EFFECTS OF TROPICAL CYCLONES ON CIRCULATION AND MOMENTUM BALANCE IN A SUBTROPICAL ESTUARY AND INLET

By

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To my beloved and “extremely” missed son, Erdem and wife, Fatma
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<td>ADCP</td>
<td>Acoustic Doppler Current Profiler</td>
</tr>
<tr>
<td>CH3D</td>
<td>Curvilinear Hydrodynamics in 3D</td>
</tr>
<tr>
<td>GTMNERR</td>
<td>Guana-Tolomato-Matanzas National Estuarine Research Reserve</td>
</tr>
<tr>
<td>H</td>
<td>Hurricane</td>
</tr>
<tr>
<td>HRD</td>
<td>Hurricane Research Division</td>
</tr>
<tr>
<td>NCB</td>
<td>Northern Coastal Basin</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>RMSE</td>
<td>Root Mean Square Error</td>
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<tr>
<td>SAI</td>
<td>St. Augustine Inlet</td>
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<td>TS</td>
<td>Tropical Storm</td>
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ESTUARIES along the coast of U.S. are subjected to extreme events such as tropical cyclones, nor’easters, and heavy rainfall. These extreme events can bring very drastic and sudden changes to the estuarine environment and habitat. This study focuses on the hydrodynamics of the subtropical Northern Coastal Basin (NCB) estuary during regular (non-storm) time periods as well as tropical cyclones. Hydrodynamics (water level, currents and salinity) of the system is simulated with a three-dimensional model, CH3D (Curvilinear-grid Hydrodynamics in 3D), during four major hurricanes (Charley, Frances, Ivan, Jeanne) in 2004 and two tropical storms (Fay and Hanna) in 2008. After successful calibration and verification of using the observed water level, salinity and current (2008) data throughout the estuary, the model is used to examine the residual circulation, momentum balance, and stratification in order to understand the effects of tropical cyclones on the estuarine hydrodynamics. Model results during a typical tidal cycle show formation of four residual eddies around the headlands of the St. Augustine Inlet due to the nonlinear advection. The dynamic structure of the residual eddies strongly influences the cross-sectional residual flow inside the inlet. Analysis of the residual momentum balance simulated by the model reveals that during a typical tidal cycle with weak external forcing, the balance is between the barotropic pressure
gradient and the nonlinear advection. Prior to the landfall of storms, strong northeasterly winds disrupted the ocean side eddies and created a uniform along-shore southerly current which forced complete inflow through the inlet due to Ekman transport, but eddies inside the inlet persisted. After the landfall, the wind direction changed to easterly followed by southeasterly winds. The change in wind direction caused the along-shore current to completely reverse and become northerly on the ocean side, while the eddies inside the inlet disrupted and the flow through inlet became complete outflow. The duration of the changes were dependent on the duration of the storm that affected the region, ranging from 3-4 days for Charley and Fay, and up to 12 days for Frances. The momentum balance within the system also changed significantly during storms. Wind stress generated by strong winds was mostly balanced by a combination of barotropic pressure gradient and bottom friction. Baroclinic pressure gradient became important coinciding with increased precipitation or river discharge events in the system and it was more significant in 2004 compared to the 2008 simulations due to the higher precipitation and river discharge (3 times higher). Salinity inside the estuary was significantly affected by the increased precipitation and river discharge especially during the storms. When the residual flow rate at the inlets was directed towards the ocean, the size of low salinity area was at its maximum. Although the salinity within the system was highly affected by precipitation and river discharge, the stratification within the system was generally very weak due to the shallow and dynamic nature of the system except the regions closer to the rivers and creeks. The model results show two potential regions with a very slow flushing rate.
CHAPTER 1
INTRODUCTION

Estuaries form the connection between the high salinity ocean water and fresh riverine water. Estuarine systems are semi-closed embayments formed through different morphological processes. Although there are different types of estuaries, they all create living environments for a variety of plants and animal communities. Because they contain the ocean and riverine waters, estuaries generally provide a highly productive water body, and have significant economic and recreational values.

Estuaries maintain a hydrodynamic balance within the system. The balance is a result of different forces interacting on the system. Tides, rivers, winds, waves, and atmospheric events will change the estuarine hydrodynamics. The circulation is generally forced by the ocean tides and modified by other external forces like wind and density gradients. The circulation patterns inside the estuaries determine the transport mechanisms for salt, nutrients and sediments. These patterns can change over a variety of time scales, from hourly, daily, weekly, monthly, to seasonally, depending on the variation in the forcing functions.

It is obvious that extreme events can exert disruptive forces on the estuarine hydrodynamics and water quality, creating possible environmental problems. Environmental problems within the estuary might be exacerbated by such factors as a large urban area within the watershed, increased human intervention, and increased number of point and non-point sources. These problems might be localized for confined areas, or might affect the water body throughout the estuary, which is directly affected by the circulation characteristics of the estuarine system.
Extreme events like tropical cyclones and heavy rainfall can disrupt these circulation patterns and modify the hydrodynamic balance inside the estuary. For example, high precipitation along with heavy river discharge might lead to sharp reductions in estuarine salinity. Strong storm winds might completely change the flow patterns within tidal inlets. After these extreme events, it will take some time for the estuarine system to recover to its pre-storm conditions, and the recovery time will depend on how quickly the ocean water can be circulated into and throughout the system. Therefore understanding the response of the estuarine system to extreme events should help developing better management and mitigation strategies for the estuarine system.

This study provides an understanding of the hydrodynamic response of the estuarine water bodies of Northern Coastal Basin (NCB) and Guana-Tolomato-Matanzas National Estuarine Research Reserve (GTMNERR) to extreme events in 2004 and 2008 by using three-dimensional numerical model simulations and observations. Chapter 2 investigates the application of the numerical model to the NCB estuary during four hurricanes (Charley, Frances, Ivan, Jeanne) in 2004 and two tropical storms (Fay and Hanna) in 2008. Verification of the 3-D model was done by comparing the simulated hydrodynamic parameters (water level, current, salinity) to the observed ones at available stations. Variation of salinity and stratification inside the estuary during the hurricanes and tropical storms in 2004 and 2008 was calculated.

Residual circulation and momentum balance during the hurricanes and tropical storms in 2004 and 2008 inside St. Augustine Inlet, the largest and most active inlet of the NCB, was studied respectively in Chapter 3 and Chapter 4. The variation of the
residual circulation around the inlet during the simulation period was compared to the
typical tidal residual circulation. The balance between the dominant forces during a
typical tidal cycle and the change in the momentum balance due to the strong winds,
increased precipitation and river discharge during tropical cyclones was studied.

A general summary of the results will be discussed in the last chapter.
CHAPTER 2
SIMULATING THE HYDRODYNAMIC RESPONSE OF NCB ESTUARY TO 2004 AND 2008 TROPICAL CYCLONES

Abstract

Northern Coastal Basin (NCB) along the northeast Florida coast was subjected to four major hurricanes (Charley, France, Ivan, and Jeanne) in 2004 and two tropical storms (Fay and Hanna) in 2008. Some of these storms passed through, while the others affected the region despite being far away. This study investigates the hydrodynamic response including the salinity dynamics inside the NCB estuary during 2004 and 2008 tropical cyclones. A three-dimensional model, CH3D (Curvilinear-grid Hydrodynamics in 3D), was used to simulate the estuarine circulation in the NCB and Guana-Tolomato-Matanzas Estuarine Research Reserve (GTMNERR). The model was found to successfully reproduce the observed water level, current, and salinity inside the estuary. Salinity inside the estuary reduced to zero at several stations (Pellicer Creek and Ormond Beach) for extended time period (~15 days) primarily due to the increased freshwater discharge, precipitation and altered residual flow patterns at the three inlets during the hurricanes. Salinity transport patterns inside the estuary show southward residual circulation especially to the south of the St. Augustine Inlet. High salinity ocean water entering the system through the inlets during non-storm time periods, and the freshwater discharged into the system soon after H Charley and Frances transported south. Recovery time for salinity to return to the pre-storm condition was quite long (~15 days) especially for two parts of the system: Pine Island at the north and Halifax River at the south. Despite increased river discharge and precipitation, the stratification

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throughout the system was never significantly high due to the shallow and dynamic nature of the system.

**Introduction**

Tropical cyclones can significantly affect the hydrodynamics, sediment transport (Walker 2001; Lynch 2004), habitat (Boesch 1976; Owen & White 2005), and water quality (Mallin et al. 1999; Paerl et al. 2001) of estuarine systems. For example, Hurricane Dora (1964) breached the barrier island between Matanzas Inlet and Intracoastal Waterway in the area (Powell 2006). Valiela et al. (1998) found that Hurricane Bob destratified the entire Waquoit Bay (MA) and the bay recovered quickly due to rapid flushing rates. Increased precipitation during Hurricane Agnes pushed the higher salinity estuarine water more than 30 miles down the Chesapeake Bay (Sherman 2003).

Many two- or three-dimensional numerical models have been developed for accurate simulation of the storm surge and inundation during tropical cyclones (Jelesnianski et al. 1992; Westerink et al. 2008; Sheng et al. 2005; Sheng et al. 2010a). However, most of these modeling studies focused on the storm surge simulation over 2-7 days and did not include the baroclinic effects. Since increased river discharge and precipitation during tropical cyclones can lead to significant salinity variations within a system, it is important to include the baroclinic effects in simulating hydrodynamics during tropical storms. Li et al. (2006) simulated (with 1km grid) the circulation in Chesapeake Bay during Hurricane Isabel and found that high salinity ocean water was forced into the estuary due to strong winds which created very strong vertical mixing, transforming the partially mixed Chesapeake Bay to a well mixed one. Similarly, response of the York River estuary to Hurricane Isabel was analyzed by Gong et al.
(2007) using a three-dimensional hydrodynamic model with a relatively fine grid (250m) over the course of a four month period. Gong et al. found that the system became highly stratified due to the combined effect of high salt influx, and increased freshwater discharge. Model results showed that the system recovered to its pre-storm conditions in almost four months. Recently, baroclinic processes have been incorporated into the storm surge forecasting system CH3D-SSMS (Curvilinear grid Hydrodynamics in 3D - Storm Surge Modeling System) for forecasting salinity and storm surge during Tropical Storm Fay in 2008 (Sheng and Paramygin 2010).

The main purpose of this study is to use the CH3D-SSMS to investigate the hydrodynamic (water level, currents, and salinity) response of the GTMNERR and NCB estuarine systems during the tropical cyclones in two active hurricane seasons in 2004 and 2008. Numerical results and observed data are compared and used to understand the changes in the estuarine hydrodynamics.

**Study Area and Methods**

The modeling study includes almost the entire Northern Coastal Basin (NCB) (Figure 2-1a), an estuary located on the northeast coast of Florida. The system extends from south of Ponce de Leon Inlet at the south to the east of Jacksonville at the north. The estuarine water body consists of Tolomato River at the north, Matanzas River at the center, and Halifax River at the south along the Intracoastal Waterway (ICWW). ICWW is a very shallow and narrow channel (mean depth=2.7m) inside the estuary. The estuarine water body is connected to the Atlantic Ocean through three tidal inlets: St. Augustine Inlet (tidal range=1.6m) at the north, Matanzas Inlet (tidal range=1.5m) at the center and Ponce de Leon Inlet (tidal range=1.2m) at the south end of the NCB. The depth inside the navigation channel is up to 15 m inside the St. Augustine Inlet, 12m
inside the Ponce de Leon Inlet, but the depth is only 3 m inside the Matanzas Inlet which is a natural and unmanaged inlet. The NCB system is fed by many small and mid-sized creeks with relatively small discharges throughout the ICWW. GTMNERR, located inside the NCB, is comprised of a north section (Guana Aquatic Preserve), located to the north of the St. Augustine Inlet and a south section, located between the south of St. Augustine Inlet and south of Marineland.

During 2004 and 2008 the area was affected by several different hurricanes and tropical storms (Figure 2-1c-d). To simulate and understand the change in estuarine hydrodynamics, the Curvilinear-Grid Hydrodynamics in 3D (CH3D) model (Sheng 1987, 1990; Sheng et al. 2010a) is used. CH3D is a robust hydrodynamic model that can be used to simulate the estuarine and coastal circulation driven by tides, winds, waves, and density gradients. CH3D can accurately resolve the complex geometry and bathymetry of the estuarine system, using a nonorthogonal boundary-fitted curvilinear grid in horizontal directions and terrain following sigma grid in the vertical direction. In CH3D, a second-order turbulence closure model (Sheng and Villaret 1989) is used to resolve the vertical turbulent mixing, while a Smagorinski-type model is used to parameterize the horizontal turbulent mixing. The CH3D model has been successfully verified with data from many estuaries throughout the coastal waters of U.S. and Florida, including GTMNERR (Sheng et al. 2008), Chesapeake Bay (Sheng et al. 2010a), Indian River Lagoon (Sheng and Kim 2009), Charlotte Harbor (Kim et al. 2010), and Pensacola Bay (Sheng et al. 2010b). Detailed equations of motion and boundary conditions for CH3D in curvilinear grid can be found in Sheng et al. 2010.
Model Simulations

The region was affected by four different storms during 2004 (Charley, France Ivan, and Jeanne) and two during 2008 (Fay and Hanna). Model simulations for both years covering all six storms are conducted. Model simulations were conducted using a high-resolution boundary fitted curvilinear grid (Figure 2-1b) which extends 150 km north from the south of Ponce de Leon Inlet and 30 km offshore. The minimum grid spacing for the grid is approximately 15 m inside the ICWW to accurately resolve the channel. Total number of cells for the grid was 37250 water, and 22640 floodable cells. Two simulate the three-dimensional flow field and resolve the sharp bathymetric changes, 8 sigma layers are used in vertical. Time step used for all the simulations was 10 s. In order to account for the inundation due to tides and storm surge, flooding-and-drying feature of the model was used.

2004 Simulations

The region was affected by four major hurricanes in 2004. Hurricane Charley first made landfall on the west coast of Florida near Ponta Gorda, as a category 4 hurricane, on August 13, 2004. After crossing the state of Florida, Charley emerged from Daytona Beach to the Atlantic Ocean on August 14, 2004. Hurricane Frances made landfall on September 5, 2004 near Hutchinson Island along the southeastern coast of Florida a category 2 hurricane. Less than 2 weeks later, tropical depression Ivan, remnants of Hurricane Ivan which made its first landfall in southern Alabama, emerged to the Atlantic Ocean and made its second landfall on September 21, 2004 at a location very near where Frances made landfall. On September 26, 2004, right after tropical depression Ivan passed through the region, Hurricane Jeanne hit the southeastern coast of Florida.
To include all four hurricanes in this study, we select a two-month simulation period between August 1, 2004 and October 1, 2004. In the simulations, tides and offshore surge were included as offshore boundary conditions, while the river discharge was used as the upstream river boundary condition. Wind, atmospheric pressure and precipitation were used as model input over the entire domain. Model simulations included the simulation of salinity and baroclinic terms since the precipitation and river discharge increased quite significantly during the two month period. In addition, to have a stable salinity and density field, a spin-up period from the beginning of June to the beginning of August was used. Spin-up period was simulated similar to the main simulation time period and included all the forcing functions used for main simulation period.

2008 Simulations
In 2008, the area was affected by two tropical storms during a two week period. On August 19, 2008 Tropical Storm Fay made landfall along the southwest coast of Florida. It then crossed the state of Florida in less than 24 hours and emerged to the Atlantic Ocean around Melbourne on August 20, 2008. After hanging around the region with a very slow forward moving speed (5-7 km/h), TS Fay moved northwest and made landfall on late August 21, 2008, near Flagler Beach within the NCB. Two weeks after TS Fay, TS Hanna was the next storm to affect the region while moving approximately 300 km offshore of the east Florida coast. At its closest point, TS Hanna was 200 km offshore on September 5, 2008.

Simulation of hydrodynamics in 2008 includes both tropical storms and covered a one-month period of from August 15, 2008 to September 15, 2008. Similar to the 2004 simulations tides and offshore surge were included as offshore boundary conditions,
while the river discharge was used at the upstream boundary of the rivers. Wind, atmospheric pressure and the precipitation were used over the entire domain as model input. In 2008 precipitation and river discharge increased significantly during the tropical storms, but it was less compared to the 2004 simulation period. To account for the changes due to precipitation and river discharge, baroclinic terms were included in the simulations as well. To ensure stability of the salinity and density fields throughout the domain, a spin-up time period from July 1, 2008 to August, 15, 2008 was used.

**Initial and Boundary Conditions for 2004 and 2008 Simulations**

The model boundary conditions and initial conditions were obtained from observed data sets and regional scale models. Tidal harmonic constituents for tidal boundaries were obtained from the ADCIRC tidal database for the East Coast (Mukai et al. 2001). Atmospheric pressure and wind data during non-storm periods are obtained from the NOGAPS model output, while those during storm time periods are obtained from a combination of winds from NOAA (National Oceanic and Atmospheric Administration) Hurricane Research Division’s (HRD) 10-m Reanalysis H*Wind (Powell et al. 1998) and atmospheric pressure from Holland (Holland 1980) analytical model. Observed daily precipitation data available at several stations are interpolated onto the model grid. Observed river discharge data available from USGS is used for river boundary conditions at upstream river locations.

**Model Verification**

For model verification, simulated water level and salinity were compared at all the available stations inside the domain. The comparisons were made over the main simulation period of 60 days in 2004 and over 30 days in 2008. In general the observed and simulated values showed a very good agreement. The comparisons of water level
for selected stations in 2004 and 2008 are given in Figure 2-2 and Figure 2-3, respectively. The simulated water level values are mostly within 15-20 cm of the observed water level values including during the tropical storms and hurricanes. The average normalized root mean square (RMS) error for all the water level stations for both during 2004 and 2008 are approximately 10%.

Similarly, the simulated salinity over 60 days in 2004 and 30 days in 2008 are generally in agreement with the observed salinity values, as shown in Figure 2-4 and Figure 2-5, respectively. The simulated salinity values are generally within 3-6 ppt of the observed values, while the mean normalized RMS error for all the salinity stations is around 25%. It is important to note that tropical cyclones are generally associated with increased precipitation and river discharge which can cause sudden changes in the local salinity. Hence, it is difficult to accurately simulate the salinity without accurate precipitation and river discharge measurements and surface runoff created by heavy rainfall. In addition to the water level and salinity observation, currents inside the deep navigation channel of St. Augustine Inlet were obtained with an Acoustic Doppler Current Profiler (ADCP) during Tropical Storms Fay and Hanna in 2008. The ADCP (Figure 2-1a) was bottom mounted and recorded the velocity profile over the water column at every 0.5 m at a ping rate of 1.5 s, averaging 900 samples per ensemble. The vertically-averaged velocities simulated by the model at the same location agree well with the measured ones in both east-west and north-south directions (Figure 2-6). In addition, comparison of several vertical velocity profiles in the dominant flow direction (east-west) are given at selected times in Figure 2-7 where model results show better agreement with data during flood and ebb than during slack tides. This is because that,
during flood and ebb tides, the tidal boundary layer is thicker and hence better simulated. The average RMS error for the simulated east-west velocities at all 8 vertical layers is approximately 20 cm/s (8% of the maximum current) and less than 10 cm/s (8% of the maximum current) for the north-south velocities. The average RMS error for vertically-averaged velocities in east-west direction is less than 20 cm/s and less than 5 cm/s for the north-south velocities.

Change in Salinity and Stratification

During 2004 and 2008 simulation periods, precipitation and river discharge increased substantially during tropical cyclones (Figure 2-8). Increased precipitation and river discharge throughout the estuary created significant variation in the salinity field. During normal conditions, most part of the subtropical estuary flushes rather quickly (~1-2 days). However, some localized sections of the system, especially near the mid-sized creeks located away from the inlets have longer residence times (~15 days) (Sheng et al. 2008).

During tropical cyclones, the structure of the residual flow throughout the estuary as well as the inlets changes completely. During tropical cyclones in 2004 and 2008, the residual flow around the inlets changed significantly which controlled the distribution and recovery of the estuarine salinity (Tutak and Sheng 2010a, 2010b). In order to understand the variation of salinity within the estuary, we examine the variation of the total surface area of estuarine water with three distinct salinity ranges: 0-10 ppt (low salinity), 10-20 ppt (moderate salinity), and 20 ppt and above (high salinity). The areas of these three salinity ranges change during tropical cyclones due to increased precipitation, river discharge and change in the residual flow structure throughout the estuary. Changes of these three salinity areas in 2004 and 2008 are shown in Figure 2-
9b and Figure 2-10b, respectively. These changes in salinity areas are highly dependent on both the river discharge and the precipitation shown in Figure 2-8. In addition, the sudden changes in the areas seem to be highly correlated with the residual flow rate (Figure 2-9c, Figure 2-10c) at each inlet especially during the hurricanes (Figure 2-9a, Figure 2-10a) and tropical storms.

In 2004, prior to Julian day 230, the salinity field appears to be rather stable. Around and after Julian day 230, the estuarine system seems to be varying temporally with semi-diurnal tide. A small jump in the low salinity (0-10ppt) area is due to a change in the system caused by Hurricane Charley. After that, salinity in the system was stable until day 245, when Hurricane Frances started to affect the region. Between day 245 and 250, the low salinity area started to reduce, while the high salinity area increased, due to increase in residual inflow (negative flow rate) at the inlets due to the easterly winds. Right between day 249 and 250, Hurricane Frances made landfall and started moving towards north across Florida. Therefore the barotropic pressure gradient created due to the strong winds relaxed in the system, along with the increase in precipitation and river discharge. The residual flow rate through the inlets reversed and became positive (out of inlet). The amount of residual flow rate was quite significant (up to 1000 m$^3$/s), thus created a quicker change in the salinity. The high salinity (20 ppt and above) area reduced approximately to one-fifth of its value in one day. At the same time, the low and moderate (10 - 20 ppt) salinity areas doubled in coverage. The low salinity area stayed high for approximately 15 days until around day 265, when it was almost equal to the high salinity area, similar to the pre-storm condition around day 240. Around day 270 during Hurricane Jeanne, the low salinity area first showed a slight
reduction and then jumped back to its pre-storm size of 50 km$^2$ coverage. The moderate salinity area did not show significant variation with time.

In 2008, the variation of salinity areas was a little different compared to the 2004 season. The high salinity area started to reduce around day 234 due to the effect of increased precipitation and river discharge. The residual flow in St. Augustine Inlet was into the estuary (negative) between day 234 and 235, and out of the estuary between day 235 and 236. However, the other two inlets never showed inflow of water during TS Fay due to the direction of the winds. The salinity did not seem to be affected much by the residual flow during TS Fay, as it occurred with Hurricane France in 2004, since Fay was a weaker storm. The low salinity area increased up to 20 km$^2$ until day 240 and remained stable until day 245, when the precipitation and river discharge became negligible. After day 245, the moderate salinity area started to increase due to mixing with high salinity ocean water. After day 250 during TS Hanna, the low salinity area started to decrease with small fluctuations and it reduced down to 10 km$^2$ until the end of the simulation period. In the mean time, the high salinity area showed a small decrease between day 251 and 253, but then recovered up to 60 km$^2$. At the end of the 30 day simulation, the moderate salinity area reached 30 km$^2$, which was formed due to the mixing of high and low salinity water inside the estuary.

**Stratification inside the Estuary**

The relatively small size of the estuary combined with the tidally dominated flow leads to a generally well mixed salinity and density field throughout the system with the exceptions around the rivers and creeks. However, since the NCB estuary is subtropical, amount of freshwater is generally limited. To understand and determine how stratification was affected during tropical cyclones inside the NCB, the difference
between the bottom and the surface salinity throughout the modeling domain was calculated. To be representative, the variation of stratification throughout the ICWW is given in Figure 2-11a for 2004, and Figure 2-12a for 2008 simulations. The difference between the bottom and surface salinity was generally less than 1 ppt throughout the estuary. The biggest differences (dark patches) were found around the river mouths. The most stratified region was at the mouth of Tomoka River (~40 km from Ponce de Leon Inlet) which had one of the strongest freshwater discharge values within the system, and was the closest river to the ICWW as well.

During tropical cyclones, the stratification disappeared even around the rivers and creeks. This was especially obvious during Hurricane Frances (~ day 250) in 2004 and TS Hanna (~ day 250) in 2008 due to the strong vertical mixing caused by the strong wind throughout the estuary. In addition, the bottom (Figure 2-11b and Figure 2-12b) and surface (Figure 2-11c and Figure 2-12c) salinity with respect to distance and time inside the ICWW are plotted to understand the transport of the high and low salinity water inside the estuary. Model results showed that the freshwater especially from the Tomoka River and Pellicer Creek (~75 km from Ponce de Leon Inlet) moved towards south inside the ICWW during the simulation period in 2004. During the 2008 simulation period, the freshwater from Pellicer Creek did not reach the ICWW, but the freshwater from Tomoka River was transported south towards Halifax River. The transport was more prominent after the tropical cyclones, between day 228 and 240 after Hurricane Charley, between day 250 and 265 after Hurricane Frances in 2004, and between 236 and 250 after TS Fay in 2008. Similarly, the high salinity ocean water that entered the estuary from St. Augustine Inlet (~100 km) and Matanzas Inlet (~80 km) moved mostly
towards the south in both simulation periods due to the higher mean water level at the north part of the system. The sudden increase of high salinity water around day 249 during the landfall of Hurricane Frances in 2004 coincided with the strong northeasterly winds and the negative (inflow) residual flow. In the ensuing day 250, the high salinity water inside the ICWW decreased suddenly due to the relaxation of wind setup, and the completely reversed (positive) residual flow through the inlets.

At the north section of the estuarine system (north of St. Augustine Inlet), the variation of salinity was controlled mostly by the small amount of freshwater discharge from several creeks. The high salinity ocean water did not reach up the estuary beyond 10-20 km north of the St. Augustine Inlet. In addition, Figure 2-11 and Figure 2-12 along with Figure 2-9 and Figure 2-10, showed that once the system received the low salinity freshwater discharge, the flushing time of the system, especially at the southern (around Halifax River) and northern (near Pine Island) sections of the estuary, was considerably longer (more than 2 weeks). The slow flushing was observed during both 2004 and 2008 simulation periods, but it was more obvious during 2004 due to the higher freshwater (3 times higher during maximum river discharge) input to the system compared to the 2008 simulation period. The same two sections of the system were shown by Sheng et al. (2008) to be the slowest flushing sections of the estuarine system.

Conclusions

Dynamics of water level, salinity and stratification throughout the GTMNERR and NCB have been investigated during 2004 and 2008. The system was affected by four major hurricanes (Charley, France, Ivan, Jeanne) in 2004 and two tropical storms in 2008 (Fay and Hanna). A three-dimensional baroclinic and flooding-and-drying
numerical model CH3D was used to simulate the estuarine hydrodynamics of water level, salinity, and flow velocities. The simulated water level, salinity and flow velocities are found to agree with the observed ones quite well. The salinity inside the system was subjected to dramatic reductions especially during the storms. Some local areas of the system such as Pellicer Creek and Halifax River were reduced to zero salinity which persisted for more than 15 days. The increased precipitation and river discharge flooded the system with low salinity freshwater. In addition, the residual flow at the three inlets was significantly modified by the tropical cyclones and prevented the high salinity ocean water from entering into the system. The variation of salinity along the ICWW showed that at the south of St. Augustine Inlet, the salinity transport was towards the south due to the higher mean water level at the north of the domain. This was observed at several different instances throughout the simulation period: the transport of high salinity ocean water entering the domain from inlets in to the system right before H Charley and Frances, and the transport of low salinity freshwater discharged from the rivers right after H Charley and Frances. Two areas of the NCB affected by the increased freshwater discharge and precipitation showed long recovery times (~15 days) due to their distance to the inlets and the modified circulation patterns inside the inlets. The northern section of the system around Pine Island (SWMP) and the southern section of the system near Halifax River showed persistent low salinity conditions for more than 2 weeks. Similarly, the flushing time for these two regions was shown by Sheng et al. (2008) to be around 15 days and designated as the two slowest flushing segments of the estuarine system. Stratification inside the system was negligible except at river mouths, although the salinity of the system went through dramatic changes.
Stratification was reduced during tropical cyclones due to increased vertical mixing caused by strong winds.
Figure 2-1. Study area, (a) map showing the study area of Northern Coastal Basin and GTMNERR. Red star at the St. Augustine Inlet denotes the ADCP location used for current measurements; (b) CH3D modeling domain on the east coast of Florida; (c) hurricanes in 2004; (d) tropical storms in 2008
Figure 2-2. Comparison of observed (.) and simulated (solid) water level time series during 2004 simulation period at a) Port Orange; b) Ormond Beach; c) Bings Landing; d) Vilano Beach
Figure 2-3. Comparison of observed (.) and simulated (solid) water level time series during 2008 simulation period at a) Ponce de Leon Inlet; b) San Sebastian (SWMP); c) Pine Island (SWMP)
Figure 2-4. Comparison of observed (.) and simulated (solid) salinity time series during 2004 simulation period at a) Fort Matanzas (SWMP); b) Pellicer Creek (SWMP); c) Crescent Beach; d) San Sebastian (SWMP)
Figure 2-5. Comparison of observed (.) and simulated (solid) salinity time series during 2008 simulation period at a) Pellicer Creek (SWMP); b) San Sebastian (SWMP); c) Pine Island (SWMP)
Figure 2-6. Comparison of observed (.) and simulated (solid) vertically-averaged velocity time series during 2008 simulation time period in a) east-west; b) north-south directions.
Figure 2-7. Comparison of observed (.) and simulated (solid) vertical velocity profiles inside the St. Augustine Inlet in the along-inlet direction at selected time instances during 2008 simulation time period
Figure 2-8. River discharge and precipitation during a) 2004 simulation period with noticeable increase during Hurricane Charley (day 225-230), Hurricane Frances (day 248-260), Hurricane Ivan (day 263-268), Hurricane Jeanne (day 268-275); b) 2008 simulation period with noticeable increase during Tropical Storm Fay (day 233-248), Tropical Storm Hanna (day 248-255)
Figure 2-9. Time variation of a) hurricane winds; b) surface area of salinity at given thresholds; c) residual flow rate through inlets, during 2004 simulation period.
Figure 2-10. Time variation of a) tropical storm winds; b) surface area of salinity at given thresholds; c) residual flow rate through inlets, during 2008 simulation period.
Figure 2-11. Time variation of a) stratification (bottom – surface salinity); b) bottom salinity c) surface salinity during 2004 simulation period along the ICWW
Figure 2-12. Time variation of a) stratification (bottom – surface salinity); b) bottom salinity; c) surface salinity during 2008 simulation period along the ICWW.
CHAPTER 3
EFFECTS OF HURRICANES ON RESIDUAL CIRCULATION AND MOMENTUM BALANCE IN A SUBTROPICAL ESTUARY AND INLET IN 20042

Abstract

In 2004, four hurricanes (Charley, Frances, Ivan, and Jeanne) affected the subtropical Northern Coastal Basin (NCB) estuary and St. Augustine Inlet (SAI). This study investigates the changes in residual circulation and momentum balance inside the NCB and SAI during these hurricanes using a three-dimensional numerical model CH3D. Residual circulation simulated by CH3D is verified with results of a 3D analytical model. During typical tidal cycles with weak external forces, simulated residual circulation shows two counter rotating (~15-20 cm/s) eddies on the estuary side and two (~5-10 cm/s) eddies on the ocean side of the SAI. This structure results in cross-sectional residual flow to change along the inlet. During hurricanes, the residual circulation changed significantly – the strong northeasterly winds disrupted the ocean-side eddies and created a southerly along-shore current, while the ensuing easterly winds created an inflow throughout the mouth of the inlet followed by an outflow throughout the inlet and a northerly along-shore flow due to southeasterly winds. The time for flow recovery was very short for Hurricanes Charley and Ivan (~1-2 days), but much longer (~10 days) for Hurricanes Frances and Jeanne. Comparison of the terms in the horizontal momentum equations show that over a typical tidal cycle the balance is predominantly between barotropic pressure gradient and nonlinear advection. Wind stress during hurricanes became significant part of the balance, causing the eddies to disrupt. Bottom friction and baroclinic pressure gradient increase significantly to

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contribute to the balance. Comparing residual circulation calculated with and without the nonlinear advection shows that the residual circulation is caused by nonlinear advection.

**Introduction**

Residual flow in an estuarine system may be created due to a variety of forces such as wind, river discharge, nonlinearities, etc., and is significantly influenced by the physical characteristics of the estuarine system. Fischer et al. (1979) defined the residual flow to be the average flow over a tidal cycle, but cautioned that each tidal cycle is different from another one.

Kjerfve (1978) used observed data obtained from North Inlet in North Carolina, a well mixed and shallow estuary with two deep channels separated by a shoal in between, to examine the relationship between residual flow and variations in bathymetry. Kjerfve found a pattern of outflow in the deep channel and inflow over the shallow region, opposite to the pattern proposed by Fischer (1976) for a partially mixed, density driven estuary with laterally varying bathymetry.

Li and O'Donnell (1997), using a two dimensional analytical model in a channel with laterally varying (v-shaped) bathymetry, obtained similar residual flow pattern as that obtained by Kjerfve (1978). They found that the residual flow was the result of the nonlinearities created by inertial effects and tides. Li and O'Donnell (2005) used a similar analytical model to study the effect of channel length (parameterized by channel depth and tidal frequency) on the residual circulation. The long channels, with progressive waves, show a residual flow structure similar to that in a well mixed estuary with laterally varying bathymetry, while the short channels with standing waves show inflow at the deep channel and outflow over the shallow shoals.
The residual flow through the mouth of the St. Augustine Inlet (SAI), Florida was measured by Webb et al. (2007) whose data support the short channel theory postulated by Li and O’Donnell (2005). In addition to the residual flow structure, Webb et al. found that the force balance inside the inlet was dominantly between barotropic pressure gradient and nonlinear advection.

Bottom friction and Coriolis force are also known to modify the tidal residual circulation. Winant (2008) using a three-dimensional analytical model inside an elongated rectangular channel showed, when rotation is considered, the tidally generated residual velocities yielded larger values compared to the cases where rotation is not considered. The rotational effects become very important at low friction conditions, even when the channel is very narrow. At high friction conditions, the residual flow structure mimics found in long channels (Valle-Levinson et al. 2003).

Tee (1976) examined the tidally generated residual circulation inside the Minas Basin of Bay of Fundy, using a two dimensional vertically-integrated numerical model, and found that the residual circulation and the formation of the residual eddies was largely due to the nonlinear advection terms. Hench and Luettich (2003) studied the momentum balance around the shallow Beaufort Inlet in North Carolina, using a two dimensional vertically-integrated numerical model, and found that the pressure gradient was balanced by the nonlinear advection in the flood phase, while the bottom friction was in balance with nonlinear advection in the ebb phase.

Episodic events such as storms, associated with strong winds and increased river discharge, might affect the residual circulation. Liu (1992) used data observed inside the Indian River Lagoon, Florida and a one dimensional numerical model to show that
barotropic pressure gradients created by storms might be on the same order as the tidal pressure gradients and drastically alter the residual exchange patterns. Valle-Levinson et al. (2002) showed that the flow structure at the mouth of the Chesapeake Bay was modified from outflow at the deep channel and inflow over the shoals to a complete outflow throughout the entire mouth during Hurricane Floyd, due to the increased freshwater discharge, increased wind speed and favorable wind direction.

The aim of this study is to obtain a comprehensive understanding on the effects of extreme events such as tropical cyclones on the residual circulation and the momentum balance inside a subtropical estuary (Northern Coastal Basin or NCB) and tidal inlet (St. Augustine Inlet or SAI) in Florida, using a three-dimensional hydrodynamic model CH3D (Sheng 1987, Sheng et al. 2010) to simulate the August-October period in 2004 when four major hurricanes affected the area.

**Study Area and Methods**

St. Augustine Inlet (Figure 3-1a) is a subtropical and tidally dominated inlet along the east coast of Florida. It is a managed inlet including a dredged navigation channel to the south of the inlet with depths up to 15 m. The depth towards the north shore of the inlet is much shallower with the maximum depth around 5 m. The inlet is dominated by semi-diurnal tides with tidal range reaching up to 1.7 m inside the inlet. SAI is directly connected to the Intracoastal Waterway (ICWW) which includes Tolomato River at the north, Matanzas River and Salt Run (an embayment) at the south. The inlet and the connecting branches are all parts of the NCB estuarine system (Figure 3-1b) which extends from east of Jacksonville at the north to the Ponce de Leon Inlet at the south. The system consists of the very shallow and narrow ICWW and two other inlets: Matanzas and Ponce de Leon. Guana-Tolomato-Matanzas National Estuarine
Research Reserve (GTMNERR) is part of the NCB estuary, established to support and provide opportunities for public education, research, and enhanced management of the estuarine habitat (FDEP 2009). Five observation stations maintained by GTMNERR provide real-time hydrodynamic, water quality, nutrient and meteorological information. The flow within the NCB is forced by tides mostly from the SAI. Tidal flow through the SAI is generally 4-5 times larger than the other two inlets.

During the 2004 hurricane season, four major hurricanes (Figure 3-1c, Table 3-1) (Charley, Frances, Ivan, and Jeanne) affected the region. To understand the complete spatial and temporal variation of the residual circulation and the momentum balance inside the SAI during these hurricanes, the CH3D (Curvilinear-grid Hydrodynamics in 3D) model (Sheng 1987, 1990; Sheng et al. 2010) is used for the hydrodynamic simulations (Tutak and Sheng 2010a). CH3D model uses horizontally boundary-fitted curvilinear grid and a vertically terrain-following sigma grid to enable accurate resolution of the complex geometry and bathymetry of estuaries. Moreover, CH3D contains a robust turbulence closure model (Sheng and Villaret 1989) for vertical turbulent mixing and a Smagorinski-type model for horizontal turbulent mixing. CH3D can be used to calculate the circulation driven by tides, winds and density gradients. In addition, the model can allow flooding-and-drying (Davis and Sheng 2003) and accept large-scale and hurricane-scale winds and precipitation to calculate storm surge and coastal inundation. Detailed explanation of equations and boundary conditions can be found in Sheng et al. (2008) and Sheng et al. (2010a).

To incorporate the pre-storm and post-storm changes to the estuarine system, the model simulations were conducted over a two month period between 08/01/2004 and
10/01/2004 with a two month spin-up period between 06/01/2004 and 08/01/2004. Although the residual circulation and momentum balance around SAI are of primary interest, the model domain for the hydrodynamic simulations includes almost the entire NCB to ensure accuracy of the simulation. The model uses a high resolution boundary-fitted curvilinear grid, with a minimum cell size of 15 m inside the estuary, and allows the flooding-and-drying process. 37250 water and 22640 floodable cells comprise the model grid (Figure 3-1d). In order to capture the bathymetry changes from shallow channels inside the estuary to deep offshore and three-dimensional velocity structure, four sigma layers are used. The model simulations were conducted with 10 s time step.

CH3D uses tidal constituents obtained from ADCIRC tidal database for the East Coast (Mukai et al. 2001) along the offshore boundary. The simulations include forcing by the wind and atmospheric pressure as well. During non-storm periods, wind and atmospheric pressure are obtained from the Navy Operational Global Atmospheric Prediction System (NOGAPS) model output. During hurricanes, the 10 m reanalysis H*Wind (Powell et al. 1998) wind snapshots generated by NOAA (National Oceanic and Atmospheric Administration) Hurricane Research Division (HRD) are used in combination with the NOGAPS wind (as background wind) (Paramygin, 2009). Atmospheric pressure during storm periods are obtained from the Holland B (Holland 1980) analytical wind model because the H*Wind reanalysis winds do not include the atmospheric pressure. In addition, for simulating the baroclinic circulation, river discharge at the upstream river boundaries and spatially interpolated precipitation based on data obtained at a few stations are used in the model simulation.
Validation of Simulated Residual Flow

Before trying to understand the residual circulation in a region with very complex geometry and bathymetry due to the interaction of different forces, numerically simulated residual circulation obtained from CH3D is compared with the circulation obtained by Winant (2008) using an analytical model for an elongated, rotating rectangular basin with a laterally varying depth. Winant obtained residual circulation for different cases of friction and rotational forces (no friction, moderate friction, high friction cases with rotation or no rotation). Although all cases are simulated with CH3D, only comparison of moderate friction case with rotation is presented in this paper. As shown in Figure 3-2, the numerical model results show excellent agreement with the analytical model results. This validation proves that the CH3D has robust physics and numerical algorithms for simulating three-dimensional residual circulation. Although analytical models can provide insight for understanding ideal and simplified basins, they cannot be applied to real estuaries with complex bathymetry and geometry, stratification and variable turbulent eddy viscosity. Therefore, CH3D will be used for simulating the residual circulation in NCB, a real and complex estuary.

Spatial Patterns of Residual Circulation

During One Typical Tidal Cycle

Tidal residual circulation calculated inside the SAI using CH3D show formation of four residual eddies (Figure 3-3a). Two stronger eddies form inside the estuary with currents up to 15-20 cm/s, while two weaker eddies (with currents ~5-10 cm/s) form on the ocean side of the inlet. Inside the estuary, a clockwise eddy in the north and a counterclockwise eddy in the south are formed. Conversely, on the ocean side, a clockwise eddy in the south and a counterclockwise eddy in the north are found. Across
the mouth of the inlet, residual currents show inflow through the deep navigation channel and outflow over the shallow north section as was observed by Webb et al. (2007). The model results show that the cross-sectional residual flow pattern observed by Webb et al. on a transect at the mouth of the inlet was part of the two three-dimensional residual eddies inside the inlet. Therefore the cross-sectional residual flow pattern at the mouth of the inlet is prone to changes with the location of the selected transect (Figure 3-11). The residual eddies inside the inlet are important because they determine the distribution and transport of the water mass inside the estuary, and control the cross-sectional flow structure at the mouth of the inlet. Understanding the structure and dynamics of these eddies is essential to the understanding of cross-sectional residual flows. The formation of these residual eddies has been shown to depend on the geometry and shape of the channel (Fischer et al. 1979), tidal flow interacting with the local bathymetry (Zimmerman 1978), and the nonlinear advection (Tee 1977). Using CH3D model results, we confirm that the formation of the residual eddies around SAI is mainly due to the nonlinear advection, while geometry and bathymetry affected the detailed structure of the eddies. Figure 3-3b shows that the residual currents are negligible (~1-2 cm/s) when the nonlinear advection terms in the model are excluded from the calculations.

Changes to the Residual Flow Pattern during Hurricane Charley

Hurricane Charley made landfall in Charlotte Harbor area on August 13, 2004. It moved across Florida and emerged to the Atlantic Ocean around Daytona Beach early morning on August 14, 2004. Since Hurricane Charley was a very compact and fast moving storm, changes to the residual flow around the SAI were. When the storm reached the NCB region, the winds were 9 m/s from northeast which quickly changed to
northwest and then southwest. Due to the strong winds, the weak eddies on the ocean side of the inlet were disrupted into a unidirectional southerly along-shore current up to 10 m/s, while the eddies inside the inlet did not change their structure or strength. Hurricane Charley was moving so fast that the strong wind conditions in the region did not persist more than 6 hours. After the winds relaxed the system returned to its pre-storm condition in 48 hours.

Changes to the Residual Flow Pattern during Hurricane Frances

Hurricane Frances made landfall approximately 325 km away from the region on the east coast of Florida, but the strong tropical storm strength winds reached the area due to its large size.

The wind started blowing from northeast at approximately 7 m/s four days before the landfall and persisted until two days before the landfall. As a result, the residual flow structure around the region started to change four days before the landfall first with the disruption of the weak ocean side eddies into a unidirectional southerly along-shore flow, followed by an increased residual flow into the inlet from the ocean. When the wind started to intensify (up to 12 m/s) from the northeast, the southerly along-shore currents reached a maximum of 20 cm/s (Figure 3-4a). In addition, the strong northeasterly weakened the north eddy inside the inlet (speed ~1-2 cm/s), and the residual inflow coming through the inlet moved towards Matanzas River revolving around the south eddy without disrupting the south eddy.

Wind speed reached approximately 14 m/s and the wind direction turned to southeast in two days following the landfall. The system responded quickly to the increasing wind speed and changing wind direction. The along-shore currents on the ocean side completely reversed and became northerly with speeds up to 25 cm/s.
Both eddies inside the inlet completely vanished and flow inside the inlet became complete outflow, supported by the flow from Matanzas and Tolomato Rivers. The structure of the residual flow inside the inlet resembles that of a tidal ebb flow. The winds relaxed in the next 24 hours and the system recovered to its pre-storm condition almost 10 days after the residual flow structure started to change.

Changes to the Residual Flow Pattern during Tropical Depression Ivan

H Ivan made landfall in Alabama and Florida border (Sheng et al. 2010b), but later reemerged to the Atlantic Ocean around Maryland and returned to the east coast of Florida as a weak storm. During the passage of a much weakened Ivan, the structure of the residual circulation did not change significantly due to the diminishing wind.

While Ivan was close to the east coast of Florida, the winds were blowing mostly from the northeast with speed up to 6 m/s. The two eddies on the ocean side were disrupted, and the along-shore current became southerly as was during H Charley.

Changes to the Residual Flow Pattern during Hurricane Jeanne

Less than a week after Ivan made its second landfall, when the system was yet to recover to its pre-Ivan conditions, H Jeanne made landfall at almost the same location where H Frances made the landfall. Before H Jeanne made landfall the ocean side of the inlet was still showing southerly along-shore flow with speeds up to 15 cm/s while the wind was blowing at 7 m/s from northeast (Figure 3-4a). Since Hurricanes Frances and Jeanne had similar track and structure, changes to the residual circulation around the system were very similar.

During H Jeanne’s landfall the residual flow structure changed drastically around the area. The winds turned from northeast to east while the speeds went up to 19 m/s. The residual flow on the ocean side started to reverse a northerly flow due to relaxed
along-shore wind. The inlet mouth at the moment did not show in-out flow condition.
After the landfall, wind speed in the region increased to almost 24 m/s and the wind
direction became southeasterly. This wind enhanced the northerly along-shore residual
currents that started to form during landfall and increased the magnitude up to 25 cm/s.
The residual flow became complete outflow through the mouth of the inlet and the
structure of the residual flow inside the inlet was very similar to a tidal ebb flow as
depicted (Figure 7.6) by Fischer et al. (1979), where all the flow was directed towards
the mouth of the inlet. This structure was very similar to the one during H Frances
(Figure 3-4b). A short summary of changes to the residual circulation with respect to the
other forces during the simulation period is given in Table 3-2.

Spatial Patterns of Momentum Balance

During One Typical Tidal Cycle

During tidally dominated periods, the residual momentum balances in along-
channel (~15° counterclockwise from E-W) (Equation 1) and cross-channel (Equation 2)
directions in the region around the inlet are primarily between barotropic pressure
gradient and nonlinear advection terms throughout the region, especially around the
inlet, which are at least an order of magnitude higher than the other terms (Figure 3-5a-
b). The other significant terms for the momentum balance are bottom friction and
baroclinic pressure gradient. Bottom friction is important especially around the mouth of
the inlet where the bathymetry is shallow around tidal flats (ebb shoals). On the other
hand, along-channel baroclinic pressure gradient during the simulation period is
significant mostly inside the Tolomato River along the east coast of ICWW. The cross-
channel baroclinic pressure gradient is strong inside the mouth of the inlet, due to the
exchange between ocean and estuarine waters. The remaining terms are generally negligible.

\[
\frac{\partial U}{\partial t} + \frac{\partial (UU/H)}{\partial x} + \frac{\partial (UV/H)}{\partial y} &= \frac{fV}{H} + \frac{gH}{\rho} \frac{\partial z}{\partial x} + \frac{gH^2}{\rho} \frac{\partial \rho}{\partial x} - \frac{\tau_{xx}}{\rho} + \frac{\tau_{bx}}{\rho} - A_H \left( \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) = 0 \quad \text{Eq. (3-1)} \\
\frac{\partial V}{\partial t} + \frac{\partial (VU/H)}{\partial x} + \frac{\partial (VV/H)}{\partial y} &= \frac{fU}{H} + \frac{gH}{\rho} \frac{\partial z}{\partial y} + \frac{gH^2}{\rho} \frac{\partial \rho}{\partial y} - \frac{\tau_{yy}}{\rho} + \frac{\tau_{by}}{\rho} - A_H \left( \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) = 0 \quad \text{Eq. (3-2)}
\]

**Momentum Balances during Hurricane Charley**

During Hurricane Charley, the momentum balance was comparable to that during a typical tidal cycle, with slight changes in the wind stress and baroclinic pressure gradient, mostly in the cross-channel direction due to the increased wind stress. The bottom friction showed a slight increase in cross-channel direction around the tips of headlands on the ocean side due to the southerly along-shore current created.

**Momentum Balances during Hurricane Frances**

The momentum balance started to show slight changes throughout the region two days prior to the landfall until right before the landfall. Right before the landfall, the wind increased up to 12 m/s from northeast. The along-channel wind stress inside the inlet and the Tolomato River increased significantly, thus creating a positive momentum flux (Figure 3-6a) which is balanced by increased negative barotropic pressure gradient due to the wind set up. Similarly, in the cross-channel direction, a positive momentum flux is created mostly inside the inlet due to the wind stress (Figure 3-7a), which is balanced by a combination of barotropic pressure gradient and bottom friction. Bottom friction is significant especially on the ocean side of the inlet. In addition to these terms, baroclinic pressure gradient gained some strength in the along-channel and cross-channel
directions, due to the increased freshwater flow into the system which modified the residual momentum balance at the mouth of the inlet.

After the landfall of Frances, the spatial structure of the wind stress in the along-channel direction did not change significantly except a slight increase inside the Tolomato River (Figure 3-6b). The along-channel wind stress is balanced by the barotropic pressure gradient. Bottom friction reversed due to reversal of the residual flow at the mouth of the inlet. Because the wind changed direction from northeast to southeast, the along-channel wind stress became completely negative throughout the region (Figure 3-7b). The strong wind stress was mainly balanced by the bottom friction, especially on the ocean side, and barotropic pressure gradient inside the inlet. In addition, inside the inlet, baroclinic pressure gradient turned from positive to negative due to the completely outward residual flow. The system started to return to pre-storm conditions when the winds started to relax in the next 24 hours. The system fully recovered in almost 12 days after the first changes within the system, with the exception of baroclinic pressure gradient which was modified due to the increased freshwater input.

**Momentum Balances during Tropical Depression Ivan**

The momentum balance did not show much change during Ivan. The balance of the system is still primarily between the barotropic pressure gradient and the nonlinear advection, since the wind was never strong around the region during Ivan. During the second landfall of Ivan, the cross-channel baroclinic pressure gradient changed slightly due to the freshwater input into the system and acted together with the nonlinear advection inside the inlet to balance the barotropic pressure gradient. This momentum balance persisted until Hurricane Jeanne started to affect the region.
Momentum Balances during Hurricane Jeanne

Before Hurricane Jeanne made landfall, wind stress in both along- and cross-channel directions increased inside the Tolomato River and inside the inlet (Figure 3-6a and Figure 3-7a), due to winds blowing from northeast with a speed of 7 m/s. While the along-shore bottom friction did not change significantly, the cross-channel bottom friction increased, especially on the ocean side of the inlet around the tips of the headlands due to the southerly along-shore currents. Along-channel baroclinic pressure gradient continued to persist on the east shore of ICWW without significant change in magnitude. However, a positive cross-channel baroclinic pressure gradient formed along the deep navigation channel inside the inlet due to the change in residual flow structure.

Right after the landfall of Hurricane Jeanne, the wind changed to southeasterly with a speed up to 24 m/s (maximum wind during the simulation period) because of the hurricane’s northward movement towards the region after the landfall. In the along-channel direction, the wind stress was still very significant inside the Tolomato River and parts of the Matanzas River (Figure 3-6b). The along-channel bottom friction increased mostly along the deep navigation channel inside the inlet. The barotropic pressure gradient balanced both the wind stress and the bottom friction in the along-channel direction. In the cross-channel direction, wind stress created a negative flux over the entire region (Figure 3-7b), while bottom friction increased significantly on the ocean side, balancing the wind stress. The wind stress is balanced by barotropic pressure gradient inside the inlet. A short summary of changes to the residual circulation with respect to the other forces during the simulation period is given in Table 3-3.
Time Variation of Momentum Balances at a Station Inside the Inlet

Snapshots of residual momentum balance over the region surrounding SAI provide excellent information for understanding the causes for changes in residual circulation during storm season. However, since these snapshots are not continuous in time, it is interesting to understand the continuous temporal variation of each term in the momentum equations. For this purpose time series of each term in the momentum equations and their total at a selected location inside the inlet are given in Figure 3-8. The time series show that the system was in balance with practically no variation in horizontal diffusion and local acceleration throughout the simulation period.

In both along- and cross-channel directions the momentum balance is between the barotropic pressure gradient and nonlinear advection terms, with considerable contribution from the cross-channel baroclinic pressure gradient. Wind stress and bottom friction changed slightly during hurricanes. The cross-channel baroclinic pressure gradient changed over a longer time period, especially after the hurricanes, compared to the wind stress and bottom friction.

River Discharge and Precipitation

River discharge and precipitation are two other external forces that might change the residual flow structure and/or the residual momentum balance. NCB has many small creeks that bring in freshwater, but discharges for most of these streams are very small to affect the entire system. As shown in Figure 3-9, during Hurricanes Charley and Frances, the precipitation increased significantly followed by a substantial increase in the river discharge. Although the system received significant amount of freshwater, it did not cause a significant variation in the residual flow structure. On the other hand, the baroclinic pressure gradients increased significantly, particularly inside the Tolomato
River in the along-shore direction and along the deep ICWW inside the inlet in the cross-channel direction (Figure 3-10). Similarly, time series for the baroclinic pressure gradient (Figure 3-8) at a station inside the inlet show two peaks coinciding with the increased precipitation and river discharge (Figure 3-9).

**Vorticity and Evolution of Residual Eddies**

Residual eddies forming around the SAI area shift or vanish during strong wind events. Their evolution is highly dependent on the wind speed, wind direction and the nonlinear advection. Before Hurricane Frances, during a typical tidal cycle, eddies around the region were stable with strong positive vorticity for the eddy to the south and with strong negative vorticity for the eddy to the north of the inlet on the estuary side (Figure 3-12a). 24 hours before H Frances made landfall, the northeasterly winds disrupted the eddies on the ocean side, created southerly along-shore current and forced inflow through the inlet due to Ekman transport (Figure 3-12b). Eddies inside the inlet were intact, but weaker due to the wind stress increasing inside the inlet. Similarly the vorticity strength for both eddies inside the inlet reduced due to a more uniform inflow through the inlet.

During the landfall of H Frances, the winds were easterly and the along-shore current on the ocean side became northerly due to the Ekman transport created by easterly winds and the relaxing wind induced setup in the along-shore direction (Figure 3-12c). Eddies inside the inlet were mostly disrupted when the wind stress overwhelmed the nonlinear advection and the strength of vorticity became very small. However, as a result of strong nonlinear advection and outflow through the inlet, another eddy with strong vorticity was formed at the mouth of the inlet. Almost 24 hours after the landfall of H Frances, the winds became southeasterly and the along-shore northerly current
became much stronger (Figure 3-12d). Eddies inside the inlet were completely vanished, and flow through the inlet became complete outflow. The eddy at the mouth of the inlet was intact, but reduced in size with stronger outflow through inlet.

The wind speed reduced and the winds turned from southeasterly to southerly in 8 hours causing the along-shore currents as well as the flow through the inlet to slow down (Figure 3-12e). However, the wind stress both inside and the ocean side of inlet was strong enough to prevent the reformation of the eddies. The eddy at the mouth of the inlet expanded towards the ocean side with the slowing along-shore currents and the strength of vorticity reduced due to the slower velocities through the inlet. In the following 48 hours, the wind stress reduced significantly and with the nonlinear advection becoming dominant again, the eddies inside the inlet reformed. The eddy at the mouth of the inlet moved towards the ocean side and expanded to form the north eddy on the ocean side. The eddies and vorticity inside the system recovered to their pre-storm conditions 12 days after the initial changes in the system occurred (Figure 3-12f).

**Conclusions**

The impacts of four major hurricanes (Charley, France, Ivan, and Jeanne) in 2004 on the residual circulation and momentum balance inside the subtropical North Coastal Basin and St. Augustine Inlet were investigated using a three dimensional hydrodynamic model, CH3D. The model simulated residual tidal circulation around the inlet show formation of four residual eddies around the barrier islands: two eddies inside the estuary with speeds up to 20 cm/s, and two weaker eddies on the ocean side with speeds up to 10 cm/s. Model results confirm that formation of residual eddies is caused by the nonlinear advection as shown by Tee (1977) and Murty (1980). In addition, the
model results indicate that the cross-sectional residual flow observed by Webb et al. (2007) was part of the two three-dimensional residual eddies formed inside the inlet. However, since the structure of the residual eddies is highly dynamic, the cross-sectional residual flow observed by Webb et al. is both temporally and spatially varying. Although the variations to the spatial structure of the residual circulation during each hurricane showed some differences, the general patterns are similar during all the storms. The approaching hurricanes first disrupted the two eddies on the ocean side and the along-shore flow became unidirectional towards south. During or right before a hurricane’s landfall, the residual flow became complete inflow throughout the mouth of the inlet due to the changing wind direction. After landfall, changing wind direction forced the residual flow at the mouth of the inlet to reverse to a complete outflow, in addition to the completely reversed northerly along-shore flow. The system returned to its pre-storm conditions after the winds and the barotropic pressure gradient relaxed. Variations in residual flow structure lasted up to 12 days during Frances (a large hurricane), but only 1-2 days for Charley (a compact and fast hurricane). This difference in the recovery time of the residual flow is also found in the residual salinity distribution. The model results reveal that the momentum balance during a regular tidal cycle is between barotropic pressure gradient and nonlinear advection. During hurricanes, as a result of strong winds, the wind stress around the region gained strength and was a significant part of the momentum balance. Baroclinic pressure gradient was especially important in the cross-channel direction with considerable increase after the hurricanes.
Figure 3-1. Study area, (a) St. Augustine Inlet; (b) Northern Coastal Basin (NCB); (c) Tracks for four major hurricanes in 2004; (d) CH3D modeling domain on the east coast of Florida
Figure 3-2. Cross-sectional residual circulation obtained in a rotating elongated rectangular basin for moderate friction case ($\delta=0.5$) including the rotational forces obtained with (a) analytical model (adopted from Winant 2008); (b) CH3D simulation; at four equally spaced cross-sections ($x=0, 0.25, 0.5, 0.75$) starting from the mouth of the channel ($x=0$) and going towards the closed end ($x=1$) of the channel. Both models used constant eddy viscosity.
Figure 3-3. Spatial pattern of 34 hour low-pass filtered vertically-averaged residual flow pattern around St. Augustine Inlet region during a regular tidal cycle calculated (a) with the nonlinear advection terms; (b) without the nonlinear advection terms.
Figure 3-4. Spatial pattern of 34-h low-pass filtered vertically-averaged residual flow patterns around St. Augustine Inlet region. (a) Right before Hurricane Frances landfall (09/04/2004 12:00 UTC); (b) When Hurricane Frances moves across Florida (09/06/2004 12:00 UTC)
Figure 3-5. Spatial pattern of 34-h low-pass filtered momentum balance around St. Augustine Inlet region during a regular tidal cycle: (a) The along-channel momentum balance; (b) the cross-channel momentum balance.
Figure 3-6. Spatial pattern of 34-h low-pass filtered along-channel momentum balance around St. Augustine Inlet region (a) Right before Hurricane Frances landfall (09/04/2004 12:00 UTC); (b) When Hurricane Frances moves across Florida (09/06/2004 12:00 UTC)
Figure 3-7. Spatial pattern of 34-h low-pass filtered cross-channel momentum balance around St. Augustine Inlet region. (a) Right before Hurricane Frances landfall (09/04/2004 12:00 UTC); (b) When Hurricane Frances moves across Florida (09/06/2004 12:00 UTC)
Figure 3-8. Non-dimensional time series of 34-h low-pass filtered along-channel (solid line) and cross-channel (dashed line) momentum flux terms at a selected station inside the inlet for approximately two month period between 08/06/2004 and 09/31/2004 covering four major hurricanes in 2004.
Figure 3-9. River discharge (Pellicer Creek) and precipitation (Domenico Circle) around St. Augustine Inlet during the simulation period.
Figure 3-10. Momentum balance occurring after hurricanes with considerable precipitation (a) along-channel; (b) cross-channel
Figure 3-11. Variation of cross-sectional residual flow at the St. Augustine Inlet at three different transects (a) location of transects; (b) transect 1; (c) transect 2; (d) transect 3. Distance for each transect is measured from the south shore of the inlet.
Figure 3-12. Evolution of residual eddies, streamlines and vorticity at different phases of Hurricane Frances (a) during a typical tidal cycle before Hurricane Frances; (b) 24 hours before the landfall; (c) during landfall; (d) 24 after landfall; (e) 32 hours after landfall; (f) 12 days after first variations to the residual flow structure
Table 3-1. Features of four hurricanes affecting the region in 2004. All of the hurricane parameters given in the table represent the conditions when the storm was at its minimum distance to the St. Augustine Inlet.

<table>
<thead>
<tr>
<th></th>
<th>Intensity</th>
<th>Max. Wind Speed (m/s)</th>
<th>Max. Wind Radius (km)</th>
<th>Min. Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charley</td>
<td>Cat 1</td>
<td>9</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>Frances</td>
<td>Cat 2</td>
<td>23</td>
<td>30</td>
<td>325</td>
</tr>
<tr>
<td>Ivan</td>
<td>Tropical Depression</td>
<td>6</td>
<td>60</td>
<td>280</td>
</tr>
<tr>
<td>Jeanne</td>
<td>Cat 3</td>
<td>24</td>
<td>25</td>
<td>325</td>
</tr>
<tr>
<td></td>
<td>Changes to the residual flow</td>
<td>Caused by*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>-----------------------------</td>
<td>-------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Charley and Ivan</strong></td>
<td>1. Ocean side eddies disrupted</td>
<td>1. Wind from northeast</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Frances and Jeanne</strong></td>
<td>1. All eddies disrupted</td>
<td>1. Northeast, southeast winds</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2. Complete inflow</td>
<td>2. Ekman transport due to northeast and east winds</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Complete outflow</td>
<td>3. Ekman transport due to southeast and south winds</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Freshwater input into the system during hurricane was not effective to change the residual flow structure
Table 3-3. Summary of changes to residual momentum balance and their cause

<table>
<thead>
<tr>
<th>Changes to the momentum balance</th>
<th>Caused by</th>
</tr>
</thead>
</table>
| Charley, Ivan, Frances and Jeanne | 1. Increased wind stress and barotropic p.g.  
2. Increased bottom friction* | 1. Increased wind speed  
2. Increased residual flow velocity |
| After hurricanes                | 1. Increased baroclinic pressure gradient* | 1. Increased freshwater input during hurricanes |

* The balance was still between barotropic pressure gradient and nonlinear advection.
CHAPTER 4
EFFECT OF TROPICAL CYCLONES ON RESIDUAL CIRCULATION AND
MOMENTUM BALANCE IN A SUBTROPICAL ESTUARY AND INLET –
OBSERVATION AND SIMULATION³

Abstract

A three-dimensional hydrodynamic model, CH3D and observations are used to investigate the effects of tropical storms Fay and Hanna (2008) on the spatial structure of residual circulation and momentum balance inside a subtropical estuarine system Northern Coastal Basin (NCB) and the St. Augustine Inlet (SAI). Simulated 3-D velocities are successfully verified with the observed velocities inside the SAI. During a typical tidal cycle, residual circulation showed formation of four residual eddies; two strong eddies inside and two weaker eddies outside of the inlet. During Tropical Storms Fay and Hanna, along-shore component of the northeasterly winds disrupted the ocean side eddies first and forced along-shore southeasterly current. Due to relatively weak local wind effects, residual flow at the mouth of the inlet never became complete inflow. However, following TS Fay’s landfall, flow inside the inlet became complete outflow due to relaxing wind and remote wind effect created by the along-shore component of the southeasterly wind. The residual circulation returned to its pre-storm condition in a short time (4 days) due to storm duration. Model results revealed that the cross-sectional residual flow pattern observed at the inlet mouth is highly variable with time and location of the cross-section. Comparison of terms in the horizontal momentum equations showed that the balance is between the barotropic pressure gradient and nonlinear advection. Although the wind stress and bottom friction briefly become significant in the

³ To be submitted as Tutak, B., Y.P. Sheng and V. Paramygin: Effect of Tropical Cyclones on Residual Circulation and Momentum Balance in a Subtropical Estuary and Inlet – Observation and Simulation
balance, barotropic pressure gradient and advection were still and order of magnitude larger. Baroclinic pressure gradient was weak despite the increase in precipitation and river discharge.

**Introduction**

Residual circulation is defined in different ways as either the average of tidal flow over a tidal cycle (Fischer et al. 1979) or net movement of water over a tidal cycle (Cheng and Casulli 1982). Residual circulation can be created due to physical characteristics of the estuary and inlet including bathymetry (Kjerfve 1978), or geometry of the channel (Li et al. 2008). In addition, the residual circulation could be created as a result of different forces like bottom friction (Winant 2008), Coriolis (Valle-Levinson et al. 2003), density gradient (Fischer 1976), nonlinear advection terms (Murty et al. 1980; Pingree and Maddock 1977) and wind forcing (Janzen and Wong 2002). It is important to have a sound understanding of the residual circulation because it affects the long-term dispersal of pollutants, nutrients and larvae, estuarine flushing times or sediment transport (Prandle 1978; Sheng et al. 2008).

Studies on the residual ocean-estuary exchange flow at the mouth of a channel or an inlet have been conducted by many researchers. Li and O’Donnell (1997) studied the effects of laterally varying bathymetry (v-shaped) for shallow estuaries and found that the residual exchange pattern was inflow over the shoals and outflow in the deep channel at the mouth of the rectangular channel. In a similar study, Li and O’Donnell (2005) used a two dimensional analytical model to study the residual circulation and channel length relation. Li and O’Donnell identified the residual exchange pattern in short channels, which are characterized by standing wave, as inflow through the deep
channel and outflow over the shoals, opposite to that in long channels characterized by progressive waves.

Webb et al. (2007), through a field study at St. Augustine Inlet, found supporting evidence of the residual flow theory developed by Li and O'Donnell (2005). The cross-sectional residual flow structure measured by Webb et al. showed inflow through the deep channel and outflow over the shoals inside the St. Augustine Inlet. Moreover, Webb et al. showed through order of magnitude analysis that the force balance inside the inlet is dominated by nonlinear advection and barotropic pressure gradient. Sheng et al. (2008) simulated the flow measured by Webb et al. (2007).

Along estuary (local) and alongshore (remote) wind forcing might create variation in the residual estuarine circulation. Variation in residual circulation might be caused by the local wind stress acting directly over the estuary, or remote wind forcing might create a change in subtidal pressure gradients at the entrance of the estuary (Wong, 1994). Subtidal currents tend to show a more unidirectional flow pattern throughout the water column when remote winds are dominant (Garvine 1985), while a vertically sheared flow structure is observed with local wind effect (Wang 1979).

A significant variation in the residual flow at the mouth of the Chesapeake Bay in response to Hurricane Floyd was shown by Valle-Levinson et al. (2002) utilizing observed data at several stations at the mouth of the bay. The flow structure that was inflow over the shoals and outflow in the deep channel prior to the Hurricane Floyd became a complete outflow throughout the bay entrance due to the effect of wind and freshwater discharge. Smith (2001) studied seasonal-scale variations in transport patterns due to the changes in sea level change and freshwater discharge. Smith found
that a flood dominated tidal inlet might become ebb dominated due to the secondary forcing functions.

Although analytical models can provide significant insight for understanding the residual circulation in idealized estuaries and inlets with simple geometry and bathymetry, they cannot be readily applied to real estuaries and inlets with complex bathymetry and geometry such as the NCB and SAI. Therefore, studies in residual circulation in real estuaries and inlets have been conducted by using two or three dimensional numerical hydrodynamic models. Tee (1977) used a two dimensional vertically-integrated numerical model to understand the behavior of the residual circulation inside the Minas Basin in Bay of Fundy and found residual eddy formation was a result of the nonlinear advective terms. Hench and Luettich (2003) studied the near inlet momentum balance inside Beaufort Inlet (North Carolina) by a two-dimensional vertically-integrated numerical model, and found that the balance during flood phase was between barotropic pressure gradient and advection, and between advection and bottom friction during the ebb phase. Li (2006) examined the residual eddies generated in tidal channels using both an analytical and a three dimensional hydrodynamic model. Li found that for complex bathymetries residual eddies might become more important than the in-out type of residual exchange flows and the structure of these residual eddies does not change with tidal range fluctuations (e.g. spring and neap). Table 4-1 is a summary of the above mentioned studies:

This Study

The main objective of this study is to understand the residual circulation and momentum balance inside the St. Augustine Inlet (SAI) (Figure 4-1b) and the Northern Coastal Basin (NCB) estuarine system (Figure 4-1a) during a typical tidal cycle as well
as to understand changes to the residual circulation and momentum balance during two tropical storms in 2008 (Fay and Hanna) by using a three-dimensional hydrodynamic model CH3D and observed velocities inside the SAI. The simulation period covers two tropical storms – Fay in August and Hanna in September 2008 (Figure 4-1c). The model domain includes the entire NCB to enable a comprehensive understanding of the system-wide hydrodynamic processes. NCB is an estuarine system that extends from Pablo Creek (east of Jacksonville, Florida) at the north to the Ponce de Leon Inlet (south of Daytona Beach, Florida) at the South, and connected all the way from north to south through the Intracoastal Waterway (ICWW) (Figure 4-1a). A comprehensive understanding of the hydrodynamics inside the NCB during extreme events is important because the area is susceptible to drastic changes due to extreme events. For example, in 2004, four major hurricanes that made landfall in Florida affected this region significantly (Tutak and Sheng 2010a; 2010b). Salinity in some regions of NCB reduced to zero and the system returned to its pre-storm conditions almost after two months from the first hurricane (Hurricane Charley). Similarly, in 2008 two tropical storms affected the region, although one of them never made landfall in Florida. Therefore, understanding the spatial and temporal variation of the residual circulation and momentum balance around the SAI and adjacent areas during regular tidal cycle and episodic storm events will help understanding the transport mechanisms within the system. This study aims to answer the following questions and provide a more comprehensive understanding of the phenomenon observed in previous studies:

- What is the spatial distribution of residual circulation around the region?
- Which forces dictate the residual momentum balance around the region?
- How do tropical storms affect the patterns of residual circulation and the momentum balance around the region?
Study Area and Methods

The NCB system is connected to the Atlantic Ocean through 3 inlets: St. Augustine, Matanzas and Ponce de Leon. SAI is the northernmost inlet within the system and it is the widest and deepest inlet of the system compared to the other two inlets. Tidal range changes approximately from 1.2m at the south to 1.5m at the north. All three inlets within the system are tidally dominated inlets and the flow within the NCB system is dominated by the tides mostly through the SAI. The volumetric flow rate through SAI is approximately 5 times larger compared to Matanzas and Ponce de Leon Inlets. The estuary, including the ICWW is very shallow (with a minimum of 0.3 m and an average of 2.7 m) and narrow. The system consists of 13 small rivers, creeks and tributaries that bring freshwater in to the estuarine waters.

For hydrodynamic simulations, the Curvilinear-Grid Hydrodynamics in 3D (CH3D) model (Sheng 1987, 1990; Sheng et al. 2010a) is used. CH3D is a robust hydrodynamic model that can simulate circulation driven by tide, wind, and density gradients. The model is also capable of importing large-scale and hurricane-scale wind fields and handling flooding-and-drying of shorelines for storm surge simulations. In addition, CH3D is chosen for this study because of its ability to (1) accurately resolve the complex shoreline and geometry of NCB with boundary-fitted curvilinear grid; (2) accurately resolve the rapid changes in bathymetry using the terrain-following vertical grid; (3) accurately represent the vertical turbulent mixing with a robust turbulence closure model (Sheng and Villaret 1989). The model has been extensively used and verified for similar Florida estuaries including GTMNERR (Sheng et al. 2008), Indian River Lagoon (Sheng and Kim 2009), Pensacola-Escambia Bay (Sheng et al. 2010b),
and Charlotte Harbor (Kim et al. 2010). Details of the equations and boundary conditions can be found in Sheng et al. (2008) and Sheng et al. (2010a).

The curvilinear boundary-fitted grid used for this study is a very high resolution grid with a minimum grid spacing of 15 m inside the estuary for resolving the narrowest navigation channels. The grid (Figure 4-1d) is composed of a total of 37250 water and 22640 floodable cells. Eight vertical sigma layers are used to handle the bathymetry changes from very shallow inside the estuary to very deep offshore and to capture the three-dimensional velocity structure of the residual circulation. Time step used for the numerical simulations is 10s. Moreover, simulations make use of the flooding-and-drying feature to accurately account for the inundation due to tides or storm surge caused by tropical storms.

Boundary and initial conditions required for simulating the hydrodynamics during extreme events are derived from observed data at stations scattered throughout the system and/or from regional scale numerical model outputs. Tidal boundary condition for CH3D is obtained from ADCIRC tidal database for the East Coast (Mukai et al. 2001) as tidal constituents at the offshore boundary of CH3D. Wind and atmospheric pressure during non-storm time periods are obtained from the Navy Operational Global Atmospheric Prediction System (NOGAPS) model (Barron et al. 2007) output. During storm periods, 3-hourly or 6-hourly snapshots of the storm winds are obtained from the NOAA (National Oceanic and Atmospheric Administration) Hurricane Research Division (HRD) H*Wind 10-m reanalysis winds (Powell et al. 1998), and blended with the background NOGAPS winds (Paramygin, 2009). Since H*Wind snapshots only contain wind information, the atmospheric pressure is obtained using the Holland B (Holland
1980) analytical wind model. To simulate baroclinic circulation, CH3D uses river discharge and precipitation data. Discharge data, available from USGS, is included into the model as boundary condition at the upstream of rivers. Precipitation data is obtained from St. Johns River Water Management District (SJRWMD).

In addition, a bottom mounted Acoustic Doppler Current Profiler (ADCP) was deployed (Figure 4-1b) inside the deep navigation channel (at approximate 15 m) to measure the vertical velocity profile over the entire water column at every 0.5 m at a ping rate of 1.5 s, averaging 400 samples per ensemble. The deployment was from July 18 to September 19, 2008 and velocity observations are used to verify the model results.

**Model Verification with ADCP observations**

Before simulating the residual circulation and momentum balance during TS Fay and TS Hanna, simulated velocities are compared with observed velocities. The simulated vs. measured vertically-averaged velocities, as shown in Figure 4-2, agree very well. The average normalized RMS error for simulated vertically-averaged velocities was less than 8%, while it was approximately 10% for the simulated three-dimensional velocities in both directions of the flow. More detailed model verification for the 2008 tropical storms as well as the 2004 season is given in Tutak and Sheng (2010a).

**Spatial Patterns of Residual Circulation**

**During One Typical Tidal Cycle**

The spatial structure of the residual flow around the SAI region shows multiple eddies forming inside and outside of the inlet during typical tidal conditions (Figure 4-3a). Two eddies formed inside the inlet were stronger (speed ~15-20 cm/s) and more
obvious than the ones formed outside of the inlet (speed ~5-10 cm/s). The two eddies inside the inlet are located towards the north and south of the inlet. The north eddy rotates clockwise enhancing the flow into the Tolomato River, while the south eddy rotates counterclockwise enhancing the flow towards Matanzas River and Salt Run. On the ocean side, the eddies rotate in the opposite direction compared to the eddies inside the inlet. The north eddy rotates counterclockwise, while the south eddy rotates clockwise. The model results confirm the cross-sectional residual flow observed along a transect at the mouth of the inlet by Webb et al. (2007). However, model results also revealed that the cross-sectional residual flow pattern was a part of the three-dimensional residual eddies (Figure 4-3c-d) observed inside the inlet. In fact, the model results show that the cross-sectional residual flow varies significantly with the location of the transect (Figure 4-12). Fischer et al. (1979) speculated that the formations of eddies might depend on the shape and geometry of the channel and the flow separation that occurs around the headlands. Zimmerman (1978), using an analytical model, showed eddy formation was due to the interaction of tidal flow with irregular bathymetry. With numerical experiments Tee (1977) showed that a significant portion of the residual eddy formation was caused by the nonlinear advection. Similarly, our model results for the residual circulation with and without the nonlinear advection for the SAI region showed that the generation of the residual circulation and eddies around the region was caused by the nonlinear advection (Figure 4-3b).

**Changes to the Residual Flow Pattern during Tropical Storm Fay**

During the progression of Tropical Storm (TS) Fay through Florida, the residual flow pattern showed several changes for limited time periods depending on the direction and the speed of the storm winds and how the estuary responded to the overall forces.
The residual flow pattern started showing signs of changes (Figure 4-4a) when TS Fay emerged to the Atlantic Ocean around Melbourne Beach approximately 200 km south of the region. The wind was blowing persistently from northeast with approximately 10 m/s reaching up to 18 m/s during the landfall. During this time the eddies on the ocean side of the inlet completely vanished (Figure 4-4a) due to the along-shore (northerly) component of the wind stress. The residual flow on the ocean side was along-shore towards south with speed up to 20 cm/s. Part of the flow still entered the inlet and moved into the estuary instead of creating an eddy. Analysis showed that along-shore component of the wind stress has a high correlation ($R = -0.75$) with the rate of change of water level ($\Delta \eta / \Delta t$) inside the inlet, which is considered the proxy for the remote wind forcing (Janzen and Wong 2002). This remote wind effect forced a unidirectional Ekman transport into the inlet. The two eddies inside the inlet preserved their shapes and locations and, with the extra flow coming from the ocean side, both eddies strengthened. This condition persisted for approximately 6 hours right until the TS Fay made landfall around Flagler Beach.

After the landfall, the flow inside inlet went through a dramatic change (Figure 4-4b) in the following 36 hours. The eddies inside the inlet lost most of their strength but still existed. However, the flow through the mouth of the inlet became completely out of the estuary. When the wind direction turned from northeasterly to southeasterly, the along-shore component of the wind stress forced a unidirectional Ekman transport out of the inlet acting as a proxy for remote wind forcing. The south eddy gained strength by flow coming through the Matanzas River and reaching into the inlet. In addition to its remote effect, the along-shore component of the wind acted as a highly correlated ($R = $...
proxy to local wind forcing due to the direction of ICWW being parallel to the shoreline. The strong outflow from the inlet helped the eddies outside the inlet to reform, but these eddies were still very weak. The residual circulation pattern inside the inlet returned to its pre-storm conditions approximately 4 days after the residual flow pattern started to change. Effect of cross-shore component of the wind stress in changing the residual circulation was very small, which was confirmed by its poor correlations to all related parameters. The variations in the residual flow structure during TS Fay show similarities to the variations obtained by Tutak and Sheng (2010b) during the four major hurricanes in 2004. However, the recovery time of residual flow to its pre-storm condition was shorter (4 days) during TS Fay, especially against the recovery time (12 days) during H Frances in 2004. In addition, due to the strength and directionality of the wind during TS Fay, a complete inflow condition was never reached.

Changes to the Residual Flow Pattern during Tropical Storm Hanna

Although TS Hanna traveled over the Atlantic Ocean without making landfall, it still affected the region and modified the residual flow pattern around the St. Augustine Inlet. The storm at its closest point was 200km away from the Florida coast. The winds from the storm reached 12 m/s around the inlet and caused the eddies on the ocean side to disrupt and become a southerly along-shore current (Figure 4-5) as it happened during TS Fay, followed by an increase in the strength of the residual eddies inside the inlet. Strengthening of the two inside eddies mainly happened due to the extra flow that came from the ocean side and enhanced the inflow. The local and remote wind forcing was also similar to that observed during TS Fay. The system recovered to its pre-storm condition in approximately 24 hours.
Spatial Patterns of Momentum Balance

During One Typical Tidal Cycle

During a typical tidal cycle, the spatial structure of the momentum balance inside the inlet is determined by two forcing functions. The most dominant forcing function inside the inlet is the barotropic pressure gradient and it is balanced by the nonlinear advection terms (Figure 4-6a-b) in both along-channel (approximately 15° counterclockwise from E-W direction) (Equation 1) and cross-channel (Equation 2) directions. Along with the nonlinear terms, bottom friction is significant especially at the mouth of the inlet and over tidal flats inside the inlet (ebb shoals), where the bathymetry is fairly shallow. Coriolis force is almost non-existent, except inside the inlet on the north shore in the along-channel momentum balance, where the shoreline shows a significant curvature. Although Coriolis and bottom friction seem to be important at specific locations, most of the time, their magnitude is at least an order of magnitude smaller than the barotropic pressure gradient and the nonlinear advection terms. Both the horizontal diffusion and local acceleration are negligible throughout the simulation period and hence are not plotted.

\[
\frac{\partial U}{\partial t} + \left( \frac{\partial (UU/H)}{\partial x} + \frac{\partial (UV/H)}{\partial y} \right) = \frac{\partial}{\partial x} \left( gH \frac{\partial z}{\partial x} \right) + \frac{\partial}{\partial y} \left( gH \frac{\partial z}{\partial y} \right) + gH^2 \frac{\partial p}{\partial x} + \frac{\partial}{\partial y} \left( \frac{\tau_{xy}}{\rho} \right) + \frac{\partial}{\partial x} \left( \frac{\tau_{yx}}{\rho} \right) - A_H \left( \frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} \right) = 0 \quad \text{Eq. (4-1)}
\]

\[
\frac{\partial V}{\partial t} + \left( \frac{\partial (VV/H)}{\partial x} + \frac{\partial (UV/H)}{\partial y} \right) = \frac{\partial}{\partial x} \left( gH \frac{\partial z}{\partial y} \right) + \frac{\partial}{\partial y} \left( gH \frac{\partial z}{\partial y} \right) + gH^2 \frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \frac{\tau_{yx}}{\rho} \right) + \frac{\partial}{\partial y} \left( \frac{\tau_{xy}}{\rho} \right) - A_H \left( \frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} \right) = 0 \quad \text{Eq. (4-2)}
\]

Changes in Momentum Balance during Tropical Storm Fay

With the arrival of TS Fay most noticeable change in momentum balance happened with the significant wind stress caused by strong storm winds (Figure 4-7a-
Figure 4-8a). The along-channel wind stress increased inside the Tolomato River, mouth of Matanzas River, and inside the inlet. The cross-channel wind stress increased significantly inside the entire inlet. Wind at the moment was blowing from northeast with approximately 10 m/s reaching up to 18m/s during landfall. Inside the Tolomato River, along with the wind stress, bottom friction showed a small increase in momentum flux in the along-channel direction. Bottom friction in cross-shore direction responded to the increase in wind stress, creating a negative momentum flux, especially on the ocean side around the shoreline. The momentum flux created by the wind stress and bottom friction was balanced mostly by the barotropic pressure gradient. Right after land fall the wind stress started relaxing. In along-channel direction it was still significant inside the Tolomato River, and in the cross-channel direction, momentum flux changed direction (Figure 4-7b-Figure 4-8b) with the movement of the storm from the east of inlet to the west of inlet, which changed the wind direction from northeast to southeast. The wind stress was balanced by the barotropic pressure gradient with bottom friction losing strength. After the landfall, with increased precipitation and river discharge around the region, the baroclinic pressure gradient started showing small increase inside the Tolomato River and at the mouth of the inlet in both along and cross-shore directions. The system recovered to its pre-storm conditions after almost 4 days. The wind stress completely relaxed along with the balancing barotropic pressure gradient and bottom friction inside the Tolomato River. The only exception to the recovery happened with the baroclinic pressure gradient inside the Tolomato River and inside the inlet. The baroclinic pressure gradient existed mainly due to the heavy precipitation and river discharge during and after the TS Fay (Figure 4-11).
Changes in Momentum Balance during Tropical Storm Hanna

During TS Hanna, the along-channel momentum balance throughout the region did not show significant variability compared to that during a typical tidal cycle. For most of the region, the balance is still between the barotropic pressure gradient and the nonlinear advection terms. For the cross-channel momentum balance, the effect of wind stress and bottom friction created a considerable momentum flux. When the storm was at its closest point to the Florida coast (200 km offshore), wind stress and baroclinic pressure gradient showed very little increase in the along-channel direction (Figure 4-9a). In the cross-shore direction, the response of the system was similar to the one seen during the TS Fay (Figure 4-9b). The momentum flux due to wind stress increased inside and outside of the inlet, while bottom friction increased to balance the wind stress. The recovery of the system after TS Hanna happened very quickly. In less than 24 hours, the system returned to its pre-storm conditions.

Time Variation of Momentum Balance at a Station Inside the Inlet

Snapshots of momentum balance at different times show the variation of the momentum balance over the given area. However, snapshots alone do not show the order of magnitude differences between the different forcing terms. For this purpose, we selected a station inside the inlet and plotted the time series of the complete momentum balance in along-channel and cross-channel directions (Figure 4-10). The location of the station was selected at the location of ADCP observations given in Waterhouse et al. (2010). The momentum flux obtained from the model results was completely at balance at the selected location during the entire simulation period. As in the snapshots, the main balance in both the along-channel and cross-channel directions was between the barotropic pressure gradient and the nonlinear advection terms. In addition, these two
terms were almost an order of magnitude greater than all the other terms. During TS Fay (~day 235), the wind stress and bottom friction at this location showed some increase, but they were still very small compared to the two main forces. Right after TS Fay, baroclinic pressure gradient in the cross-channel direction (directed along ICWW), showed a substantial increase in magnitude and contributed to the balance of two significant forces until the end of TS Hanna. Since the cross-channel direction indicates the changes in the ICWW, the sudden dramatic change in baroclinic pressure gradient can be attributed to the increase in precipitation and river discharge right after TS Fay (Figure 4-11). Coriolis force, which was almost non-existent in the along-channel direction, generated a cross-channel momentum flux that was comparable to the bottom friction during the TS Fay. Horizontal diffusion and local acceleration in both along-channel and cross-channel directions were non-existent. In addition, Waterhouse et al. (2010) calculated the momentum balance for the same location using observed data around the region in a similar time period and also suggested that the balance was between barotropic pressure gradient and nonlinear advection.

Conclusions

The spatial distribution of residual circulation and momentum balance in the subtropical Northern Coastal Basin (NCB) and St. Augustine Inlet (SAI) during two tropical storms in 2008 is calculated using a three-dimensional numerical model. The simulated vertically-integrated velocities agree very well with those obtained by a bottom mounted ADCP inside the SAI. During a typical tidal cycle, the spatial structure of the residual circulation show that four eddies form around the inlet, two strong eddies (speed ~15-20 cm/s) inside the inlet and two relatively weaker eddies (speed ~5-10 cm/s) form outside of the inlet. The two counter-rotating eddies inside the inlet create a
cross-sectional residual flow pattern of outflow at the shallow north section and inflow at the deeper south section at the mouth of inlet consistent with the cross-sectional observation by Webb et al. (2007). However, since the residual eddies inside the inlet show highly spatially variable rotating motion, the cross-sectional residual flow along different transects can be very different. The analysis of the momentum balance inside the inlet and surrounding area showed that the balance was predominantly between the barotropic pressure gradient and nonlinear advection terms. In addition, model results with and without the nonlinear terms showed that the residual circulation was largely due to the nonlinear advection, as discovered by others.

The residual eddies generated on the ocean side during typical tidal cycles were disrupted by the along-shore component of the strong northeasterly winds before landfall and forced to a southerly along-shore current. The residual flow structure after TS Fay became complete outflow for almost a day with the relaxing winds and the Ekman transport created by the along-shore component of the southeasterly wind, which acted as a proxy for remote wind forcing. The total amount of time during which the residual circulation was from the typical tidal residual circulation was approximately 4 days starting from almost a day before TS Fay made its landfall. With the effect of stronger wind, the wind stress gained strength, and balanced by the combination of barotropic pressure gradient and bottom friction. In addition, with the effect of river discharge and considerable precipitation, the baroclinic pressure gradient showed slight increase. Although some of the terms in the momentum balance strengthened, overall balance was not significantly modified from the balance between barotropic pressure gradient and nonlinear advection terms. Both the barotropic pressure gradient and the
nonlinear advection were generally an order of magnitude higher compared to the other terms throughout the simulation period.
Figure 4-1. Study area, (a) Northern Coastal Basin (NCB); (b) St. Augustine Inlet; (c) Tracks for TS Fay and TS Hanna in 2008; (d) CH3D modeling domain on the east coast of Florida
Figure 4-2. Comparison of observed (.) and simulated (solid) vertically-averaged velocity time series during 2008 simulation time period in a) east-west; b) north-south directions.
Figure 4-3. Spatial pattern of 34-h low-pass filtered residual circulation pattern around St. Augustine Inlet region during a regular tidal cycle (a) vertically-averaged with the nonlinear advection terms; (b) vertically-averaged without the nonlinear advection terms; (c) 3-D bottom velocity; (d) 3-D surface velocity.
Figure 4-4. Spatial pattern of 34-h low-pass filtered vertically-averaged residual flow patterns around St. Augustine Inlet region (a) During landfall of TS Fay (08/21/2008 19:00 UTC); (b) After TS Fay landfall (08/22/2008 00:00 UTC)
Figure 4-5. Spatial pattern of 34-h low-pass filtered vertically-averaged residual flow pattern around St. Augustine Inlet region when TS Hanna closest to the Florida Coast (09/05/2008 12:00 UTC)
Figure 4-6. Spatial pattern of 34-h low-pass filtered momentum balance around St. Augustine Inlet region during a regular tidal cycle in (a) The along-channel momentum balance; (b) the cross-channel momentum balance.
Figure 4-7. Spatial pattern of 34-h low-pass filtered along-channel momentum balance around St. Augustine Inlet region (a) During landfall of TS Fay (08/21/2008 19:00 UTC); (b) After TS Fay landfall (08/22/2008 00:00 UTC)
Figure 4-8. Spatial pattern of 34-h low-pass filtered cross-channel momentum balance around St. Augustine Inlet region (a) During landfall of TS Fay (08/21/2008 19:00 UTC); (b) After TS Fay landfall (08/22/2008 00:00 UTC)
Figure 4-9. Spatial pattern of 34-h low-pass filtered momentum balance around St. Augustine Inlet region when TS Hanna closest to the Florida Coast (09/05/2008 12:00 UTC) in a) along-channel; (b) cross-channel directions
Figure 4-10. Non-dimensional time series of 34-h low-pass filtered along-channel (solid line) and cross-channel (dashed line) momentum flux terms at a selected point inside the inlet for a month period between 08/15/2008 and 09/15/2008 covering TS Fay (day 235) and TS Hanna (day 250).
Figure 4-11. Observed river discharge at Pellicer Creek (south of St. Augustine Inlet) and cumulative daily rainfall at Domenico Circle station (12 km south of St. Augustine Inlet)
Figure 4-12. Variation of cross-sectional residual flow at the St. Augustine Inlet at three different transects (a) location of transects; (b) transect 1; (c) transect 2; (d) transect 3. Distance for each transect is measured from the south shore of the inlet.
Table 4-1. Summary of the existing literature

<table>
<thead>
<tr>
<th>Study</th>
<th>Method</th>
<th>Domain</th>
<th>Nonlinear Advection</th>
<th>Bottom Friction</th>
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<td>Quadratic with constant coefficient</td>
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<td>Yes</td>
<td>Manning-Chezy</td>
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<td>Indian River Lagoon</td>
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<td>Yes (perturbation)</td>
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<td>Li (2005)</td>
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<td>Quadratic by Fourier decomposition</td>
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<td>Rectangular channel + Wassaw Sound</td>
<td>Yes (perturbation)</td>
<td>Quadratic by Fourier decomposition</td>
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<td>Observed Data</td>
<td>St. Augustine Inlet</td>
<td>Scaling Analysis</td>
<td>Scaling Analysis</td>
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<td>Observed Data</td>
<td>Chesapeake Bay Mouth</td>
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<td>-</td>
</tr>
<tr>
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<td>Yes (perturbation analysis)</td>
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<td>This Study</td>
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<td>NCB Estuarine System</td>
<td>Yes</td>
<td>Quadratic with variable coefficient</td>
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CHAPTER 5
CONCLUSION

In this study, different aspects of the effects of tropical cyclones on the estuarine hydrodynamics were examined at each of the chapters.

During tropical cyclones in 2004 and 2008, the salinity inside the system was subjected to significant variations. The changes were generally larger and more prominent close to the mouth of the rivers and creeks due to the increased freshwater discharge associated with the tropical cyclones. Two of these local areas inside the Northern Coastal Basin (NCB) were identified as the Pellicer Creek and Halifax River regions. The variation of salinity was investigated using surface area of pre-determined salinity ranges as: a) low salinity (0-10 ppt), b) moderate salinity (10-20 ppt), and c) high salinity (20 ppt and above). The variation of areas with different salinity ranges was very well correlated with the freshwater input either river discharge or precipitation. In addition, the residual flow rate through each of the three inlets (St. Augustine, Matanzas and Ponce de Leon) was highly correlated with the sharp changes in the area of high or low salinity conditions. For example, in 2004 right before Hurricane Frances made landfall, the winds associated with the hurricane were northeasterly/easterly and were pushing the high salinity ocean water into the system through all three inlets. Therefore the area of the high salinity significantly increased. However, when the winds changed direction after the landfall and the wind induced surface setup relaxed along with the increased precipitation and river discharge, the residual flow at the inlets reversed and became complete outflow. This resulted in sharp reduction in the area of high salinity and increase in the low salinity. This shows that strong winds associated with tropical cyclones might enhance or hinder the transport depending on the modified residual...
circulation patterns. In addition, variation of surface and bottom salinities as well as the stratification throughout the entire ICWW was analyzed. The analysis of bottom and surface salinities inside the ICWW showed that the flushing of the system was quite slow with up to 15 days around Halifax River at the south and near Pine Island at the northern section of the system as previously shown by Sheng et al. (2008). The transport of salt was towards south inside the Halifax River and around the inlets. High salinity ocean water was moving towards south after entering the system from both St. Augustine and Matanzas inlets due to a southward residual flow created by the higher mean surface elevation at the north of the system. Similarly, the freshwater that was discharged into the system from the rivers and creeks was moving towards south along the ICWW due to mean surface elevation difference between north and south. Although the system went through many cycles of low and high salinity variations during both 2004 and 2008 simulation periods, the stratification was almost negligible. Only regions with considerable stratification were localized around the mouths of rivers and creeks. The average difference between bottom and surface salinity was generally less than 1 ppt. In addition, during strong winds due to hurricanes or tropical storms, stratification even at the mouth of rivers and creeks almost disappeared due to large vertical mixing by the winds.

In addition to the instantaneous hydrodynamic variations during tropical cyclones in 2004 and 2008, the residual hydrodynamic parameters were calculated inside the NCB and around the St. Augustine Inlet. In order to understand the variation in the residual flow during tropical cyclones, first the tidal residual flow was calculated. Tidal residual flow around the St. Augustine Inlet show formation of four residual eddies. Two
of the four eddies form inside the estuary and they were strong with flow speed up to 15-20 cm/s. The other two form on the ocean side of the inlet and they were relatively weaker with flow magnitude up to 5-10 cm/s. Numerical simulations with and without the use of nonlinear advection terms show that the residual circulation around the SAI is almost negligible (~1-2cm/s) without the nonlinear advection terms. The structure of the residual eddies showed that the cross-sectional residual flow along the inlet is highly variable depending on the location of the cross-section. The cross-sectional residual flow along a transect on the estuary side of the inlet shows inflow through the deep channel and outflow over the shallow sections. However, along a transect on the ocean side of the inlet, the cross-sectional flow shows inflow through the shoals and outflow through the deep channel. Although each tropical storm or hurricane acted differently on the system, the variation of the residual circulation around the St. Augustine Inlet was quite similar during each of the storms. The change in the system started with the northeasterly winds before the landfall of the storm, which disrupted the two residual eddies on the ocean side and created a uniform along-shore southerly flow. In the mean time, inflow through the SAI was forced due to the Ekman transport created by the northeasterly winds and the southerly along-shore currents. The two residual eddies inside the estuary persisted. When the winds started to intensify, the residual eddies inside the estuary started to slow down. After hurricanes or tropical storms made landfall, the winds changed direction to easterly followed by southeasterly. As a result of direction change and increase in wind speed, the flow on the ocean side completely reversed and became uniform northerly flow in the along-shore direction. Similarly, the flow inside the estuary as well as the mouth of the inlet reversed and became complete
outflow due to the Ekman transport, and relaxing of the wind induced surface setup inside the estuary. The flow inside the inlet was quite strong with velocities up to 20 cm/s. The recovery time of the system to its pre-storm conditions was highly dependent on the strength and the duration of the hurricanes. The recovery of the system was around 1-2 days during Hurricane Charley (a fast moving compact hurricane), 4 days for TS Fay (a weak, but slow moving storm) and approximately 12 days for Hurricane Frances (a distant, but strong Category 2 hurricane).

Similar to the residual flow, residual momentum balance was calculated around the St. Augustine Inlet. During a regular tidal cycle the residual momentum balance is dominantly between the barotropic pressure gradient and the nonlinear advection terms. Bottom friction is relatively important at several shallow sections of the inlet. During the tropical cyclones the change in the residual momentum balance was less complicated compared to the residual flow, as the main force contributing or changing the balance was wind stress. When the wind speed increased during storms, the wind stress became important in the residual momentum balance. The increase in the wind stress is generally balanced by an increase in the barotropic pressure gradient, corresponding to a surface setup, and bottom friction, particularly on the ocean side where the residual velocities are stronger. Nonlinear advection during storms lost some strength due to the overwhelming wind stress. An analysis of the evolution of eddies shows that the residual eddies inside the estuary is maintained by nonlinear advection and wind stress. The residual eddies are persistent and strong when the nonlinear advection is dominant. However the intensification of the relatively uniform wind stress during tropical cyclones inside the estuary causes the residual eddies to weaken or disrupt
depending on the strength of the wind stress. Baroclinic pressure gradient becomes significant after several storms due to the increased precipitation and river discharge inside the system especially in 2004, since the river discharge and precipitation were 3 times larger than those in 2008. Baroclinic pressure gradient gains strength generally inside the inlet due to the exchange of freshwater and high salinity ocean water. Other forcing functions in the momentum equations do not contribute significantly to the balance. Coriolis, horizontal diffusion and local acceleration are almost zero.

The major findings for this study can be summarized as:

- 4 residual eddies form around SAI during a typical tidal cycle caused by the nonlinear advection;
- Cross-sectional residual flow is highly variable with location of cross-section and dominant forcings within the St. Augustine Inlet;
- Around St. Augustine Inlet, residual momentum balance during a typical tidal cycle is between barotropic pressure gradient and advection
- During tropical cyclones, uniform wind stress overwhelms the nonlinear advection inside the estuary to disrupt the residual eddies
- The duration of variation in residual flow structure and momentum balance depends on the strength and duration of tropical cyclones and can range from 3-4 days to 12 days.
- During tropical cyclones, wind speed and direction determines spatial structure of residual circulation at the St. Augustine Inlet
- Baroclinic pressure gradient was less prominent in 2008 compared to 2004 simulation period, due to lower precipitation and river discharge
• Stratification inside the estuary is very small and residual flow rate at inlets play major role determining estuarine salinity

• Tidal and residual flow rate at St. Augustine Inlet is 4-5 times larger than other 2 inlets
REFERENCES


Paramygin, V. A., 2009: Towards a real-time 24/7 storm surge, inundation and 3-D baroclinic circulation forecasting system for the state of Florida. Ph.D. dissertation, University of Florida,


BIOGRAPHICAL SKETCH

Bilge Tutak was born in 1980 in Bandirma, Turkey. He received his B.S. degree in Civil Engineering from Bogazici University in 2003 where he continued his M.S. degree until 2005. He studied wave mechanics and meshless methods for numerical models. He started his Ph.D. degree in August 2005 at University of Florida under the supervision of Y. Peter Sheng. He worked on estuarine and ocean modeling. He was a National Estuarine Research Reserve (NERR) Graduate Fellow for 3 years with a funding for his research on the effects of extreme events on estuaries. After obtaining his Ph.D. degree, he wishes to pursue an academic career.