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Modeling Hydrodynamics of the Mississippi Sound and Adjoining Rivers, Bays and Shelf Waters

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Abstract

A regional scale modeling system is being developed for the Mississippi Sound and adjoining Mobile Bay, Biloxi Bay, Bay St. Louis, and Lake Borgne. The modeling system, consisting of a three-dimensional circulation model, a cohesive and non-cohesive sediment transport model and a wave model, will provide a reliable means to forecast littoral circulation, sediment suspension and transport, and surface waves. The modeling framework adopts a high-resolution orthogonal curvilinear grid that adequately resolves the bathymetric and coastline features of the Sound, especially the region of the barrier islands. The southern model boundary follows the 200m isobath, a natural dynamical barrier between the Sound and the rest of the Gulf of Mexico. The model performance has been evaluated to date by conducting tidal simulations using boundary conditions derived from a global tidal model and then compared with tides at the IHO stations across the Mississippi Sound. Freshwater plume dynamics emanating from various estuarine systems dynamically connected to the Sound have also been evaluated using the current model. Future model improvements will involve novel open boundary condition schemes and wave-induced physical processes. A comprehensive model calibration/validation effort will then follow.

I. INTRODUCTION

Forecasting conditions in the littoral region involves numerous physical processes including tides, local atmospheric forcing and freshwater inflows. In addition, significant effects on circulation can result from waves. Moreover, sediment loads that impact clarity and optics within the water column are dependent on both circulation characteristics as well as surface waves. Sediment within the bottom boundary layer of the surface wave field impact the net drag at the bottom of the water column which in turn impacts circulation pattern. An accurate simulation of circulation patterns is vital for water quality modeling in the region. Thus, to produce reliable predictions of circulation in the Mississippi Sound littoral region, one must consider processes due to both surface waves and tidal-atmospheric-freshwater circulation. In order to model such physical processes, a physically comprehensive, three-dimensional estuarine and coastal ocean model (ECOM family of models) developed by [1] is being used. The model is driven by forcing mechanisms which include hydrographical (runoff), meteorological (surface wind), open ocean (large-scale ocean circulation), astronomical (tides) and internal (density gradients) forcing functions.

II. PHYSICAL CHARACTERISTICS OF MISSISSIPPI SOUND

The general morphological features of Mississippi Sound are illustrated in Figure 1. The present modeling study focuses on the processes governing circulation and tides in the Mississippi Sound and the adjoining bays, rivers, and shelf waters. These physical processes are depended on the geomorphology, freshwater discharge, tidal energy dissipation, and atmospheric and meteorological conditions in the system.

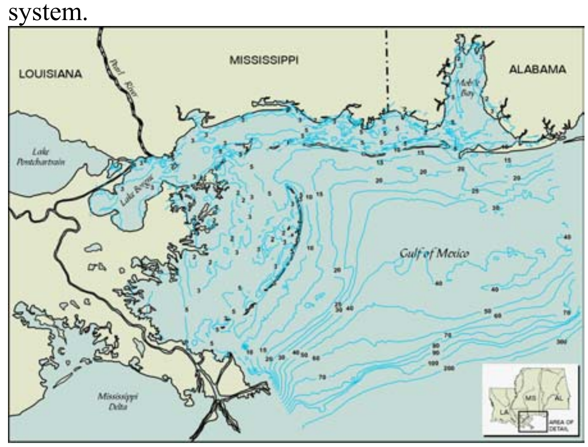

Fig. 1. Geographic and Bathymetric Features of the Study Area

The morphology tends to divide the entire study area into two different regions with markedly different bathymetric features. The upper and western Mississippi Sound is very shallow. The depth ranges from 1 to 3 m and is separated from the rest of the sound by series of barrier islands in the north and the Chandeleur Islands in the west. The rest of the sound is fairly deep with depths ranging from 3 m to 200 m. This deeper portion of the system is open to the Gulf of Mexico. The Mississippi Delta is located in the southwest part of the study area. Due to the complex bathymetric features of the Mississippi Sound, the circulation and tidal regimes are also significantly complex. Several bays, rivers and estuarine systems are included in the present modeling framework. These are Mobile Bay, Biloxi Bay, Bay St. Louis, and Lake Borgne.

III. HYDRODYNAMIC MODELING FRAMEWORK

The hydrodynamic model used in this study is a three-dimensional, time-dependent, estuarine and coastal circulation model developed by [1] and [2]. The model incorporates a 2.5 level turbulent closure model [3] to provide a realistic parameterization of vertical mixing. A system of curvilinear coordinates is used in the horizontal direction, which allows for a smooth and accurate representation of variable shoreline geometry. In the vertical, the model uses a transformed coordinate system known as the σ-coordinate transformation to permit better representation of bottom topography. Water surface elevation, water velocity (in three dimensions), temperature and salinity, and water turbulence are calculated in response to weather conditions (wind and incident solar radiation), freshwater inflows, and tides, temperature, and salinity in open boundaries connected to the coastal waters.

The model solves a coupled system of differential, prognostic equations describing the conservation of mass, momentum, temperature, salinity, turbulent energy and turbulence macroscale. The governing equations for velocity $U_i = (u, v, w)$, temperature (T), salinity (S), and $x_i = (x,y,z)$ are as follows:

$$\frac{\partial U_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(U,V) + \frac{\partial}{\partial x_i}\left[U_i(U,V) + f(-V,U)\right] = -\frac{1}{\rho_o}\left[\frac{\partial P}{\partial x}, \frac{\partial P}{\partial y}\right] + \frac{\partial}{\partial z}\left[K_M \frac{\partial}{\partial z}(U,V)\right] + \left(F_U, F_V\right) \qquad (2)$$

$$\frac{\partial T}{\partial t} + \frac{\partial}{\partial x_i}\left(U_i T\right) = \frac{\partial}{\partial z}\left[K_H \frac{\partial T}{\partial z}\right] + F_T \qquad (3)$$

$$\frac{\partial S}{\partial t} + \frac{\partial}{\partial x_i}\left(U_i S\right) = \frac{\partial}{\partial z}\left[K_H \frac{\partial S}{\partial z}\right] + F_S \qquad (4)$$

The horizontal diffusion terms, (F_U, F_V), F_T and F_S, in equations 2 through 4 are calculated using a horizontal diffusion formulation as in [5]. The hydrostatic approximation yields:

$$\frac{P}{\rho_o} = g(\eta - z) + \int_z^{\eta} g \frac{\rho - \rho_o}{\rho_o} dz' \qquad (5)$$

where P is pressure, z is water depth, η(x,y) is the free surface elevation, ρo is a reference density, and $\rho = \rho(T,S)$ is the density.

The vertical mixing coefficients, K_M and K_H, in equations 2 through 4 are obtained by appealing to a 2.5 order turbulence closure scheme and are given by:

$$K_M = \hat{K}_M + \upsilon_M, K_H = \hat{K}_H + \upsilon_H \qquad (6)$$

$$\hat{K}_M = q l S_M, \ \hat{K}_H = q l S_H \qquad (7)$$

where $q^2/2$ is the turbulent kinetic energy, l is a turbulence length scale, S_M and S_H are stability functions defined by solutions to algebraic equations given by [3] as modified by [6], and υ_M and υ_H are constants. The variables q^2 and l are determined from the following equations:

$$\frac{\partial q^2}{\partial t} + \frac{\partial u q^2}{\partial x} + \frac{\partial v q^2}{\partial y} + \frac{\partial w q^2}{\partial z} = \frac{\partial}{\partial z}\left[K_q \frac{\partial q^2}{\partial z}\right] + 2K_M\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right] + \frac{2g}{\rho_o} K_H \frac{\partial \rho}{\partial z} - 2\frac{q^3}{B_1 l} + F_q \qquad (8)$$

$$\frac{\partial q^2 l}{\partial t}+\frac{\partial u q^2 l}{\partial x}+\frac{\partial v q^2 l}{\partial y}+\frac{\partial w q^2 l}{\partial z}=\frac{\partial}{\partial z}\left[K_q \frac{\partial q^2 l}{\partial z}\right]$$
$$+E_1 l\left\{K_M\left[\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right]+\frac{g}{\rho_o} K_H \frac{\partial \rho}{\partial z}\right\}$$
$$-2\frac{q^3}{B_1} W + F_l \tag{9}$$

here $K_q = 0.2ql$, the eddy diffusion coefficient for turbulent kinetic energy; F_q and F_l represent horizontal diffusion of the turbulent kinetic energy and turbulence length scale and are parameterized in a manner analogous to either Equation 6 or 7; W is the wall proximity function [2] defined H is the water depth, η is the free surface elevation, and E_1, E_2 and B_1 are empirical constants set in the closure model.

The basic equations, 1 through 9, are transformed into a terrain following σ-coordinate system in the vertical scale and an orthogonal curvilinear coordinate system in the horizontal scale. The resulting equations are vertically integrated to extract barotropic variables; and a mode splitting technique is introduced such that the fast-moving, external barotropic modes and relatively much-slower internal baroclinic modes are calculated by prognostic equations with different time steps. Detailed solution techniques are described in [2].

IV. MODEL CONFIGURATION

An orthogonal, curvilinear grid system used in the present study is shown in Figure 2. The model grid consists of 170x122 segments in the horizontal plane and 11 equally spaced σ-levels in the vertical plane. The transformed σ-coordinate system in the vertical plane allows the model to have an equal number of vertical segments in all computational grids. It should be noted that

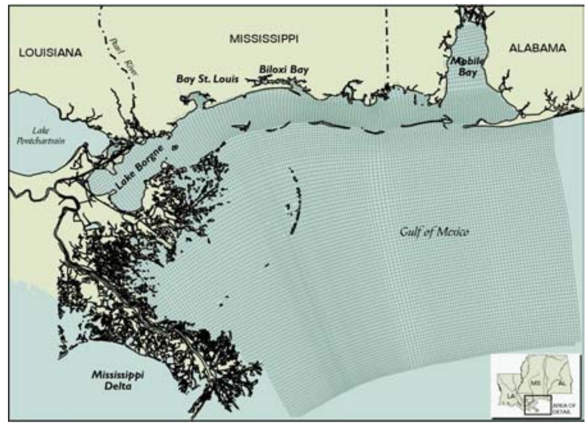

Fig. 2. 170x122 Orthogonal Curvilinear Grid

the curvilinear grid system allows for much finer grid resolution near areas of interest, such as the upper Mississippi Sound especially in the regions of Barrier Islands. A coarser grid system is adopted in the lower and deeper Mississippi Sound where modeling results are of secondary importance. This technique allows for the design of an efficient and computationally time-effective modeling framework.

The southern boundary of the model domain follows the 200m isobath, a natural dynamical barrier between the sound and the rest of the Gulf of Mexico. The eastern boundary follows the coastal bathymetry perpendicularly.

V. MODEL FORCING CONDITIONS

The purpose of the hydrodynamic modeling study is to reproduce the important physics of Mississippi Sound. This includes the three-dimensional circulation dynamics and transport mechanisms for sediment and other conservative and transformable substances. The model predicts these parameters in response to the boundary conditions assigned. Therefore, a credible and reliable set of boundary conditions is necessary in order to accurately reproduce the physical processes.

At present, there is little site-specific data available for boundary forcing conditions. Time-dependent sea surface elevation data are necessary to drive the model at all open boundary locations. A regional tidal prediction model has been used to generate tidal harmonic constants at the center of all open boundary grids. The present model uses these harmonics to generate real-time tides using a tidal prediction program by [7]. There are few freshwater sources in the Mississippi Sound system such as Mobile Bay, Biloxi Bay and Bay St. Louis. Annual freshwater flows through these sources were used for modeling simulations. It may be noted that the outflow from the Mississippi River was not included in the present modeling framework. Therefore, freshwater flow through the Delta was also not included. For these preliminary simulations of the model, only tides and freshwater flows were used to force the model. In the present modeling effort, the salinity and temperature along the open water boundary were assumed to be constant both spatially and temporally.

VI. CALIBRATION AND SKILL ASSESSMENT

The hydrodynamic modeling simulation was performed for 15 days starting from January 1, 1995. In order to firmly establish the credibility and robustness of the model used in this study, calibration and skill assessment of the model was accomplished by comparing model results against the predicted tides at eight International Hydrologic Office (IHO) stations across the Mississippi Sound as shown in Figure 3. Model performance was also assessed by examining the freshwater plume behavior in the Mississippi Sound.

A. Calibration against tidal data

Figures 4a and 4b present a comparison of model-computed (solid line) and predicted tides at IHO locations. The predictions of tides at these stations were made by using the tidal prediction program of [7] and the measured tidal harmonics by the IHO.

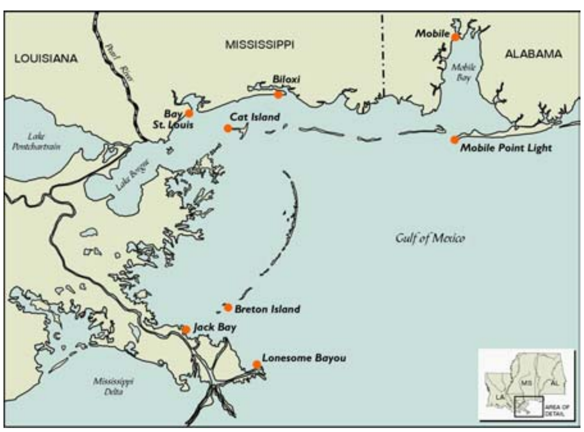

Fig. 3. IHO Stations

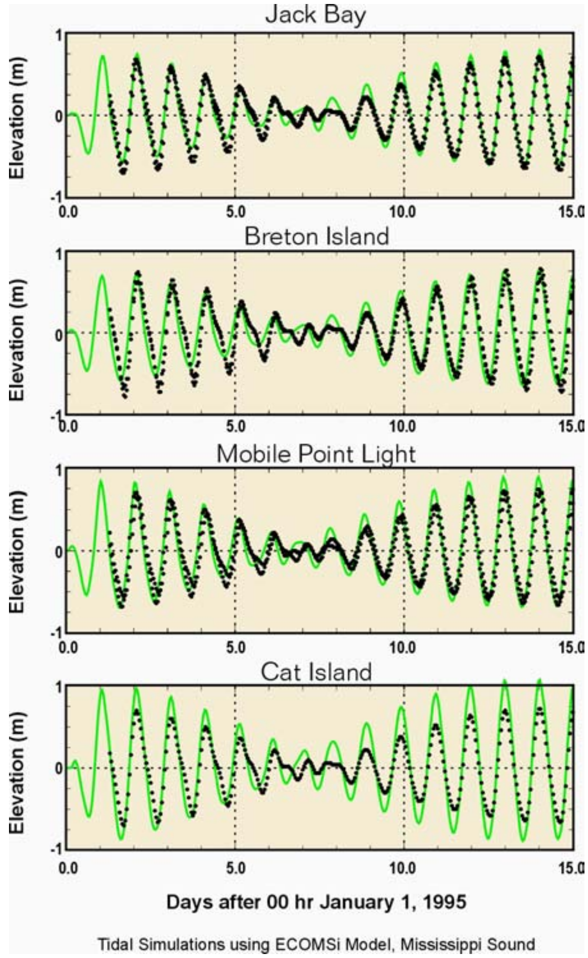

Fig. 4a. Model Computed Tides Comparing with IHO Data

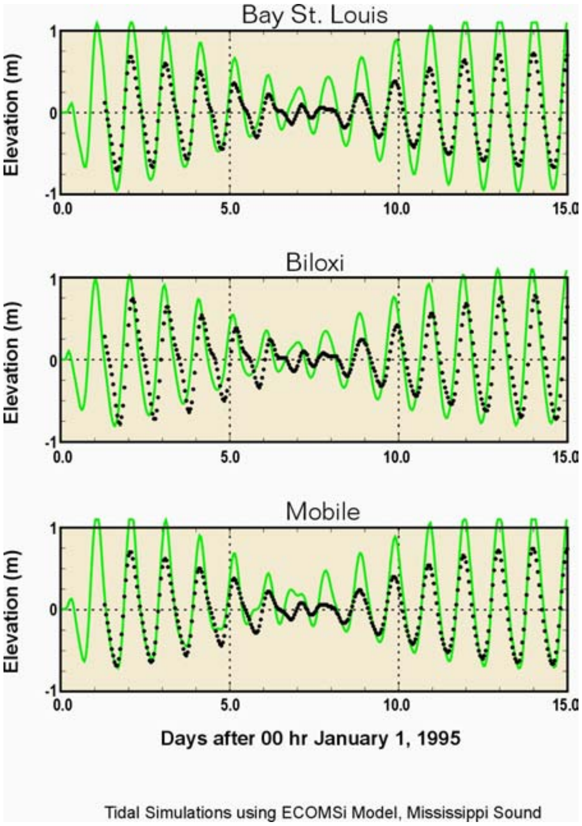

Fig. 4b. Model Computed Tides Compared with IHO Data

Figures 4a and 4b show that the model underestimates the tides at locations Cat Island, Bay St. Louis, Biloxi and Mobile. Note that these stations are located either inside the bays or in the region sheltered by the barrier islands. These regions are characterized by shallow depths which may significantly imparts bottom friction that may attenuate wave amplitudes. The model calibration needs to be improved by considering enhanced bottom friction in this area. It is important to note here that the model reproduces the tidal variations very well at stations Jack Bay, Breton Island, and Mobile Point Light. Also, the model reproduces the overall predominantly diurnal tidal fluctuations very well, with negligible phase differences. It is also evident from the figure that the model reproduces spring and neap tidal signals very well.

B. Examination of Tidal Propagation and Freshwater Plume Behavior

An important measure of model performance is how well the model computes the tidal regime in a region where significant variation in depth exists and tidal propagation is hindered by series of barrier islands. Figure 5 illustrates a three-dimensional graphical presentation of tides across the model domain for two periods with about 4 hours phase difference.

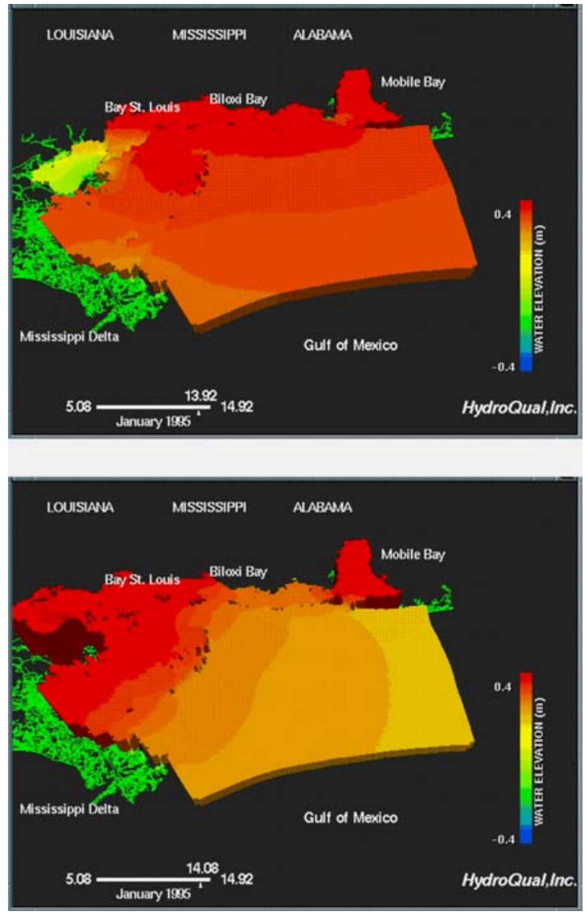

Fig. 5. Tidal Elevation Distribution in Mississippi Sound

Water level distribution shown in the top panel of Fig. 5 represents a flood tide event. It is clearly seen from the figure that there is a significant phase difference exists between tides in Lake Borgne and in the Lower Mississippi Sound area (outside the Chandeleur Islands). Similarly, the lower panel of Fig. 5 illustrates an ebb tide showing phase difference between the two regions inside and outside of the barrier and Chandeleur Islands. As mentioned before, the shallower regions and the barrier and Chandeleur Islands provide a significant resistance to tidal propagation, resulting in a phase difference in tides.

To gain an overview of the processes controlled by freshwater discharges from several sources such as Mobile Bay, Biloxi Bay and Bay St. Louis, modeling simulations have been performed using annual average freshwater flows through these sources.

Figure 6 illustrates the model computed freshwater plumes emanating from these sources and surface currents. It can be noted here that the modeling simulations are driven by only tides and freshwater discharges. Therefore, processes that are illustrated in Fig. 6 are direct response to these two forcing mechanisms. It appears from Figure 6 that the plumes resulting from these bays turned right upon exiting the bays. This is may be a result of the Coriolis effect or net tidal transport. It is interesting to note that the plumes stay predominantly in the upper Mississippi Sound region which is separated from the rest of the system by the barrier islands and the Chandeleur Islands. It is also seen that the surface currents in the region bounded by the barrier and Chandeleur Islands are much stronger than the rest of the sound.

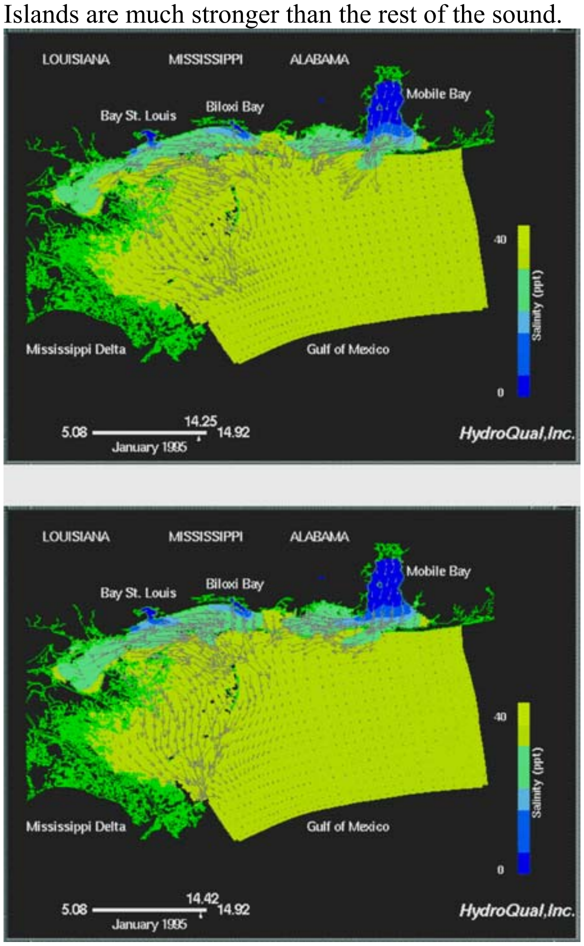

Fig. 6. Freshwater Plumes and Surface Currents in Mississippi Sound

VI. CONCLUSIONS

The time variable, three-dimensional hydrodynamic model of Mississippi Sound system was verified using observed tidal data at eight IHO stations. The hydrodynamic model represents the overall circulation and mixing characteristics of the Mississippi Sound based on the reasonable agreement between observed and predicted tidal fluctuations. The modeling effort presented here is part of an ongoing study. Significant upgrades to the model physics are in progress. Novel open boundary conditions are being evaluated [8] and other important physics are being added to the modeling framework. These include wave-enhanced bottom friction, Stokes drift, the Coriolis wave stress, etc. An extensive data collection effort is underway. Model performance will be re-evaluated using these data when they become available.

ACKNOWLEDGEMENTS

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