# Development of a Forecast Capability for Coastal Embayments of the Mississippi Sound

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***Abstract*-The present work focuses on results from the second phase of development of a forecast system for coastal circulation in the Mississippi Sound and surrounding embayments in the northeast Gulf of Mexico. The basis of the forecast system is the 3-D finite element model, ADCIRC, driven by tides, river inflow, and wind. Sensitivity of the forecast model to wind stress and offshore boundary forcing is demonstrated. Limited area domain models of Bay St. Louis and the Pearl River highlight the influence of seasonal river flux.**

## I. INTRODUCTION

Coastal embayments link inland marshes to open coastal waters, serving as filters for runoff, nurseries for a variety of fish species, protection for coastal communities, and hosts for recreational activities. Each of these functions is affected in a primary way by circulation within the embayment. A numerical model that incorporates the range of important dynamical forcing and represents embayment shoreline and bathymetry at fine scales can be exercised as a virtual laboratory for understanding embayment circulation with a distinct economic advantage over the maintenance of dense and varied observational networks.

A forecast system for coastal circulation in Mississippi Sound and surrounding embayments is being developed in three phases. The first phase entailed the development and testing of the software infrastructure that automates model predictions over a regional domain defined by the Mississippi Bight. In the second phase, individual models of surrounding embayments and rivers are constructed and their sensitivity to forcing conditions is assessed. Select results from this second phase are the primary topic of this paper. The final phase will incorporate the nearshore embayment and river models into the regional forecast system and predictions will be evaluated using available in-situ observations for comparison. The anticipated result is a robust and accurate coastal circulation forecast system that will aid in understanding the movement of pollutants within the Mississippi Sound and surrounding bays and their impact on important fisheries in the region.

Descriptions of the forecast system including the circulation model ADCIRC, the Mississippi Bight and limited area (i.e., Bay St. Louis and the nearby Pearl River) computational domains, and the applied dynamical forcings are given in section II. A discussion of the sensitivity of current forecasts to wind stress, the offshore boundary, and river forcing is presented in sections III, IV, and V. Concluding remarks drawn from the analyses and a summary of future directions are given in section VI.

## II. THE COASTAL FORECAST SYSTEM

### *A. Description of the Circulation Model*

The coastal forecast system as presently configured contains a 3-D circulation model based on shallow water dynamics and forcing modules that account for contributions from rivers, tides, and surface wind stress. The circulation model that forms the core of the forecast system is ADCIRC, the ADvanced CIRCulation model, developed by [1] and [2]. ADCIRC-3D is a fully nonlinear, time domain finite element hydrodynamic model that solves the vertically-integrated continuity equation and the 3-D momentum equations (subject to the Boussinesq and hydrostatic pressure approximations) for surface water elevation and currents. ADCIRC-2DDI is the two-dimensional depth-integrated form of the ADCIRC model. To avoid the spurious oscillations that are associated with a primitive Galerkin finite element formulation of the continuity equation, ADCIRC utilizes the Generalized Wave Continuity Equation (GWCE) ([3]). All calculations discussed in this paper are performed using ADCIRC-2DDI, selected because of its successful history of tidal and storm surge prediction in coastal waters and embayments ([4], [5], [6], [7]) and the inherent flexibility in representing realistic geometry afforded by the use of finite elements.

A software infrastructure developed for the forecast system during phase one handles the processing of real-time forcing data, including temporal interpolation for missing data and spatial interpolation onto the computational grid of the circulation model. The software is also responsible for set-up and execution of the model and the post-processing of computed sea surface height and current fields to create standard forecast products.

*B. Description of the Computational Domain*

The domain encompasses the Mississippi Bight (MSBIGHT, Fig. 1), which lies in the NE Gulf of Mexico. Shallow bathymetry of less than 200 m requires resolution that ranges from 4.5 km in the deeper waters to 120 m at the coast. Model bathymetry is derived from the three arc-second survey of the Northern Gulf of Mexico Littoral Initiative (POC: John Blaha at the Naval Oceanographic Office, Stennis Space Center, MS).

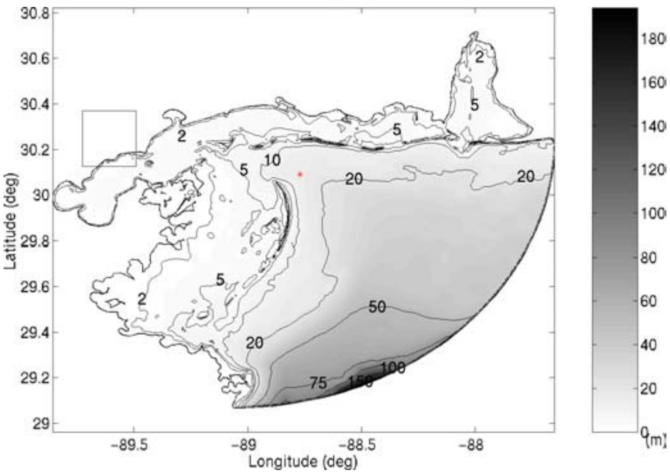


Fig. 1. Bathymetry of the Mississippi Bight domain. Contours are shown at 2, 5, 10, 20, 50, 100, and 150 m. The location of NDBC buoy 42007 is depicted by an asterisk (*). The location of the Pearl River model is identified by the bounding box in the NW corner of the domain.

Developments within phase two include the construction of individual high-resolution models of bays and rivers, using the bathymetry of the MSBIGHT regional domain and refining the coastline and the computational grid. Ultimately, these limited domain models may be incorporated into the regional MSBIGHT domain with the result being a comprehensive forecast system shelf to shore. As individual models, they allow more timely numerical investigations into local processes such as the effect of forcing mechanisms on circulation. Two of the limited domain models discussed in the analyses presented are a model for Bay St. Louis, MS and the nearby Pearl River, MS.

Bay St. Louis is a shallow bay with an average depth of 1.5 m (Fig. 2) situated in the northeast Gulf of Mexico along the Mississippi coast. A connection to the offshore waters of the Mississippi Sound (the waterbody between the shore and the barrier islands) is provided through an inlet approximately 3 km wide and 300 m long. The depth contours are fairly uniform in the bay except along the axis of the inlet and along dredged shipping channels that extend both west and east from the center of the bay where waters deepen to nearly 4 m. Depths increase monotonically towards the shelf, although some shallow shoals are found in the Mississippi Sound outside the bay. The open ocean boundary of the computational domain is situated within the Mississippi Sound some distance away from the entrance to the inlet. The bay itself is approximately 12 km in the east-west direction, and is resolved to between 70 and 100 m using a finite element mesh. Coarser resolution, up to 700 m, extends offshore.

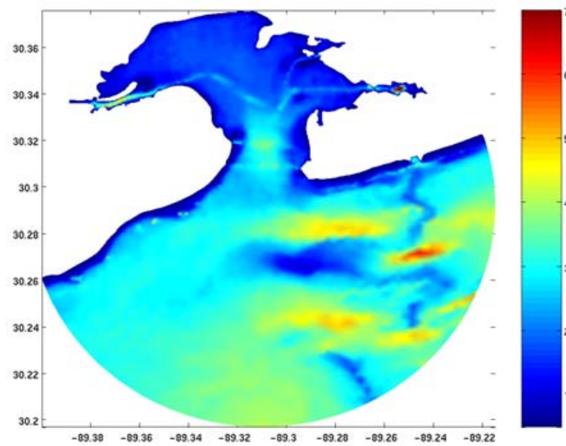

Fig. 2. Bathymetry of the Bay St. Louis model. Bathymetry contour range from 1 to 6 meters.

The Pearl River drains into the Mississippi Sound west of Bay St. Louis forming a border between Mississippi and Louisiana. The domain is identified in Fig. 1 by a bounding box in the NW corner of the Mississippi Bight. The shallowest water depths (based on NGLI bathymetry) are 5 m above sea level and occur at the head of the river; water depths gradually increase moving southward along the river to a maximum of 14 m at the west entry of the Pearl River into the Mississippi Sound (see Fig. 3).

The grid for the Pearl River contains 29304 computational points that provide resolution from 3 to 275 m (Fig. 4). The finest resolution is found along tributaries that flow into the main channel of the river (e.g. Fig. 4). Two open ocean boundaries, one to the east and one to the west, are located within the Mississippi Sound as depicted in Fig. 3.

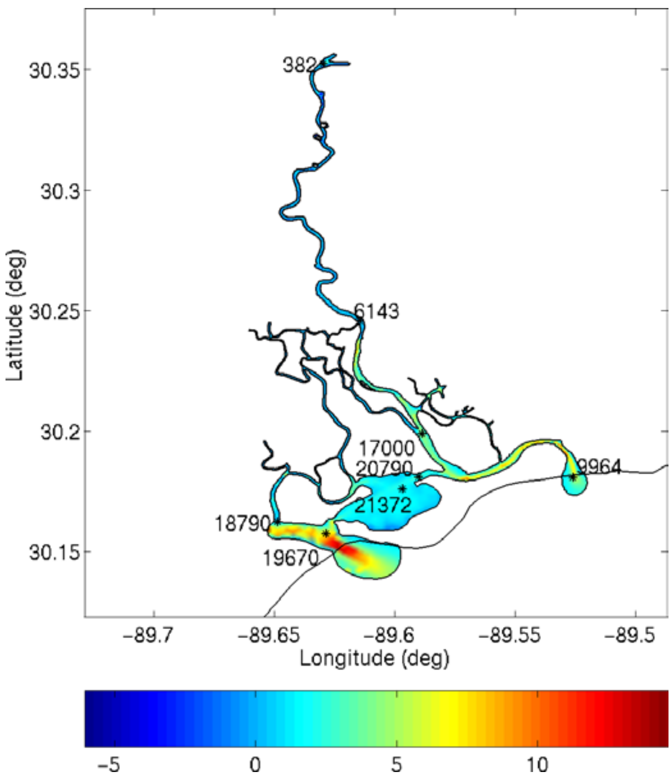


Fig. 3. Bathymetry of the Pearl River model. Contours range from 5 m above sea level to 14 m below. Eight stations are identified by their node number and the intersection of the MSBIGHT boundary with the Pearl River model is shown.

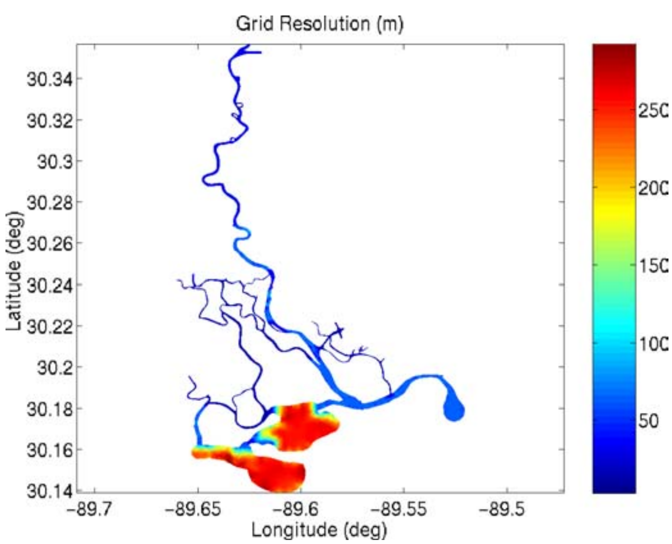


Fig. 4. Resolution of the Pearl River model grid. The range is 3 to 275 m.

### *C. Model Forcing*

Forcing from tides, winds and rivers are presently included within the model forecasting system. Tidal forcing at the open boundary of both regional and limited area domains are based on larger domain model solutions. The MSBIGHT model derives its forcing from the eight primary constituents of the recent EC2001 tidal database computed over the western north Atlantic model domain (an updated version of [8]); boundary values for this database are taken from the assimilative global tidal model of LeProvost [9]. Those same eight constituents force the tides internal to the domain through standard tidal potential terms. When additional forcing is required, streamflow measured by USGS river gauges is applied as a flux time series at the upstream boundary of the river. Surface wind stress is typically computed using the formulation of [10] and 10 m winds obtained from the Coupled Ocean Atmospheric Mesoscale Prediction System (COAMPS) [11].

Two types of forcing are considered for the limited area domain studies of Bay St. Louis and the Pearl River: river flux from USGS gauge data and specified elevations which takes the form of harmonic tidal forcing from the MSBIGHT solution. Six primary tidal constituents ($K_1$, $O_1$, $Q_1$, $M_2$, $N_2$ and $S_2$) are prescribed in the form of amplitudes and phases along the open boundary of the Bay St. Louis grid. All but the $Q_1$ and $N_2$ are used for Pearl River simulations.

Historically, the Jourdan River connects to Bay St. Louis from the east but no measurable flow exists today. Daily historical data for measured discharge from the Wolfe River is obtained from a USGS stream-flow gauge. Spring rains are the major source of river discharge though strong winter storms can lead to significant flow. An average spring flow condition (30 $m^3/s$) is defined by the mean of the daily discharge during the months of February–April 1993-1997. A representative maximum discharge of 300 $m^3/s$ is taken from the maximum flow conditions during 1996.

At the head of the Pearl River, a time series of USGS streamflow data measured at the Pearl River, LA station from October 1, 1963 to September 30, 1970 is processed for the spring (March-May) and fall (September-November) seasons. Both the norm (the mean after the removal of outliers beyond three standard deviations) and the maximum (the mean of the data between one and two standard deviations of the norm) streamflows are computed and applied as fluxes at the northernmost boundaries. Table 1 details values for the norm and max streamflow used as forcing during the spring and fall seasons.

TABLE 1
Seasonal Streamflow ($m^3/s$) at the Pearl River, LA Station

| | SPRING | FALL |
|---|---|---|
| Norm | 46.72 | 8.99 |
| Maximum | 87.05 | 14.77 |

## III. SENSITIVITY TO WIND STRESS

AUVFEST 2001, a two-week period for experimental autonomous underwater vehicle (AUV) operations off Ship and Horn Islands in the Mississippi Sound, provided a forum for testing a preliminary version of the ADCIRC model forecast system. Predictions of computed sea surface height and currents at 3-hour intervals for a 48-hour period were provided once per day from October 22 –

November 2, 2001. For this application, tides were the only forcing considered given that the primary goal of the exercise was to develop the software infrastructure to automate model forecast applications. Details of the operational forecast system are identical to those described by [12]. The inclusion of wind forcing into the model forecast system provides the motivation for the examination discussed here.

The Navy wind product often used to drive coastal circulation forecasts is obtained from COAMPS. Over the Mississippi Bight, the resolution of COAMPS products is 27 km, a rather coarse resolution for capturing small-scale coastal dynamics. An evaluation of the sensitivity of predicted currents to the wind stress forcing is thus warranted.

A comparison of the currents computed using two sources of wind forcing provides a basis for assessing the forecast system sensitivity to wind stress. The period of May 15-29, 2001 is selected because of the availability of other in-situ observations for later comparisons. During these 15 days the circulation model is forced by wind stress computed using COAMPS winds shown in Fig. 5 for the location identified by the asterisk in Fig. 1. Simulations that include a) tidal forcing and no wind stress, and b) tidal forcing and wind stress together are compared in Fig. 5. Winds initially directed towards the SW switch after 4 days to a northwesterly direction with magnitudes decreasing within a diurnal cycle for nearly 5 days. On May 24 (day 9) winds then turn back toward the SW increasing in intensity through May 29. For the final day of simulation, winds are from NW at a magnitude double that previously experienced. Upon removal of the tidal currents from the tide and wind forced solution, residual currents (tide plus wind forcing solution minus the tide forcing solution) retain a northerly component despite of the reversals of wind direction.

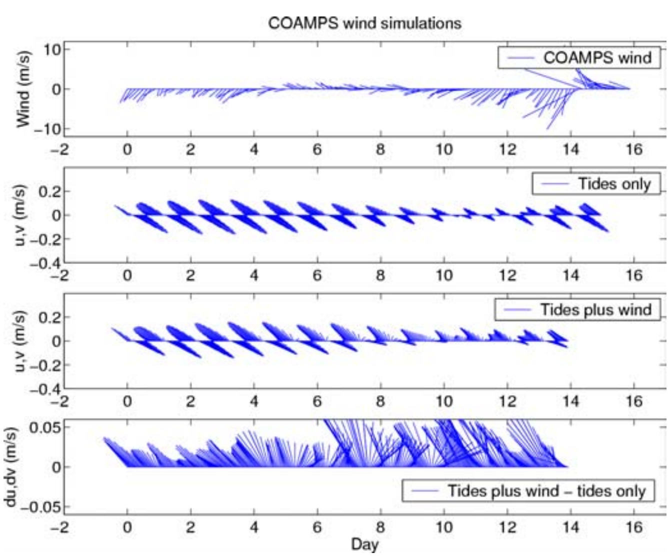


Fig. 5. Sensitivity to wind forcing. 1) COAMPS winds May 15-29, 2001; 2) computed currents forced by tides only; 3) computed currents forced by tide and wind stress; 4) currents from 3) minus the currents from 2).

The series of simulations described above is repeated with the exception that wind stress forcing over the entire domain is obtained from winds measured at the National Data Buoy Center (NDBC) buoy station 42007 (indicated by an asterisk in Fig. 1). Note the considerable difference in the wind magnitude and direction recorded at the buoy (Fig. 6) versus those provided by the COAMPS data (Fig. 5). Buoy winds are directed primarily to the SW with larger magnitudes than those of the COAMPS product, but most notable is the presence of storm events that yield northerly winds. As seen in Fig. 6, the residual current is quite different from that of the COAMPS forced simulation. Further, response to the wind events is apparent at the buoy location.

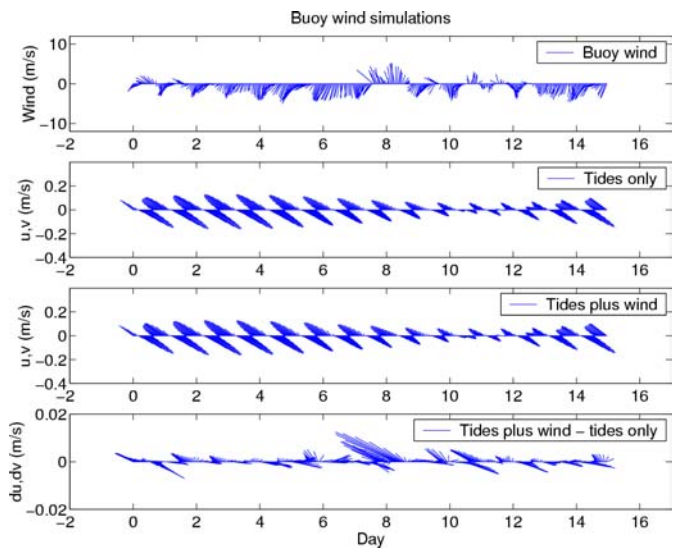


Fig. 6. Sensitivity to wind forcing. 1) NDBC Buoy 42007 winds May 15-29, 2001; 2) computed currents forced by tides only; 3) computed currents forced by tide and wind stress; 4) currents from 3) minus the currents from 2).

The importance of the wind stress field is evident through contrasting the computed circulation on May 22, 2001 09Z (day 7.325) shown in Fig. 7 with the currents predicted on May 23, 2001 09Z (day 8.325) (Fig. 8). The northerly wind burst occurring on May 23 damps current magnitudes, a consequence of Ekman turning of the currents eastward in opposition to the NW directed tidal currents. The currents around Chandeleur Island (nearest to the NDBC buoy in Fig. 1) and through barrier island passes in the northwest are particularly affected. Wind conditions on May 22 are more quiescent and current magnitudes more iontense in shallow passes along the path of tidal propagation. Overall, however, circulation patterns remain unchanged by the presence of wind stress.

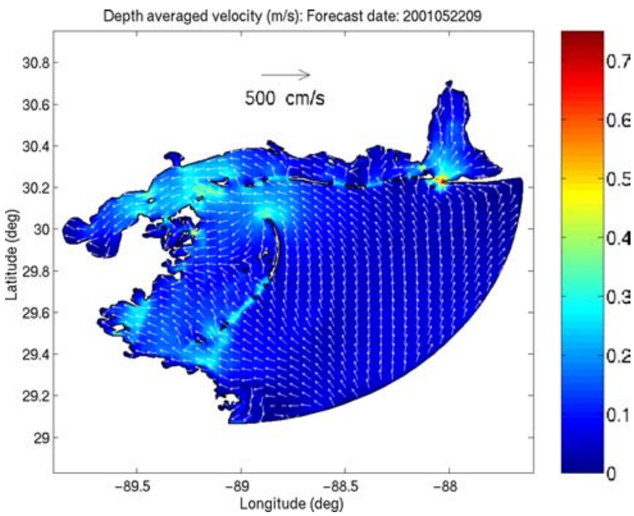


Fig. 7. ADCIRC computed currents on May 22, 2001 09Z forced by NDBC buoy winds and tides. Current magnitudes are contoured; directions are indicated by the arrows.

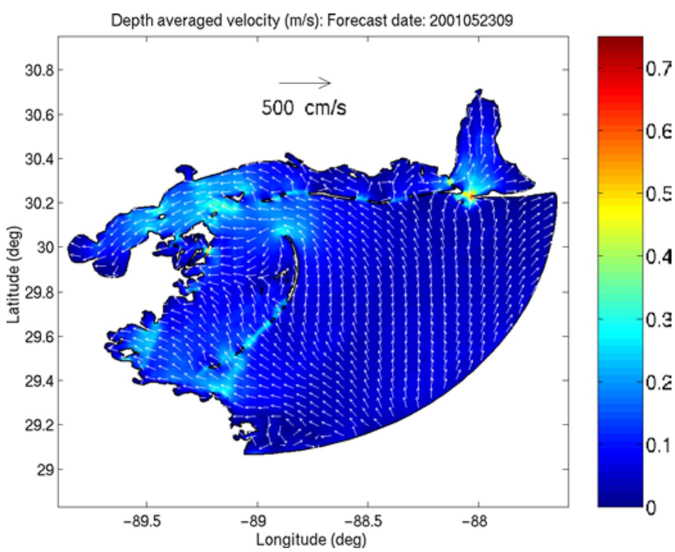


Fig. 8. ADCIRC computed currents on May 23, 2001 09Z forced by NDBC buoy winds and tides. Current magnitudes are contoured; directions are indicated by the arrows.

## IV. INFLUENCE OF OPEN BOUNDARY FORCING

A data assimilative approach can be used to obtain optimal boundary conditions, but also serves as an important diagnostic for the sensitivity to open boundary forcing. The finite element, frequency-domain based inverse model TRUXTON [13] is applied to the MSBIGHT domain for this purpose (similar to the study by [14]). A 50x50 array of theoretical observations is sampled at the two dominant tides, $M_2$ and $O_1$, and assimilated given the linear dynamics of the inverse model. A 'correlation' matrix effectively records the response of velocity to unit forcing at each of the boundary nodes for each observation. Shown in Fig. 9 for $M_2$ and Fig. 10 for $O_1$ are the mean absolute values of the modulus of the complex correlations where the means are taken over all boundary nodes.

Obviously a strong correlation between the offshore currents and the boundary values for both tidal constituents exist. The $O_1$ tide propagates from offshore in a northwesterly direction perpendicular to the bathymetric contours. Correlation bands mirror the direction of diurnal tidal propagation but the influence of the boundary values is noticeably reduced in the shallower waters and bays. The one exception is the pronounced correlation between currents at the barrier island passes and the N-S component of velocity.

This general pattern is also true for the semi-diurnal tide. In Fig. 10, the $M_2$ tide most definitely exhibits a dependency on boundary forcing throughout much of the open ocean (particularly with respect to the E-W component of velocity). Correlations in the shallow coastal waters behind the barrier islands and into the embayments are more significant. The type of analyses presented here offers a succinct approach for assessing the relative importance of the boundary forcing; additionally the correlations can prove quite useful in planning an observational program.

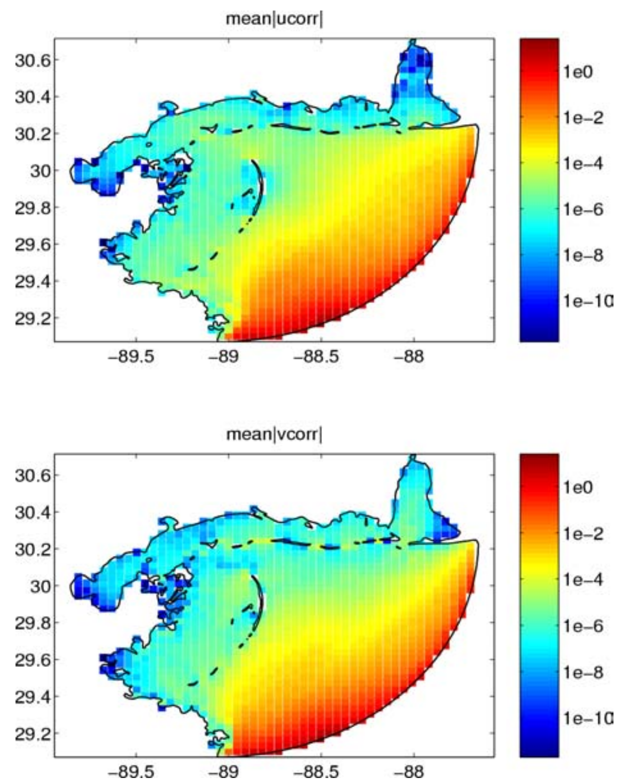


Fig. 9. Mean absolute values of the modulus of the complex correlations for the $O_1$ tide E-W and N-S velocity components.

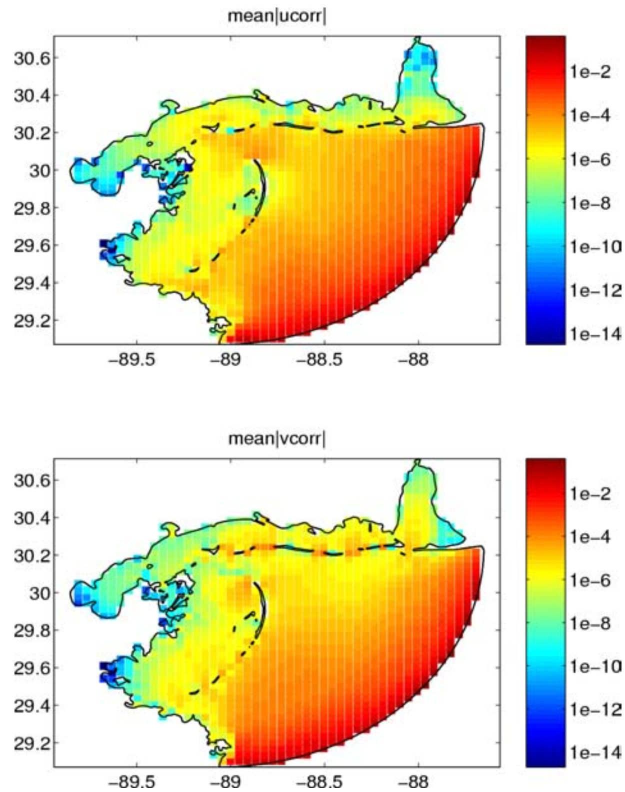


Fig. 10. Mean absolute values of the modulus of the complex correlations for the $M_2$ tide E-W and N-S velocity components.

## V. INFLUENCE OF SEASONAL RIVER FLUX

### *A. Bay St. Louis, MS*

The retention of high fecal coliform levels in Bay St. Louis suggests that flushing of the bay is limited or occurs over very long time scales. This is confirmed and detailed by the analyses of [15]. To summarize, simulations are performed that reflect summer and fall conditions (tidal forcing with no discharge from the Wolfe River), spring and winter conditions (tidal forcing and an average river discharge) and severe isolated storm events (tidal forcing and a maximum river discharge). An examination of passive drogue pathways under these varied forcing conditions suggests that Bay St. Louis is flushed over a period of 15-30 days only in response to extreme, isolated river discharge events.

### *B. Pearl River, MS*

The estuarine influence of the Pearl River is known to extend into the Mississippi Sound eastward to the marshes of Biloxi, MS and westward to Lake Ponchartrain and Lake Borgne in Louisiana, affecting important nursery areas for fish and shellfish. River sediments from the Pearl River are also known to contain very high levels of mercury and have resulted in contaminated fish populations now found in the Mississippi Sound and spreading through the Rigolets to Lake Ponchartrain. A first step towards assessment of this problem is the simulation of Pearl River outflow and its interaction with waters of the Mississippi Sound.

To examine interactions of the offshore tides with the Pearl River currents, a series of experiments under varied forcing conditions is conducted. Several mechanisms are responsible for the dynamical forcing along the Pearl River channel: a) tidal excursion from the tidally influenced open water boundaries (elev only case), b) an upstream river flux as measured by a stream gauge (flux only case), or a combination of tidal and streamflow forcing (elev+flux case). Mean streamflow values during the spring and fall are selected to represent the extremes between wet and dry periods. Simulations extend for 5 days following a 1-day spin-up period. Note that the model configuration for the Pearl River presently imposes a 1 m minimum depth and allows nonlinearities only through the bottom friction term.

Time series of the Pearl River current components are depicted at five stations (Figs. 11-15). Stations are ordered following a N-S progression down the river from the northernmost station (#382) to the two stations near open coastal waters, one to the west (#19670) and one to the east (#9964). Locations of the stations within the Pearl River domain are labeled in Fig. 4.

In the northernmost reach of the river, represented by stations 382 and 6143, the tidal signal (elev only) is clearly muted by the streamflow of the river itself (elev+flux) as seen in Figs. 11 and 12. However, a diurnal signal does persist throughout the 5 days and asymmetries in the peak and troughs further indicate the presence of nonlinear interaction between the tidal excursion and currents generated by the river flux. The largest differences between spring and fall conditions occur at stations 382 and 6143 (Figs. 11 and 12).

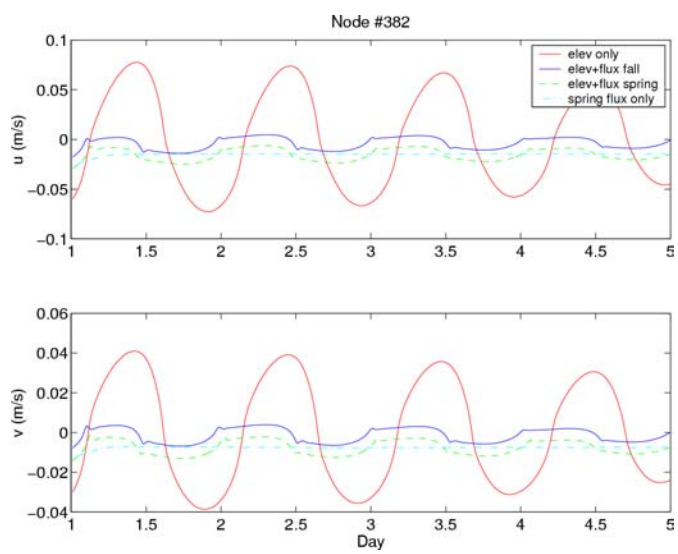


Fig. 11. Pearl River E-W and N-S velocity components at station #382 for three forcing conditions in spring and one in fall.

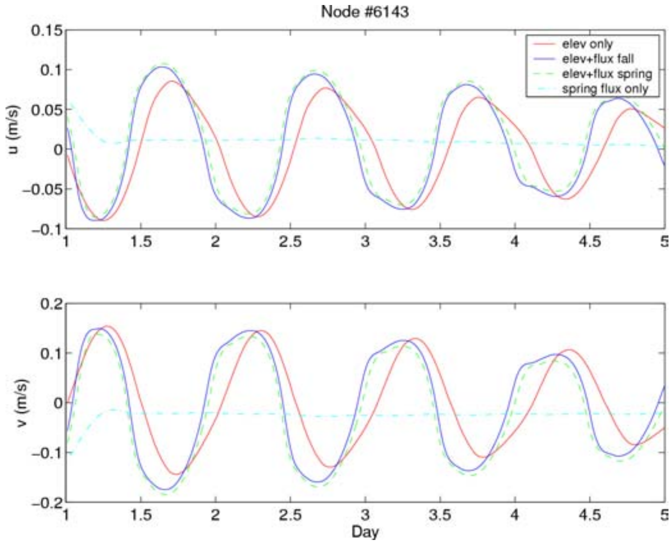


Fig. 12. Pearl River E-W and N-S velocity components at station #6143 for three forcing conditions in spring and one in fall.

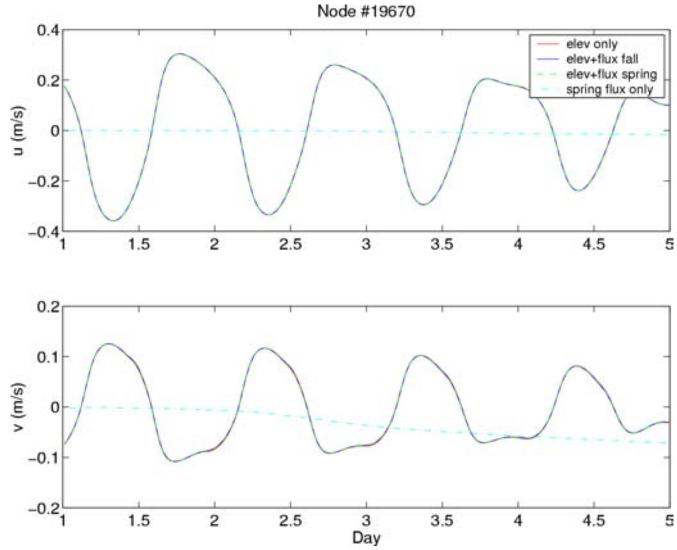


Fig. 14. Pearl River E-W and N-S velocity components at station #19670 for three forcing conditions in spring and one in fall.

While all stations are diurnally-dominated, the southernmost stations show some influence of the semi-diurnal tides, manifest as weak higher-low water and trace signals of a lower-high water. At stations 21372, 19670, and 9964 (Figs. 13-15), fall and spring current components are essentially identical indicating a dominance of tidal dynamics in the southern portion of the river. The clear sensitivity of the river currents to tidal forcing ties the river dynamics explicitly to the dynamics of the coastal ocean.

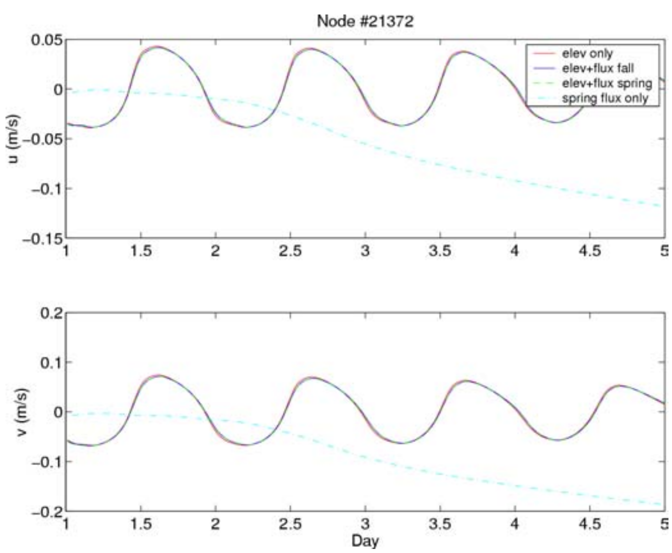


Fig. 13. Pearl River E-W and N-S velocity components at station #21372 for three forcing conditions in spring and one in fall.

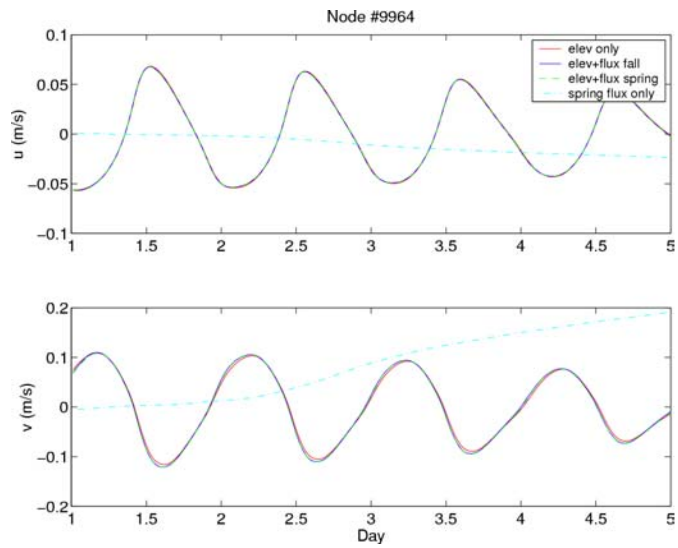


Fig. 15. Pearl River E-W and N-S velocity components at station #9964 for three forcing conditions in spring and one in fall.

## VI. CONCLUDING REMARKS

A forecast system for coastal circulation based on the finite element model ADCIRC consists of a regional domain for the Mississippi Bight (MSBIGHT) and several limited area domains of surrounding embaymants and rivers; these local models contain higher resolution and more refined coastal geometries. Together the MSBIGHT model and local models of Bay St. Louis and the Pearl River provide a testbed for the sensitivity studies presented. Of particular interest is the importance of wind stress forcing on the circulation dynamics and the sensitivity of the computed current response to wind field source. The Navy operational winds from COAMPS are found to be unrepresentative of the observed NDBC buoy winds at one location. The discrepancy is perhaps due to the coarse resolution of the COAMPS products (27 km) and the sensitivity of the model circulation to localized short-term wind events. Forecast currents respond without a notable time lag to the northerly wind bursts in the Mississippi Bight reducing tidal currents associated with the NW diurnal tide propagation particularly through the barrier island passes.

The application of a data assimilative model to assess the influence of boundary data on linear circulation dynamics illuminates the differing responses of the diurnal versus the semi-diurnal tidal components of the currents. The semi-diurnal tide is most affected by the open ocean boundary forcing throughout the domain and especially in shallow waters and in embayments. In contrast, the boundary influence on diurnal currents is limited to the direction of propagation and generally decreases with increasing distance from the boundary. Circulation through the barrier island passes (N-S current components) is most clearly influenced by the boundary forcing.

An assessment of the river flux contributions to barotropic circulation is examined for both Bay St. Louis and the Pearl River. Each model was subjected to tidal forcing and river flux at the wet/dry seasonal extremes. For both regions the river flux had a notable influence only in the context of severe storm events. Tidal excursions up the Pearl River are considerable based on model predictions. From these analyses one concludes that the river contribution to coastal circulation largely comes from buoyancy-driven mixing as opposed to an advective flux.

From observations made in the presented work, there is motivation to for a higher resolution wind field source in order to properly capture small-scale coastal circulation. In the future, the wind band can be included within the inverse model to fully assess the influence of boundary forcing with respect to both wind and tides. Based on the analyses presented, observations located at the barrier island passes appear particularly useful within a data assimilative scheme that determines optimal boundary forcing values. Additionally, several improvements to the Pearl River model are planned including the use of a shoreline inundation mechanism that eliminates the need for the imposed 1 m minimum depth and the activation of all nonlinear terms including advection, surely an important process within a river. Furthermore, streamflow fluxes applied at the head of Pearl River tributaries and implementation of spatially varying frictional coefficients at the seabed will likely reduce the tidal dominance of the river flow and lead to more realistic predictions. Clearly density–driven dynamics must also be included to properly account for the influence of the rivers.

## VII. ACKNOWLEDGMENTS

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## REFERENCES

[1] Luettich, R. A., J. J. Westerink, and N. W. Scheffner, "ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries, Report 1: Theory and Methodology of ADCIRC-2DDI and ADCIRC-3DL," *Technical Report DRP-92-6*, U.S. Department of the Army, 137 pp., 1992.

[2] Westerink, J. J., C. A. Blain, R. A. Luettich, and N. W. Scheffner, "ADCIRC: An Advanced Three-Dimensional Circulation Model for Shelves, Coasts, and Estuaries, Report 2: User's Manual for ADCIRC-2DDI," *Technical Report DRP-92*, Department of the Army, 1994a.

[3] Kinnmark, I. P. E., "The Shallow Water Wave Equations: Formulation, Analysis and Application" Ph.D. dissertation, Department of Civil Engineering, Princeton University, 1984.

[4] Grenier, R. R., R. A. Luettich, and J. J. Westerink, "A Comparison of the nonlinear frictional characteristics of two-dimensional and three-dimensional models of a shallow tidal embayment", *J. Geophys. Res.,* 100, C7, 13719-103735, 1995.

[5] Fortunato, A. B, A. M. Baptista, and R. A. Luettich, Jr., "A Three-dimensional model of tidal currents at the mouth of the Tagus Estuary", *Cont. Shelf Res.*, 17(14), 1689-1714, 1998.

[6] Luettich, Jr., R. A., J. L. Hench, C. W. Fulcher, F. E. Werner, B. O. Blanton, and J. H. Churchill, 1999: Barotropic tidal and wind-driven larval transport in the vicinity of a barrier island inlet. *Fisheries Oceanography*, 8 (Suppl. 2), 190-209.

[7] Westerink, J. J., R. A. Luettich, and J. C. Muccino, "Modeling Tides in the Western North Atlantic Using Unstructured Graded Grids," *Tellus*, 46A, 178-199, 1994.

[8] Le Provost, C., M. L. Genco, F. Lyard, P. Vincent, and P. Canceil, "Spectroscopy of the world ocean tides from a finite element hydrodynamical model", *J. Geophys. Res.*, 99, 24777-24797, 1994.

[9] Garratt, J.R., "Review of Drag Coefficients over Oceans and Continents", *Mon. Wea. Rev., 105*, 915-929, 1977.

[10] Hodur, R., "The Naval Research Laboratory Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS)", *Mon. Wea. Rev*., 125, 1414-1430, 1997.

[11] Blain, C. A., R. H. Preller, and A. P. Rivera, "Tidal Prediction using the Advanced Circulation Model (ADCIRC) and a Relocateable PC-based System", *Oceanography*, 15(1), 77-87, 2002.

[12] Lynch, D. R., C. E. Naimie, and C. G. Hannah, "Hindcasting the Georges Bank circulation. Part I: Detiding", *Cont. Shelf Res.*, 18, 607-639, 1998.

[13] Edwards, C. R. and C. A. Blain, "Applications of the incremental approach to Yellow Sea modeling", *Estuarine and Coastal Modeling, Proceedings of the 7th International Conference,* ASCE, 2002 (in press).

[14] Blain, C. A. and J. Veeramony, "The role of river discharge and vertical mixing formulation on barotropic circulation in Bay St. Louis, MS", *Estuarine and Coastal Modeling, Proceedings of the 7th International Conference,* ASCE, 2002 (in press).