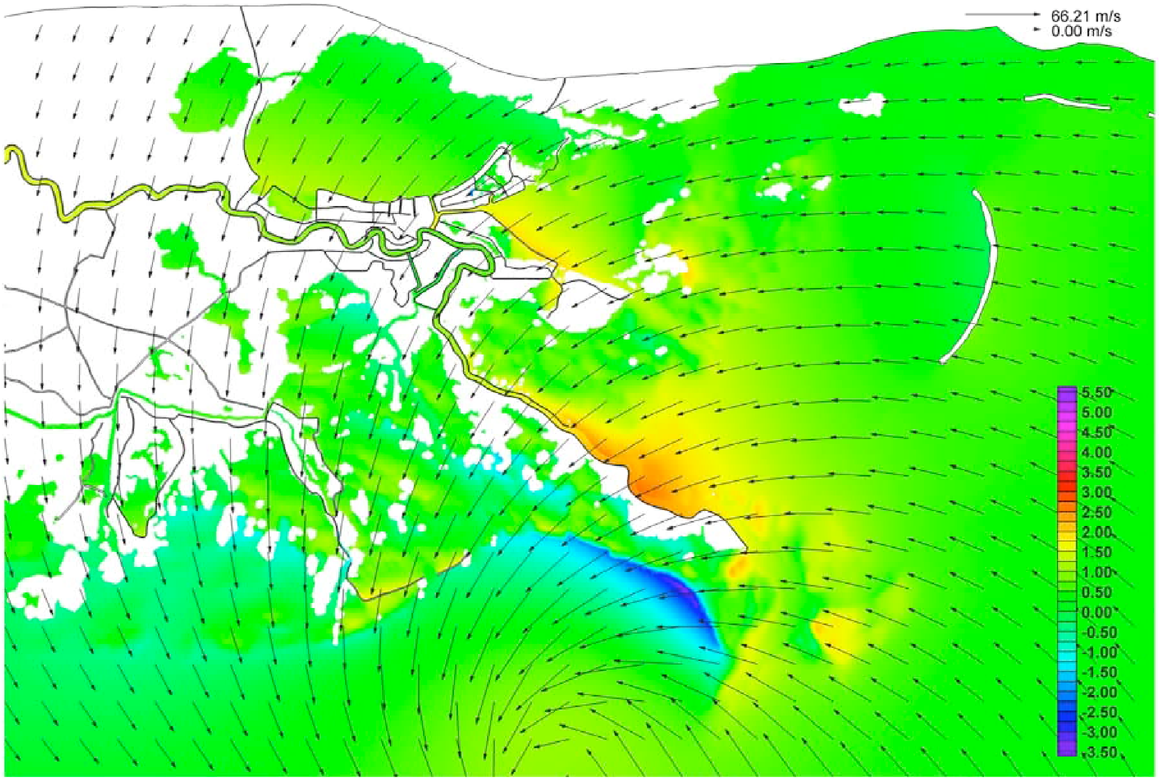

Figure 7b. Water surface elevation with respect to the geoid (m) with marine wind velocity vectors (m/s) during Hurricane Betsy on September 10, 1965 at 0200UTC.

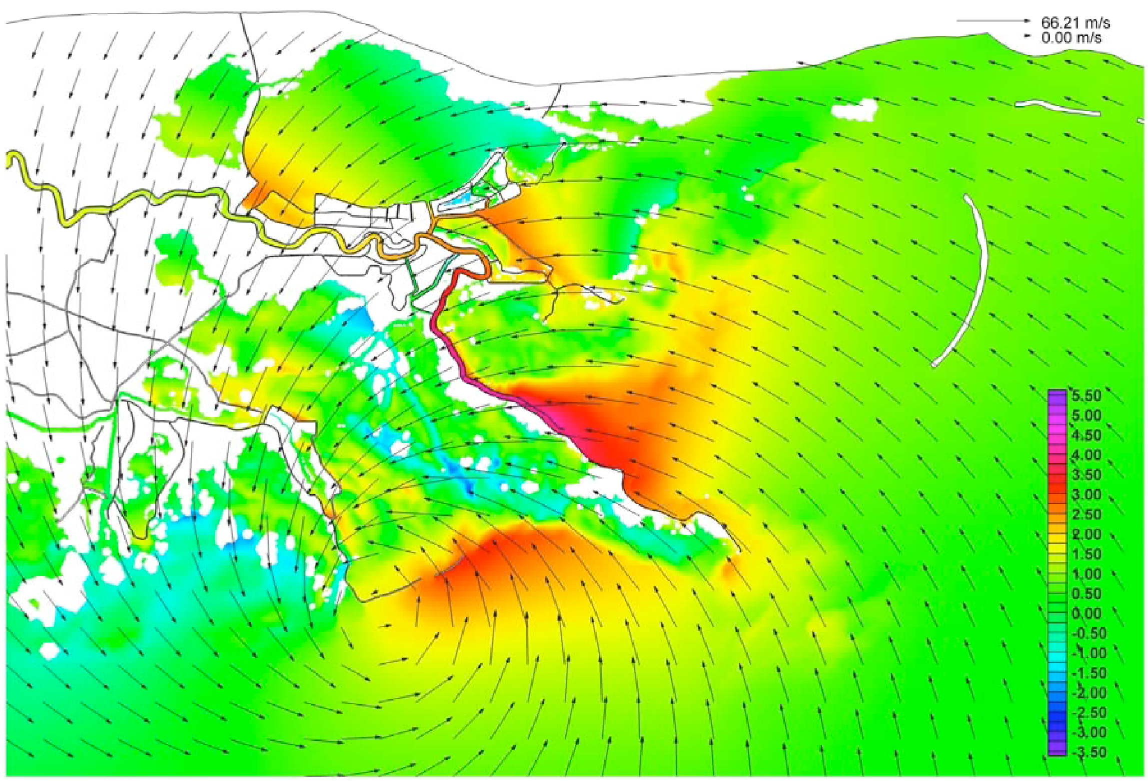

Figure 7c. Water surface elevation with respect to the geoid (m) with marine wind velocity vectors (m/s) during Hurricane Betsy on September 10, 1965 at 0400UTC (at landfall).

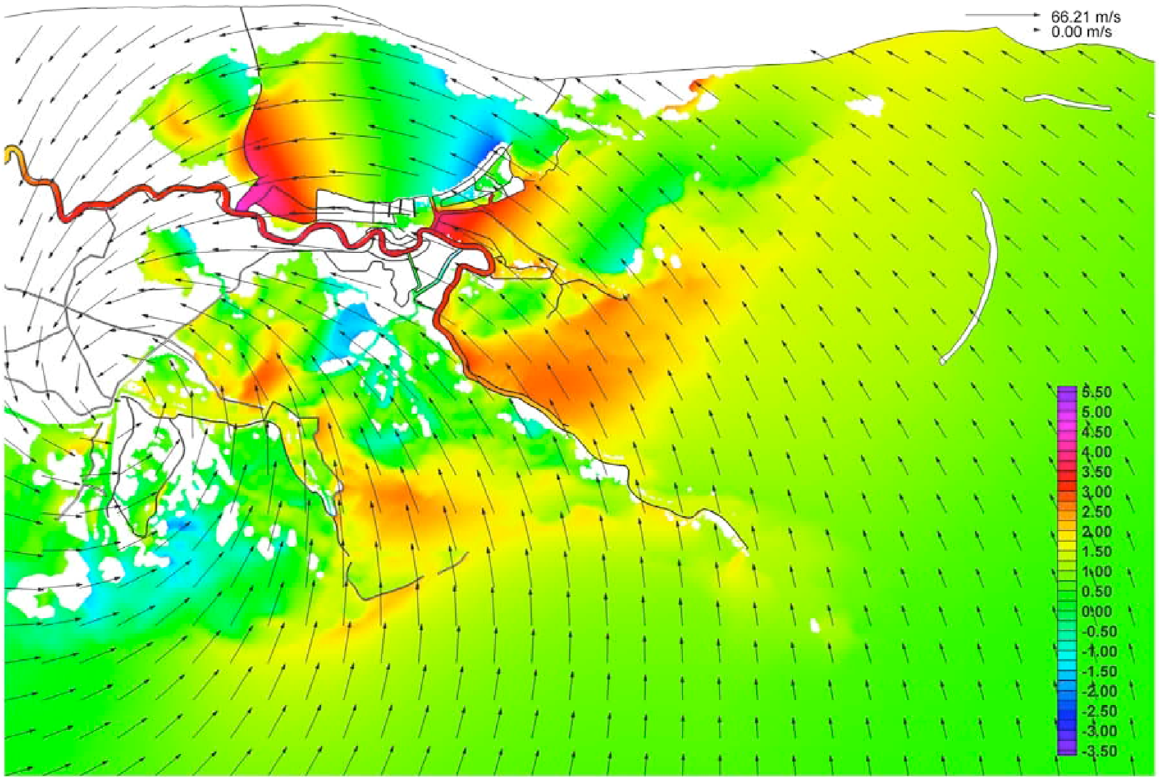

Figure 7d. Water surface elevation with respect to the geoid (m) with marine wind velocity vectors (m/s) during Hurricane Betsy on September 10, 1965 at 0600UTC.

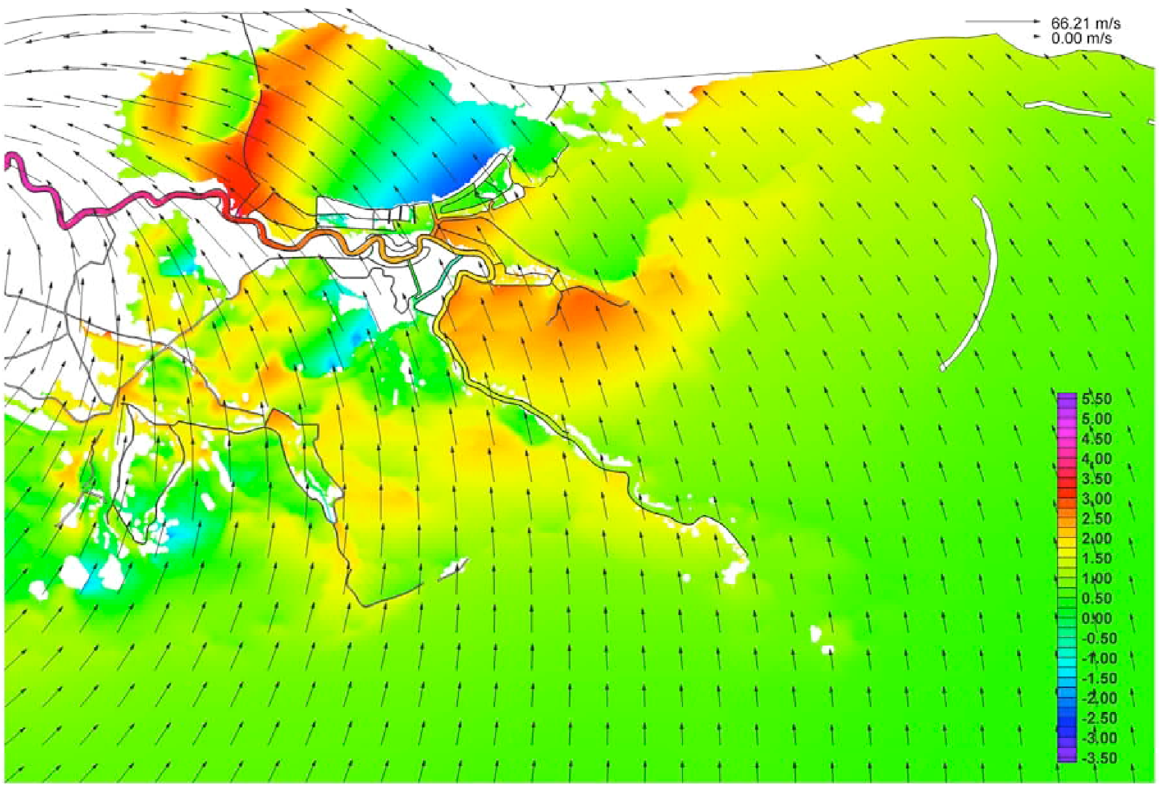

Figure 7e. Water surface elevation with respect to the geoid (m) with marine wind velocity vectors (m/s) during Hurricane Betsy on September 10, 1965 at 0800UTC.

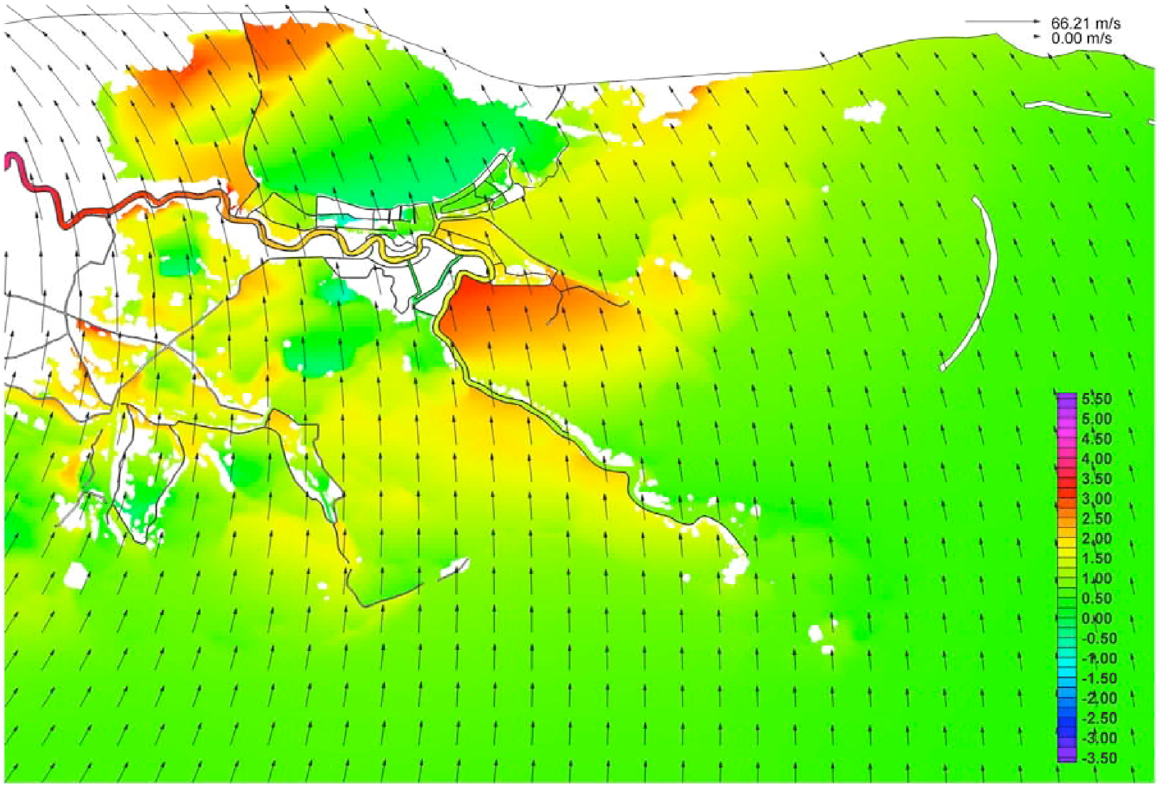

Figure 7f. Water surface elevation with respect to the geoid (m) with marine wind velocity vectors (m/s) during Hurricane Betsy on September 10, 1965 at 1000UTC.

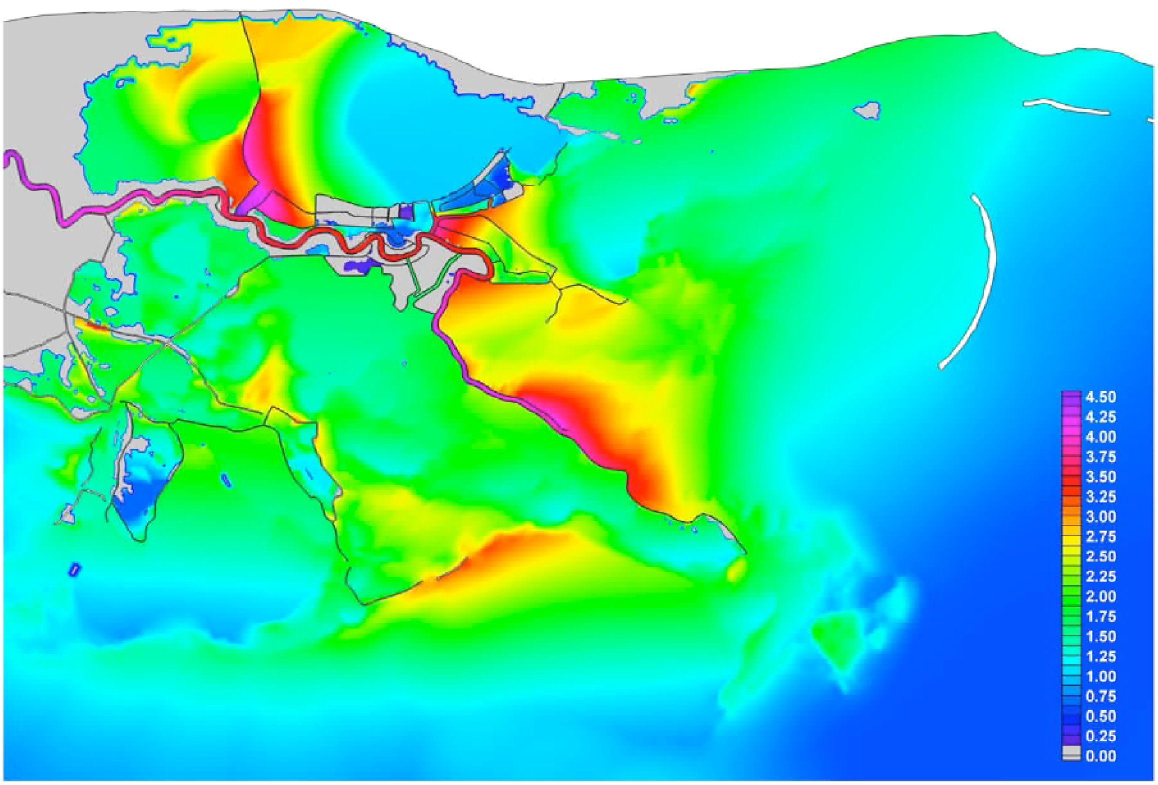

Figure 8. Peak storm surge elevation with respect to the geoid during the Hurricane Betsy event (m).

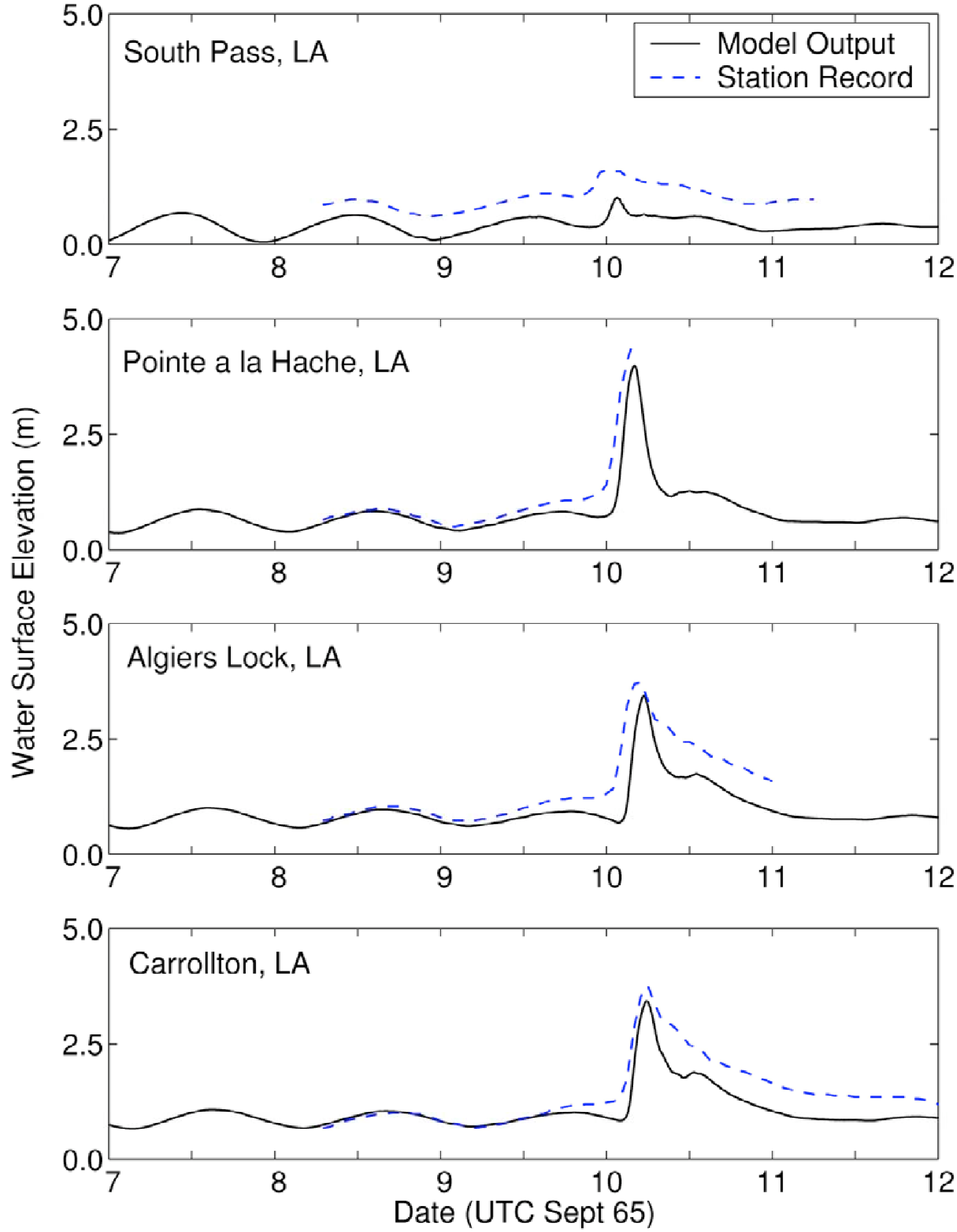

Figure 9. Hydrographs comparing recorded and modeled storm surge with respect to the geoid for Hurricane Betsy at locations along the Mississippi river (m).