Journal of Coastal Research	18	4	674–684	West Palm Beach, Florida	Fall 2002

Tidal Hydrodynamics in a Multiple-Inlet Estuary: Apalachicola Bay, Florida

Wenrui Huang†, H. Sun‡, S. Nnaji†, W.K. Jones§

†Florida A&M University–Florida State University
College of Engineering
Tallahassee, FL 32310, U.S.A.

‡Department of Marine Sciences
Rider University
Lawrenceville, NJ 08648, U.S.A.

§PBS&J Engineering, Inc.
Tallahassee, FL 32310, U.S.A.

ABSTRACT

HUANG, W.; SUN, H.; NNAJI, S., and JONES, W.K., 2002. Tidal hydrodynamics in a multiple-inlet estuary: Apalachicola Bay, Florida. *Journal of Coastal Research,* 18(4), 674–684. West Palm Beach (Florida), ISSN 0749-0208.

Tidal hydrodynamics in a multiple inlet estuarine system, Apalachicola Bay, were investigated in this study. The estuary is connected to the Gulf of Mexico through five tidal inlets. From eastern inlets to western inlets, the tidal amplitude decreases and the dominant tidal constituents change from mixed diurnal and semi-diurnal to diurnal components. The tidal hydrodynamics in the bay are complex due to different tidal forcing from multiple tidal inlets in the estuary. In order to characterize the tidal forces in the boundary inlets, we applied harmonic analysis to determine the dominant tidal components at the inlets using field measurements of water levels. Then we applied a previously validated hydrodynamic model to investigate the 2-D tidal circulation during a twenty-four hour period. Snapshots of model simulations at high, mid-ebb, low, and mid-flood tidal conditions were used to characterize the propagation of tidal waves and vertically averaged currents in the bay. Model simulations indicated that currents in the bay were driven mainly by the surface gravity gradients corresponding to the propagation of the tidal waves in the bay. At high tide, the higher surface elevation in the eastern tidal inlets drove the bay water from east to west. At low tide, the lower water level in East Pass caused strong eastward currents in the eastern region of the bay. One of the interesting issues in Apalachicola Bay is the effect of an artificial inlet (Sikes Cut) on the estuary circulation and aquatic ecosystem. This study indicates that strong tidal currents occur in this inlet and allow an exchange of waters between bay and Gulf. The results will benefit the biological research programs in this important estuarine system.

ADDITIONAL INDEX WORDS: *Tidal circulation modeling.*

INTRODUCTION

Apalachicola Bay is a barrier island estuarine system located in the Florida panhandle. The bay was formed by deltaic processes of the Apalachicola River and is situated on a prominent point of land that extends onto the Gulf of Mexico continental shelf (Figure 1). It is a highly productive estuarine system, which supports a diverse and abundant commercial and recreational fishery. The southward freshwater discharge from the Apalachicola River is perpendicular to the long axis of the estuary. According to LIVINGSTON *et al.* (1997), the bay provides important nursery and feeding grounds for large varieties of commercial and non-commercial fish and shellfish. The bay has the third largest catch of shrimp statewide and accounts for 90 percent of Florida's and 10 percent of the nation's oyster harvest. The total aquatic area of Apalachicola Bay, including East Bay, St. Vincent Sound, and St. George Sound covers over 450 km^2. The study area extends from the western tip of St. Vincent Sound at Indian Pass, east to the eastern tip of Dog Island at Lanark Reef. St. Vincent Island, Little St. George and St. George Islands, and Dog Island bound the bay on the south. The study area is approximately 63 km long and 12 km at its widest point. The bay is a shallow estuarine system with an average 2–3 m depth at mean sea level. It is connected to the Gulf through four natural inlets (Indian Pass, West Pass, East Pass, and Lanark Reef), and one artificially cut pass (Sikes Cut). West Pass and Sikes Cut connect Apalachicola Bay with the Gulf of Mexico, Indian Pass is the inlet into St. Vincent Sound, and East Pass is the large pass connecting the Gulf with St. George Sound.

According to IPPEN (1966) and OFFICIER (1975), tidal circulation in an estuary is affected by the boundary tidal forcing at the boundary inlets. For different estuaries, different numbers and locations of inlets may cause different circulation patterns in the bay. HUANG and SPAULDING'S (1995) study indicated standing wave patterns in a small one-inlet tidal estuary of Mt. Hope Bay. MILITELLO and ZARILLO (2000) conducted a hydrodynamic modeling study to investigate tidal waves and circulation in a one-inlet bay system, Ponce de Leon Inlet located in US Florida coast. When multiple inlets exist, tidal circulation in an estuary may be more complex, dependent on the topography of the estuaries and inlets. KRAUS and MILITELLO (1999) conducted a numerical model investigation of hydrodynamics in a two-inlet system, East Matagorda Bay, located in US Texas coast. They also applied the hydrodynamic model to examine the feasibility of a proposed-third inlet by comparing the results of water lev-

00128 received and accepted in revision 12 June 2002.

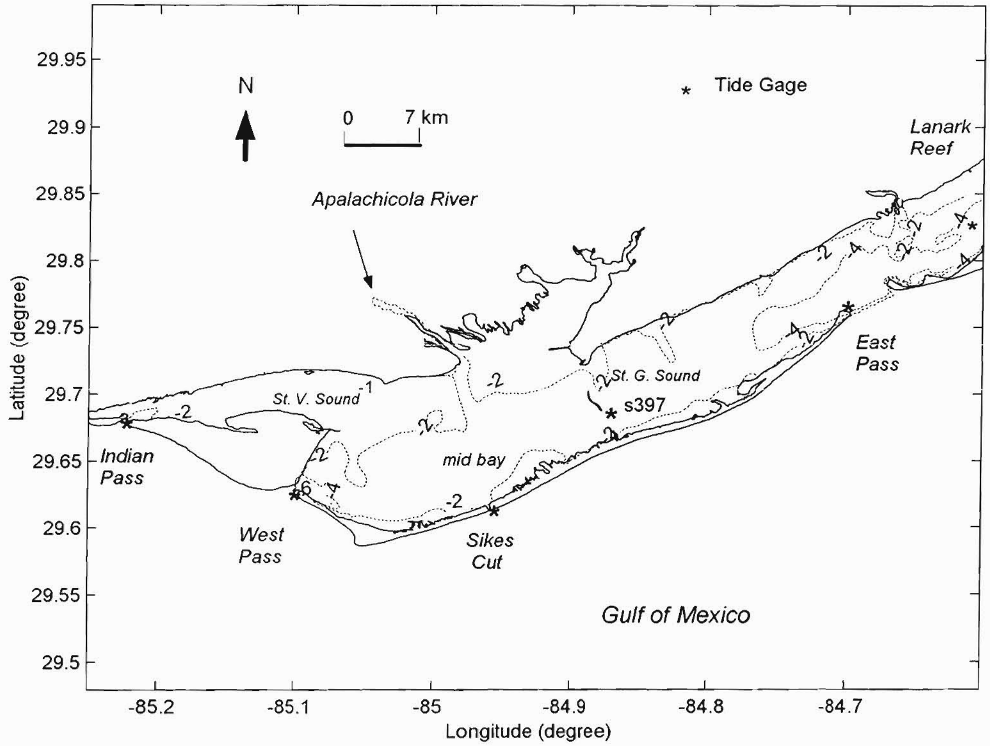

Figure 1. Selected Depth Contours (m) and tidal gage location in Apalachicola Bay (National Geodetic Datum).

els and velocity under conditions with and without the new inlet. Their study indicated that, for complex multiple inlet estuarine system, numerical hydrodynamic model is a useful tool in the investigation of tidal circulation in the bay. Apalachicola Bay consists of more inlets than those mentioned above and many other estuaries, for examples, Bristol Channel estuary in the west coast of Great Britain (EVANS *et al.*, 1989), Pearl River estuary of China (CHEN *et al.*, 2000), San Francisco Bay in the US California coast (KING and RACHIELE, 1989), and Tampa Bay in US Florida coast (BURWELL *et al.*, 2000).

Tidal motion in Apalachicola Bay is complex due to its special characteristics of estuarine topography and multiple tidal inlets, which include 1) five tidal inlets distributed to east, west, and south of the estuary, 2) significant changes of tidal amplitude and phase in the boundary tidal forcing in the inlet, and 3) shallow and long estuary. The artificial inlet of Sikes Cut was dredged by the United States Corps of Engineers in 1954, and continues to be maintained on a regular basis. The existence and continued maintenance of the Sikes Cut inlet has long been a point of controversy between people dependent on the fishing industry within the bay and those who transit the inlet as a shorter access for fishing in the Gulf. One contentious issue concerns about the exchange of fresher bay water and saltier Gulf water through this artificially cut inlet, which may change the circulation patterns and salinity in the inlet vicinity and adversely impact oyster productivity (LIVINGSTON *et al.*, 1997).

In this paper, tidal hydrodynamics in Apalachicola Bay was investigated through harmonic analysis of field observations of water levels, and the numerical simulations of a two-dimensional hydrodynamic model. Tidal harmonic analysis of field observations of water levels characterizes the changes of tidal amplitude and phase in monitoring stations in the inlets and bay. The hydrodynamic model simulations gives details of spatial distributions of currents and the propagation of tidal waves thought the bay in different tidal phases. The exchange of bay and Gulf waters though the artificial inlet was shown by the presentation of spatial current pattern near the artificial inlet.

TIDAL CHARACTERISTICS

Field Observations of Water Levels

JONES and MOZO (1994) conducted field measurements of water levels at the stations shown in Figure 1 during the period between April 1993–April 1994. Hourly water levels were measured using Handa 550 water level recorders. Datum for each station was established by surveying the elevations from known National Geodetic Datum stations. The water levels at tidal inlets during the summer of 1993 are given in Figure 2.

Observations of surface elevations for the period of July 2–3, 1993 at East Pass, West Pass, Indian Pass, and S397 gage are given in Figure 3. The figure shows that surface elevations change from mixed semi-diurnal and diurnal in the east to predominately diurnal in the west. The strongest tidal amplitudes are in the east with the energy diminishing as the

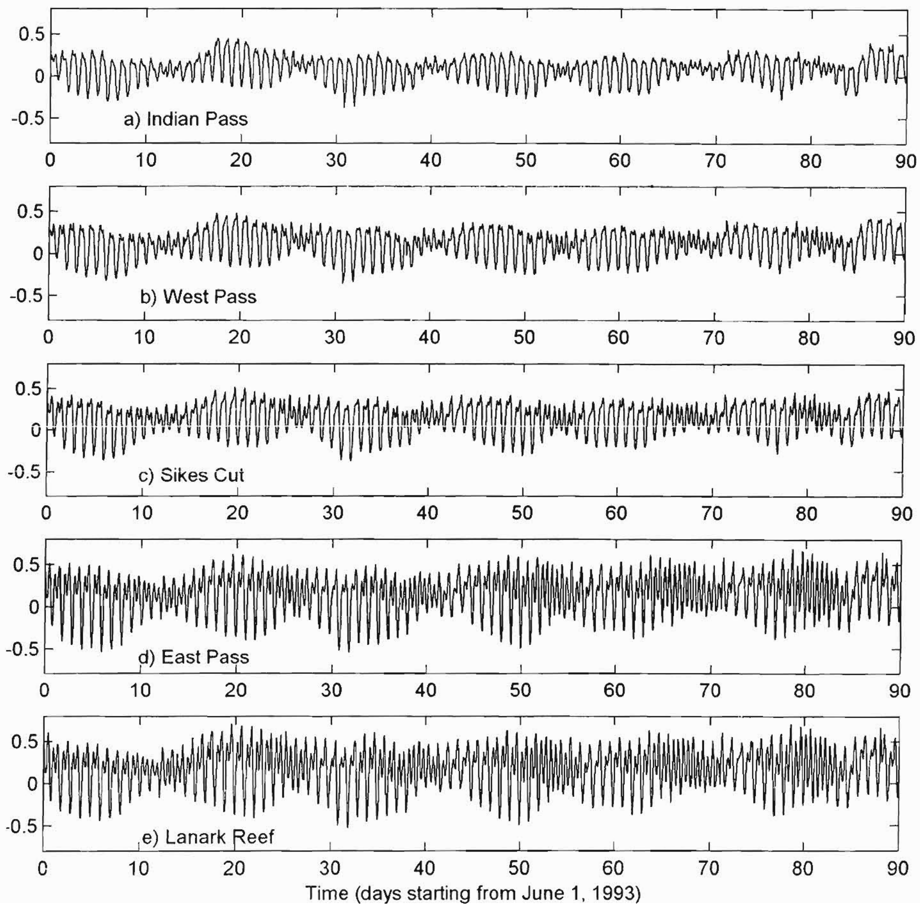

Figure 2. Water levels at tidal inlets during the summer of 1993 from the observations by JONES and MOZO (1994) to show the spring/neap tidal variations.

wave moves west due to bottom friction in the shallow bay. Observations of surface elevation show that the tidal amplitude decreases from the eastern inlet of East Pass to the western inlet of Indian Pass. At the maximum high tide (at 12 hr), the surface elevation at East Pass is about 12 cm higher than that of West Pass, and 21 cm higher than that of Indian Pass. At the minimum low tide (at 20 hr), surface elevations at both Indian Pass and West Pass are 18 cm higher than that of East Pass. The maximum high and low tides are approximately in phase at the inlets of East Pass, West Pass, and Indian Pass. However, the secondary high tide in East Pass (at 26 hr) has about a 3-hr lead compared to the tides in West Pass and Indian Pass. The tidal signal at tidal gage S397 in the bay shows a pattern similar to that in East Pass, but is lagged by about 2 hrs. Because there are considerable differences in the maximum daily tidal amplitude and phase of the semi-diurnal tide between the eastern and western inlets, an east-west horizontal gravity gradient is formed and varies according to the magnitude of tidal forcing at the inlets. The maximum horizontal gradient in water elevation occurs approximately in the diurnal maximum high and minimum low tide. Differing tidal variations between the five tidal inlets in the east, south, and west directions result in a complicated interaction of water levels in the bay.

Harmonic Analysis

Harmonic analysis was conducted in this study using measurement data obtained by JONES and MOZO (1994) for the period from April 1993 to April 1994. Tidal harmonic analysis was based on a decomposition of the observed tidal height h(t) into the basic periodic tidal components.

$$h(t) = h_0 + \sum_{i}^{N} a_i \sin\left(\frac{2\pi t}{T_i + \delta_i}\right) \tag{1}$$

where h_0 is the average equilibrium height, a_i the amplitude, T_i the period, δ_i the phase or epoch (here the modified epoch for Apalachicola Bay, related to 75°W) of the i^{th} tidal component, t is time in hour (GMT), and N is the maximum number of astronomical tidal constituents, 35 in this study. Following BOON and KILEY (1978), the values of the unknown coefficients, a_i and δ_i, for each of the 35 constituents can be found using discrete Fourier analysis and the least square method.

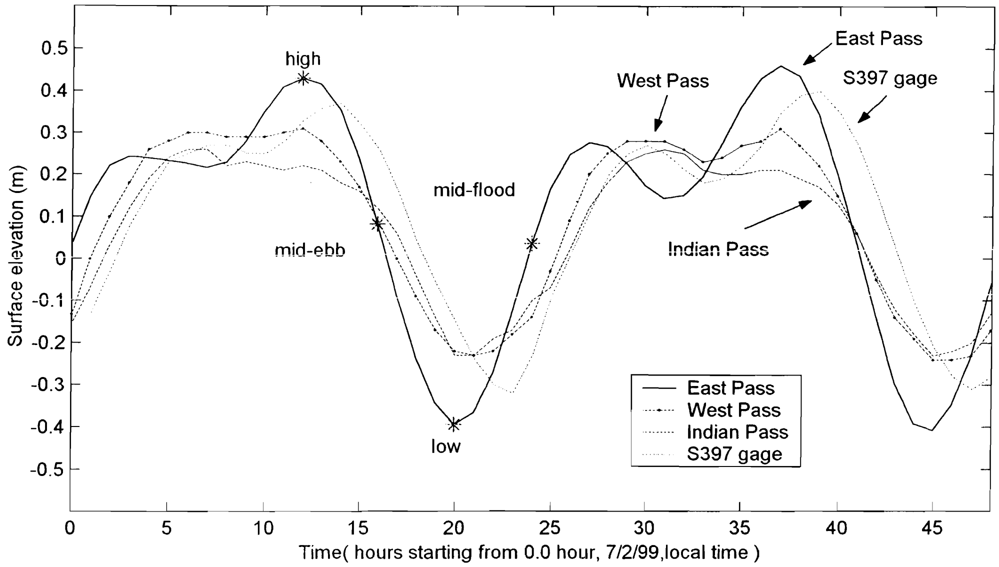

Figure 3. Time series water levels from the observations by JONES and MOZO (1994) showing the variation of tidal amplitude and phase between the tidal inlets.

Results of harmonic analysis show that the dominant tidal constituents consist of two semidiurnal components (M2 and S2) and two diurnal components (K1 and O1). The amplitudes and epochs of major tidal components from harmonic analysis are given in Table 1 and Table 2, which shows that tidal amplitudes generally decrease from east (East Pass inlet) to west (Indian Pass). From eastern bay to western bay, both diurnal (K1 + O1) and semi-diurnal (M2 + S2) tidal amplitudes decrease from maximum amplitudes at Landard Reef to minimum amplitudes at Indian Pass (Table 3, Figure 4). At the eastern tidal inlets (Landard Reef and East Pass), the amplitude of the diurnal tide is about the same as that of the semi-diurnal tide. However, at the western tidal inlet of Indian Pass, the diurnal tidal amplitude is about three times larger than the semi-diurnal tidal amplitude. Because tidal circulation in the bay is driven by tidal forcing functions at the boundary tidal inlets, the differences between tidal constituents at the tidal inlets cause complex circulation in the bay. Tidal circulation patterns calculated by numerical modeling are described in the following sections.

TIDAL CIRCULATION IN THE BAY

Hydrodynamic Model Description

In order to investigate circulation in the Apalachicola Bay, the Princeton Ocean Model (POM) by BLUMBERG and MELLOR (1987) was applied to the bay. It is a semi-implicit, mode-separate, finite-difference model that can be used to determine temporal and spatial changes of water surface elevation, salinity, temperature, and velocity in response to wind, tide, buoyancy, and Coriolis force. The model separates the three-dimensional hydrodynamic equations into an external mode and an internal mode. The external mode solves two-dimensional vertically averaged equations for surface elevations and vertically averaged currents, and the internal mode solves the vertical distributions of currents and salinity. In vertical direction, the model uses sigma-coordinate transformation that divides the water column into equal number of vertical layers or grids. The model solves a coupled system of differential, prognostic equations describing conservation of mass, momentum, heat, and salinity at each horizontal and vertical location determined by the computational grid. Ac-

Table 1. *Amplitude of major tidal constituents in Apalachicola Bay determined from harmonic analysis of field observation data between April 1993–April 1994.*

Station ID	M2 (m)	S2 (m)	K1 (m)	O1 (m)
Lanark Reef	0.216	0.075	0.172	0.135
East Pass	0.201	0.073	0.165	0.143
s397 (mid-bay)	0.129	0.052	0.140	0.125
Sikes Cut	0.099	0.030	0.138	0.122
West Pass	0.075	0.022	0.128	0.112
Indian Pass	0.059	0.017	0.122	0.104

Table 2. *Epoch of major tidal constituents in Apalachicola Bay determined from harmonic analysis of field observation data between April 1993–April 1994.*

Station ID	M2	S2	K1	O1
Lanark Reef	34.5	58.4	306.4	298.4
East Pass	40	72	315.8	298.6
s397 (mid-bay)	63	123.4	329.1	309.3
Sikes Cut	73.5	101.5	316.1	295.4
West Pass	71.9	104.3	325.1	294.5
Indian Pass	86.5	127.4	322.6	301.9

Note: The epoch is in degree.

Table 3. *Diurnal and semi-diurnal tidal amplitude at tidal inlets and mid bay determined from harmonic analysis of field measurements between April 1993–April 1994.*

	Diurnal (K1+O1) (m)	Semi-diurnal (M2+S2) (m)	Factor: (K1+O1)/(M2+S2)
Lanark Reef	0.306	0.291	1.1
East Pass	0.308	0.274	1.1
s397 (mid-bay)	0.265	0.181	1.5
Sikes Cut	0.260	0.129	2.0
West Pass	0.240	0.097	2.5
Indian Pass	0.226	0.076	3.0

cording to MELLOR and YAMADA (1982) and GALPERIN *et al.* (1988), the model also incorporates a second-order turbulence closure sub-model that provides eddy viscosity and diffusivity for the vertical mixing. This model has a history of successful applications in other estuaries. For example, BLUMBERG and GOODRICH (1990) have applied the model to the Chesapeake Bay. In these studies, comparisons with available data show that the model realistically reproduces the predominant physics. The model is capable of simulating time-dependent wind and multiple river inputs as well as a variety of other forcing conditions. An important feature of the version of the POM model (BLUMBERG and GALPERIN, 1990) for Apalachicola Bay is the use of a horizontal orthogonal, curvilinear coordinate system that allows for a more realistic representation of coastline irregularities in the Apalachicola Bay system. The computational model grid for Apalachicola Bay is given in Figure 5. Details of model descriptions are discussed by BLUMBERG and MELLOR (1987), and the enhanced version of the curvilinear coordinate formulation is given by BLUMBERG and GALPERIN (1990).

Model Setup

There are several input parameters in the hydrodynamic model that required calibrations. The Apalachicola Bay hydrodynamic model was previously calibrated in coupling hydrodynamics and salinity modeling study by HUANG and JONES (1997, 2001). The model was calibrated for the period of June 1993 and validated for the period of July 1993 by using field observations of hourly surface elevation and salinity at several stations in the bay. Model parameters (bottom drag coefficient, bottom roughness, horizontal diffusion and viscosity, time step, vertical and horizontal grid) were selected to minimize the difference between model predictions and observations of water levels. The model employs the horizontal grids as given in Figure 5 and five vertical layers for the internal mode. The results of surface elevations and vertically-averaged currents from the external mode are used to investigate the tidal circulation in this study. The time step used in model simulation is 2 minutes for internal mode and 30 seconds for external mode. During 30-day model calibration period, model coefficients, such as bottom friction, were adjusted to minimize the difference of model predictions and observations of water levels. Summary of parameters select-

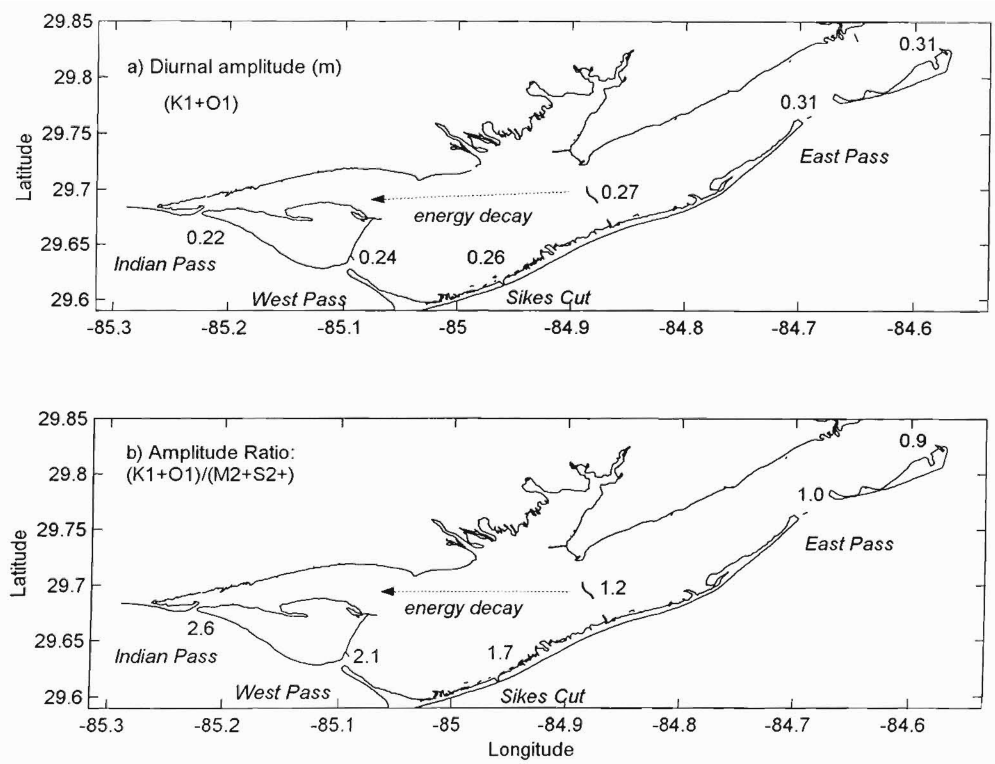

Figure 4. Tidal amplitudes (m) from harmonic analysis of tidal data a) Semi-diurnal amplitude (M2 + S2), b) Amplitude ratio: (K1 + O1)/(M2 + S2).

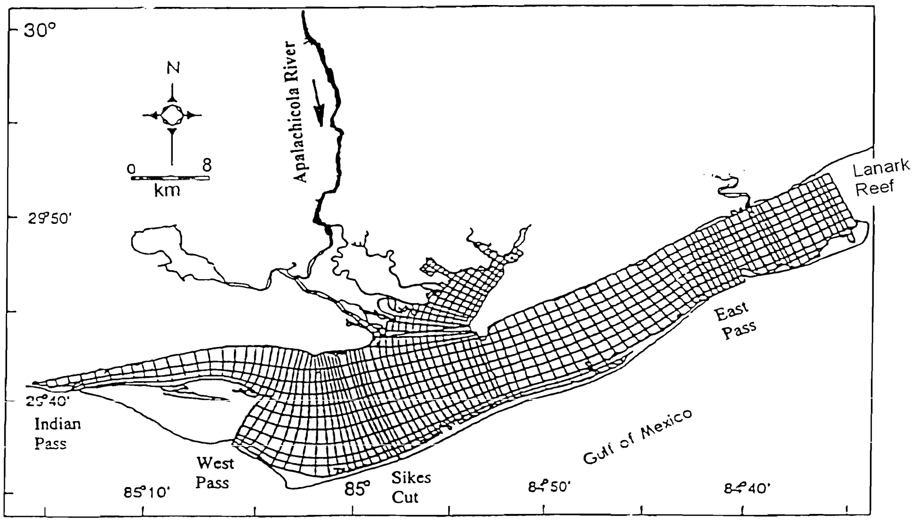

Figure 5. Horizontal computational grid for the hydrodynamic model of Apalachicola Bay.

ed from model calibration is given in Table 4. During model verification period, model parameters selected from model calibrations were verified using another independent data set of water levels. As shown in Figure 6, model predictions of hourly water levels compare well with observations of at station S397 (mid-bay). The correlation value is 0.99, and the root-mean-square error is 0.02 m. More details about calibration of the Apalachicola Bay hydrodynamics model were given by HUANG and JONES (2001).

Modeling Tidal Motions in the Bay

The validated hydrodynamic model was used to study the tidal circulation patterns in the bay during July 2–July 3, 1993. During this period, wind speeds were weak. Model simulations were performed in the vertical-averaged, two-dimensional mode to calculate the vertically averaged currents in this shallow estuary. The wind-induced non-tidal water levels were negligible since no strong wind was observed during the study period. Because the tidal-induced circulation can be better observed under minimum wind and river forcing conditions, wind forcing was omitted and 157 m^3/s river inflow (minimum historic daily flow) was specified during the simulation period. Observed water levels (Figure 3) were specified at the ocean boundaries. A 60-day simulation using observed tidal boundary conditions (HUANG and JONES, 2001) established appropriate initial conditions for modeling tidal circulation patterns during the period of July 2–July 3, 1993. Model simulations given below provide snapshots of velocity and surface elevation field throughout the bay at high tide (12:00, EST), mid-ebb tide (16:00), low tide (20:00), and mid-flood tide (24:00). The corresponding time series of boundary water levels at East Pass and West Pass are given in Figure 3. The model calculated surface elevations in the bay and the observed boundary water levels are referred to the same National Geodetic Datum (NGVD) throughout the following discussions.

Table 4. *Calibrated Parameters Used in the Model*

Parameters	Value
Wind Stress Drag Coefficient (C_d)	0.0012
Bottom Friction Coefficient (C_f)	0.003
Coefficients for Calculating Horizontal Eddy Viscosity Horizontal Diffusivity (C_m)	0.05
Vertical Sigma Layers (internal mode for vertical distribution)	5
Time Step in external mode (vertically-average mode)	30 seconds
Time Step in internal mode (3D vertical distribution mode)	2 min.

High Tide (Figure 7)

High tide (12:00) is the maximum water level reached in a tidal cycle. The tides at boundaries were in phase and the velocities were generally low at all tidal inlets. However, due to differences in tidal amplitude between the east and west boundaries and shallow water friction, surface elevation gradually decreased from East Pass, through mid-bay, to the western tidal boundaries of West Pass and Indian Pass. The difference in surface elevation was about 12 cm between East Pass and West Pass and about 20 cm between East Pass and Indian Pass. The strongest gradient of surface elevation was located near tidal gage S397 where the width of the bay is reduced by one-third due to the existence of an island. The horizontal gravity gradient results in westward currents in the bay. Velocity was about 0.33 m/s in St. George (St. G.) Sound and between 0.18 and 0.25 m/s in St. Vincent (St. V.) Sound. The strongest currents occurred in narrow estuarine vicinity near the tidal gage S397 due the. Weaker currents were observed in the western mid-bay region where the westward tidal currents from St. George Sound met the south-

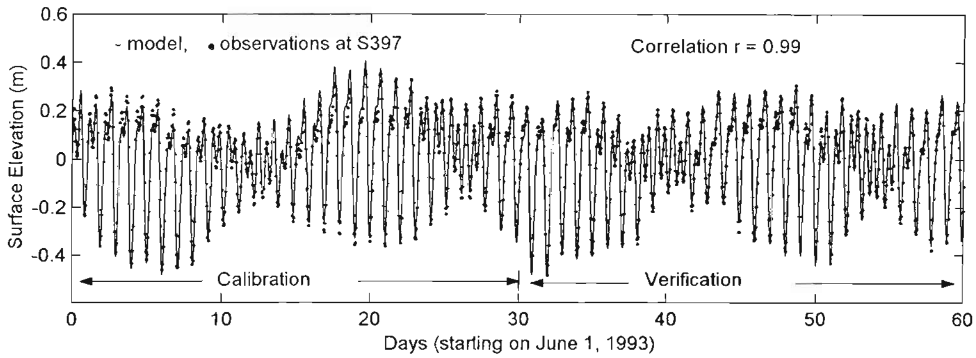

Figure 6. Comparison of model predictions of water level with observations at station S397. In calibration period, model parameters were adjusted to provide best fit to data. In verification period, model parameters selected from calibration were verified.

ward currents of the Apalachicola River discharge. Due to the westward current effects, the southward river discharge diverged, flowing in the west and southwest directions. In the vicinity of Sikes Cut inlet, the water in the bay moved from east to west. However, the velocity vector in that inlet was directed out of the bay as a result of the higher water level in the bay than in the inlet.

Mid-Ebb Tide (Figure 8)

At mid-ebb tide (16:00), water levels everywhere in the estuary were falling at a fastest rate of the tidal cycle with the eastern side of the bay falling faster than the western side. Water was leaving the bay through all tidal inlets. At mid-ebb tide, water levels at all tidal inlets in the bay were approximately equal with the maximum water level occurring in mid-bay. Because West Pass is closer to mid-bay than Indian Pass or East Pass, the strongest gravity gradient and currents occurred between mid-bay and West Pass. Waters in St. G. Sound moved in an eastward direction toward East Pass, while currents in St. V. Sound moved in a westward direction toward Indian Pass. The divergence of the current at mid-bay, southeastward to West Pass and eastward to

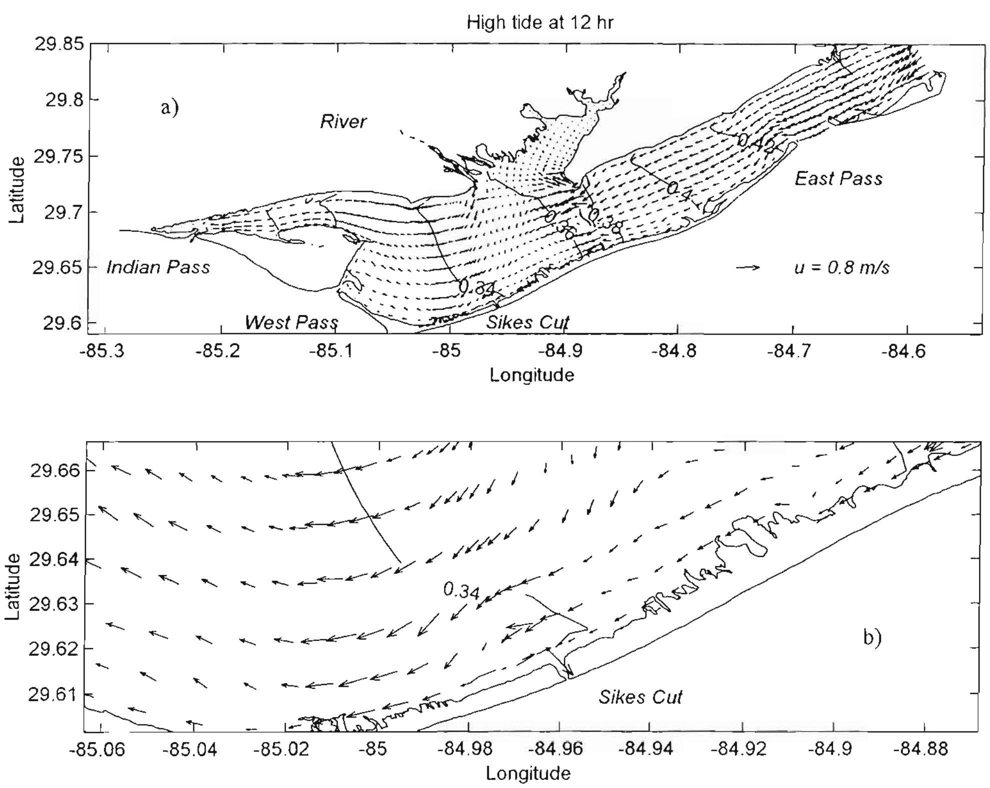

Figure 7. Model predictions of water level contour (m) and currents (m/s) at high tide. a) Entire bay, b) Details at Sikes Cut inlet

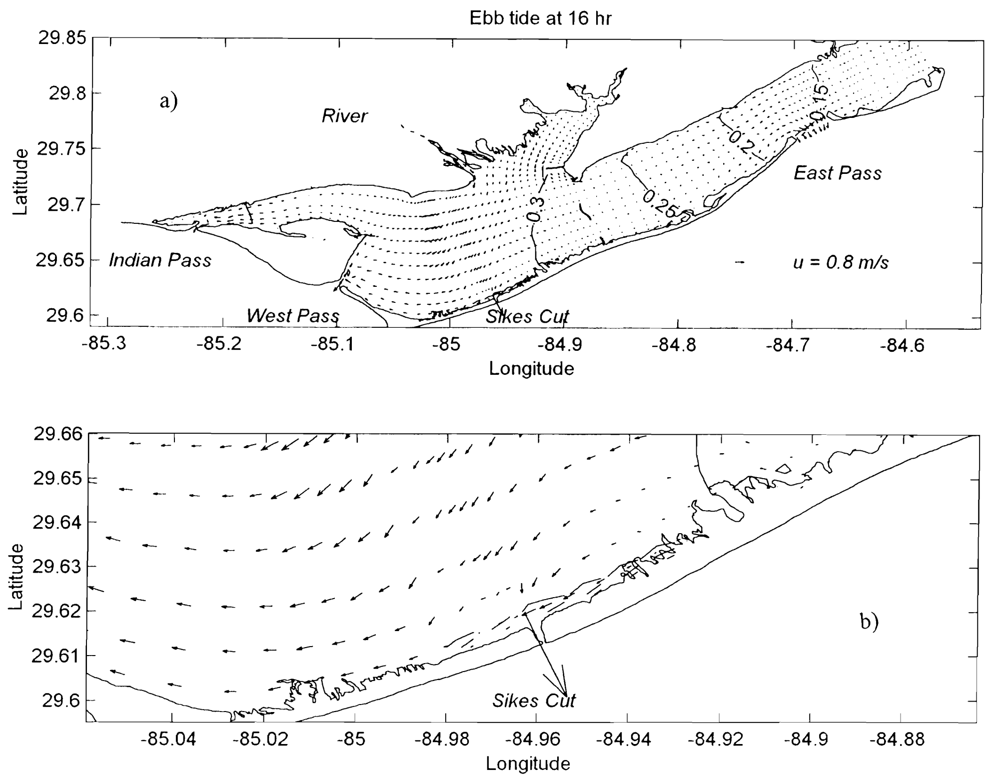

Figure 8. Model predictions of water level contour (m) and currents (m/s) at ebb tide. a) Entire bay, b) Details at Sikes Cut inlet

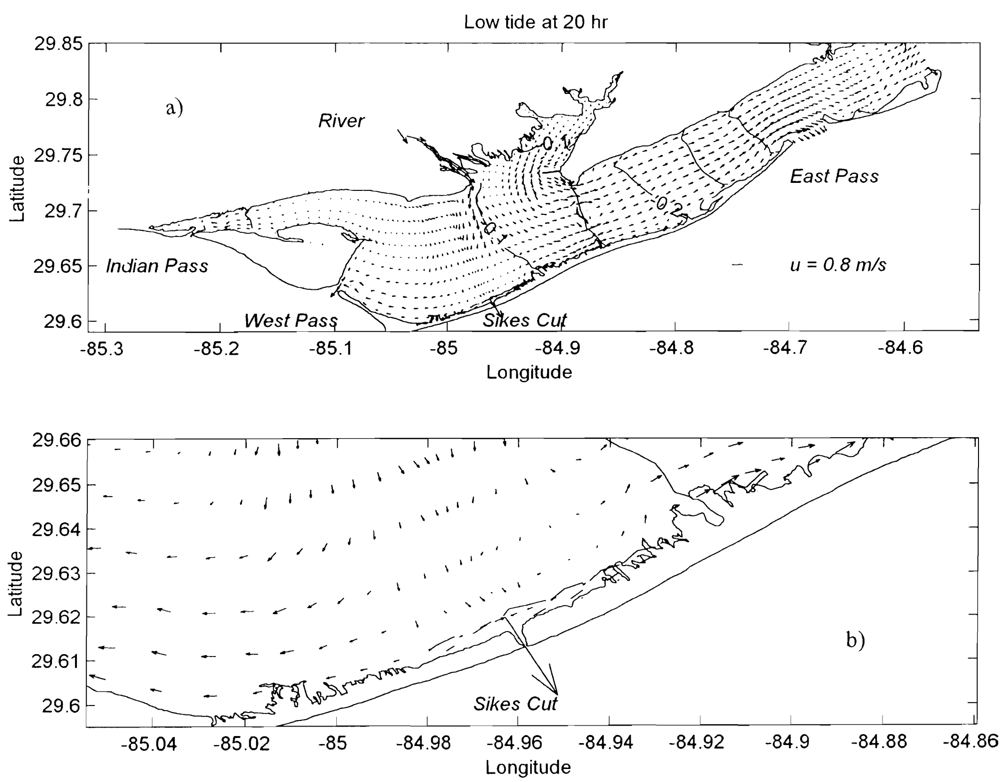

Figure 9. Model predictions of water level contour (m) and currents (m/s) at low tide. a) Entire bay, b) Details at Sikes Cut inlet

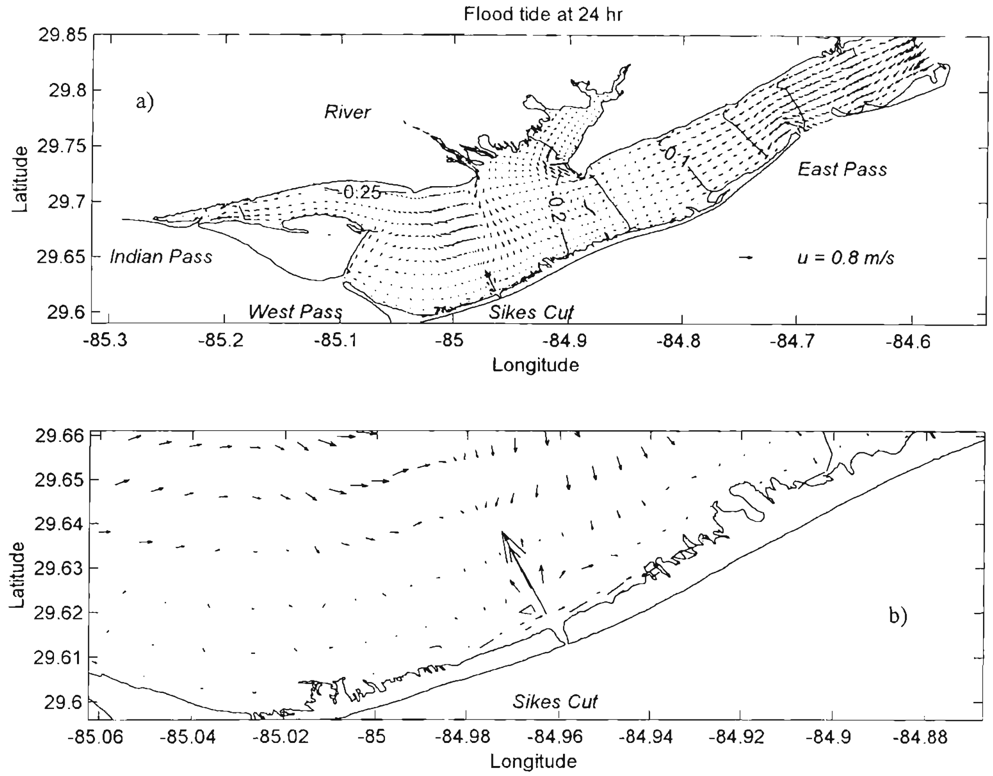

Figure 10. Model predictions of water level contour (m) and currents (m/s) at flood tide. a) Entire bay, b) Details at Sikes Cut inlet

East Pass in St. G. Sound, caused a slack zone to develop between mid-bay and St. G. Sound where tidal currents were negligible. Velocity was about 1 m/s in East Pass, 0.18–0.25 m/s in St. G. Sound, 0.25–0.35 m/s in mid-Bay, 1 m/s in West Pass, and 0.4 m/s in Indian Pass. At Sikes Cut, the current was stronger, about 1.1 m/s.

Low Tide (Figure 9)

At low tide (20:00), the water levels at all the boundaries were at their minimum levels and were approximately equal. Water level in the bay was higher than at the tidal inlets. The maximum water level in the bay was −0.1 m at mid bay with its contour line approximately following the strongest currents from the Apalachicola River discharge. Water levels were about −0.35 m near East Pass and −0.2 m near West Pass and Indian Pass. In St. V. Sound, water moved into the Gulf through Indian Pass, while waters near West Pass and the western mid-bay region exited the bay through West Pass. A strong gravity gradient between mid-bay and East Pass caused strong eastward currents in St. G. Sound and the eastern mid-bay region which varied between 0.2 and 0.6 m/s depending on the location. Due to the low water level in the bay, currents from the river discharge became stronger. The currents resulting from the river discharge were about 0.8–1.0 m/s near the river mouth and were much stronger than those at the high and mid-ebb tides. The southward currents from the river discharge stretched south almost 8 km from the river mouth before splitting into the eastward and westward currents due to the block created by the barrier island. The current at the Sikes Cut inlet flowed out of the bay into the Gulf.

Mid-Flood Tide (Figure 10)

At mid-flood tide (24:00), water level rose faster in East Pass than in the western inlets. The surface elevations in all the tidal boundaries were higher than in the bay. The minimum water level at mid-bay was about −0.2 m to −0.25 m, while the surface elevation was about 0.0 m at East Pass and −0.1 m at West Pass and Indian Pass. Due to the low water level mid-bay, the currents from the Apalachicola River discharge into the bay were strong. The southward currents from the river discharge extended south about 12 km from the river mouth nearing the south barrier island. Waters from all the tidal boundaries moved towards the estuary. The flood currents from East Pass and the river discharge formed a convergence zone in the area between mid-bay and St. G. Sound. Waters near East Pass were moving at about 0.5 m/s and gradually decreased in speed as they neared the western portion of St. G. Sound. Part of the water from St. G. Sound flowed into the northern portion of the bay. The flood currents from the western tidal boundaries (Indian Pass, West Pass, and Sikes Cut) caused another mixing area in the western mid-bay region. The currents near the southern barrier island were week as a result of the mixing between the

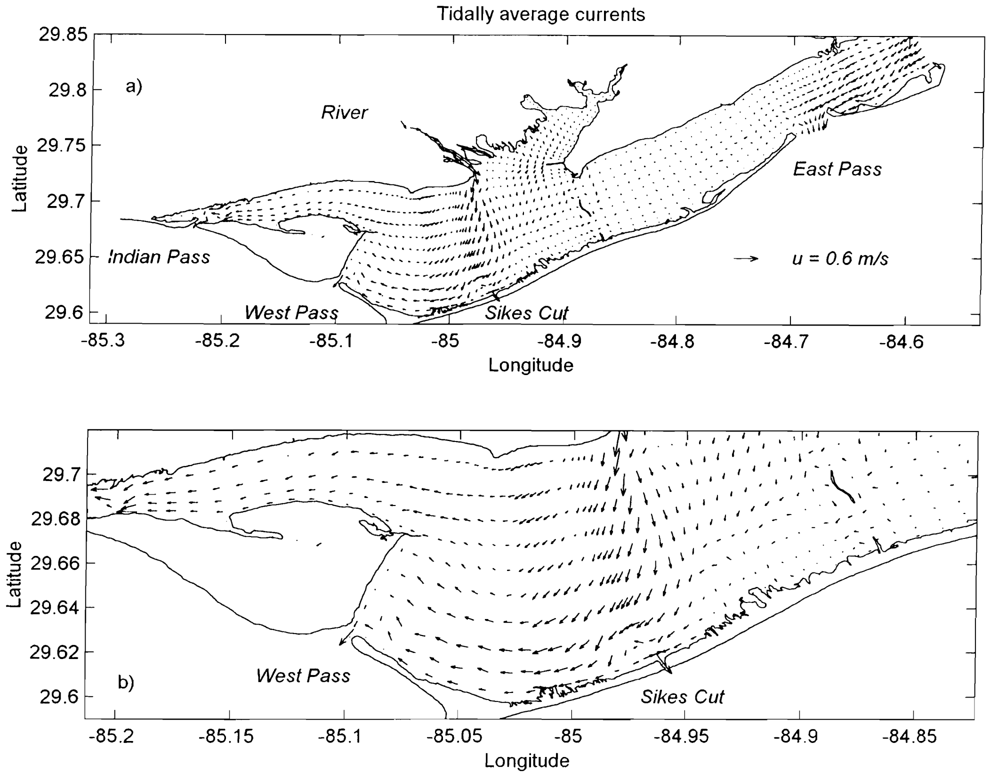

Figure 11. Model predictions of average currents (m/s) over two M2 tidal cycles (24.84-hr) a) Entire bay, b) Details at Sikes Cut inlet

southwestward river discharge and the northeastward tidal currents from West Pass. The tidal currents at the artificial inlet at Sikes Cut were strong during the flood tide, about 1.2 m/s. This indicates that saline ocean water could enter the bay during the flood tide through Sikes Cut and cause an increase of salinity in the bay.

Tidally Average Currents

Based on the results of harmonic analysis (Tables 1–3, and Figure 4), boundary tidal forcing in Apalachicola Bay consists of semi-diurnal and diurnal components with amplitudes and phases changing from one inlet to another. As shown in Table 1, the strongest tidal harmonic component in East Pass inlet is M2 with a 12.42-hour tidal period. However, in West Pass inlet, the strongest tidal harmonic component is K1 with a 23.93-hour tidal period. The amplitude of combined diurnal components (K1 + O1) is the same as the semi-diurnal components (M2 + S2) in East Pass, but is about three times stronger than the semi-diurnal components in Indian Pass. The change of dominant tidal component at different inlet, together with the mixed tidal constituents with different periods, at the tidal boundaries makes it difficult to investigate the residual circulation over the even number of the tidal cycles.

In order to estimate the average tidal circulation in the bay, model simulations were conducted during a 24.84-hour period starting from the 12th hour (12:00) of July 2 (Figure 3). This period covers two tidal cycles of the semi-diurnal M2 tide, which is the strongest in East Pass Inlet. Averaging model simulations of velocity and surface elevation over two M2 tidal cycles provides a picture of the approximate residual currents in the bay (Figure 11). Model results show that the net freshwater discharge from the Apalachicola River was dominant in the residual currents in the bay. Near river mouth, currents from the river directed southward into the bay before encountering the barrier-island that borders the bay to the south. The majority of the currents dispersed to the west and exited the bay though the inlets of Indian Pass and West Pass. In the eastern part of the bay (St. George Sound), the residual currents were very weak and were almost negligible in comparison to the net river discharge.

At the artificial inlet of Sikes Cut, residual currents directed out of the bay to the Gulf of Mexico. Since Sikes Cut is located in a barrier island opposite the point of river discharge into the bay, the inlet would cause net water flux between from the bay to the coastal ocean. The results of the tidally average currents provide a good reference for biologists conducting studies on the relationship between oyster productivity and estuarine circulation.

CONCLUSION

Tidal hydrodynamics in Apalachicola Bay were characterized through harmonic analysis of time series of tidal data and hydrodynamic model simulations. The circulation in the bay is complex because of the presence of tidal waves with different amplitudes and phases at multiple inlets from different directions. Harmonic analysis of tidal data was performed to characterize tides at the inlets. At the eastern tidal inlets (Landard Reef and East Pass), the diurnal tidal amplitude is found to be almost in the same as semi-diurnal tidal amplitude. However, at the western inlet of Indian Pass, diurnal tidal amplitude is about three times larger than semi-diurnal tidal amplitude. In general, tidal amplitudes decrease from east to west cross the bay. This multiple-inlet estuarine system produces in complex variations of horizontal gravity gradients in the bay when the water level at different boundary tidal inlet fluctuates with different amplitude and phase.

A hydrodynamic model was applied to investigate circulation pattern in the bay driven by the tidal forcing from the multiple tidal inlet system. Tidal circulation in the bay is strongly controlled by the differences of water levels between the tidal inlets, which induce spatial and temporal variations of surface gravity gradients in the bay. At high tide, the higher surface elevation in the east tidal boundary drives bay water from east to west. During ebb tide, a majority of water from mid-bay moves through West Pass into the Gulf. At low tide, the lower water level in East Pass causes strong eastward currents in the eastern region of the bay. During flood tide, the flood tidal currents from all tidal boundaries and the river discharge converged in the bay.

The interactions of tidal forcing from multiple inlets and river flow result in the complex circulation and mixing in the estuary. Although East Pass and West Pass are the most important tidal boundaries, model simulations show that the small artificial inlet at Sikes Cut also affects interactions of bay and ocean waters. The Sikes Cut inlet is ebb dominated. The residual current at Sikes Cut is toward the Gulf from the bay. Since the circulation has significant effects on the mixing and transport processes and water quality in the bay; the results of this study will contribute to the biological research programs in this highly productive estuarine ecosystem.

ACKNOWLEDGMENT

Data used in this study was provided by the Northwest Florida Water Management District. Model simulations were performed with the SGI 2000 computer at the Super Computer Center of the Florida State University. The authors would like to thank the reviewers for their valuable comments.

LITERATURE CITED

BLUMBERG, A.F. and GALPERIN, B., 1990. On the summer circulation in New York Bight and contiguous estuarine waters. *In*: CHENG, D.T. (ed): *Coastal and Estuarine Studies, Volume 38: Residual Currents and Long-term Transport.* New York: Springer, pp. 451–68.

BLUMBERG, A.F. and GOODRICH, D.M., 1990. Modeling of wind-induced destratification in Chesapeake Bay. *Estuaries*, 13, 3–13.

BLUMBERG, A.F. and MELLOR, G.L., 1987. A description of a Three-dimensional Coastal Ocean Circulation Model. *In*: HEAPS, N.S., (ed): *Coastal and Estuarine Sciences, Volume 4: Three-dimensional Coastal Ocean Models.* Washington D.C.: American Geophysical Union, pp. 1–16.

BOON, J.D. and KILEY, K.P., 1978. Harmonic analysis and tidal prediction by the method of least square. Glocester Point, Virginia: Virginia Institution of Marine Science, *Special report No. 186*, 46p.

BURWELL, D.; VINCENT, M.; LUTHER, M., and GALPERIN, B., 2000. Modeling residence times: Eulerian vs Lagrangian. *In*: SPAULDING, M.L. (ed), *Estuarine and Coastal Modeling, Proceeding of the 6th International Conference.* Virginia: American Society of Civil Engineers, pp. 995–1009.

CHEN, J.C.; LEE, O., and MAN, C.W., 2000. Pearl River estuary pollution project: an integrated approach. *In*: SPAULDING, M.L. (ed), *Estuarine and Coastal Modeling, Proceeding of the 6th International Conference.* Virginia: American Society of Civil Engineers, pp. 1010–1018.

EVANS, G.P.; MOLLOWNEY, B.M., and SPOEL, N.C., 1989. Two dimensional modeling of Bristol Channel, UK. *In*: SPAULDING, M.L. (ed), *Estuarine and Coastal Modeling, Proceeding of the 1st International Conference.* New York: American Society of Civil Engineers, pp. 331–339.

GALPERIN, B.; KANTHA, L.H.; HASSID, S., and ROSATI, A., 1988. A quasi-equilibrium turbulent energy model for geophysical flows. *Journal of Atmospheric Science*, 45, 55–62.

HUANG, W. and JONES, W.K., 1997. Hydrodynamic modeling of circulation and salinity of Apalachicola Bay for low flow seasons. Havana, Florida: Northwest Florida Water Management District, *Water Resources Special Reports, 97-1.* 118p.

HUANG, W. and JONES, W.K., 2001. Characteristics of long-term freshwater transport in Apalachicola Bay. *Journal of American Water Resources Association*, 37(3), 605–615.

HUANG, W. and SPAULDING, M.L., 1995. Numerical modeling of CSO-induced pollutant transport in Mt. Hope Bay, *Journal of Environmental Engineering*, 12(7), 492–498.

IPPEN, A., 1966. *Estuary and Coastline Hydrodynamics.* New York: McGraw-Hill Book Company, 744p.

JONES, W.K. and MOZO, M.R., 1994. Apalachicola Bay freshwater needs assessment program, geophysical data collection program. Havana, Florida: Northwest Florida Water Management District, *Water Resources Special Report, 94-1.* 110p.

LIVINGSTON, R.J.; NIU, X.; LEWIS, F.G., and WOODSUM, G.C., 1997. Freshwater input to a Gulf estuary: long-term control of tropic organization. *Ecological Applications*, 7, 277–299.

KING, I.P. and RACHIELE, R., 1989. Multi-dimensional modeling of hydrodynamics and salinity in San Francisco Bay. *In*: SPAULDING, M.L. (ed), *Estuarine and Coastal Modeling, Proceeding of the 1st International Conference.* New York: American Society of Civil Engineers pp. 511–518.

KRAUS, N.C. and MILITELLO, A., 1999. Hydraulic study of multiple inlet system: East Matagorda Bay, Texas. *Journal of Hydraulic Engineering*, 125(3), 224–232.

MELLOR, G. and YAMADA, T., 1982. Development of a turbulent closure model for geophysical fluid problems. *Review of Geophysics and Space Physics*, 20(4), 851–875.

MILITELLO, A. and ZARILLO, G.A., 2000. Tidal motion in a complex inlet and bay system, Ponce de Leon Inlet, Florida. *Journal of Coastal Research*, 16(3), 840–852.

OFFICIER, C., 1975. *Physical Oceanography of Estuaries.* New York: John Wiley and Sons, 465p.