The Circulation of Tampa Bay Driven by Buoyancy, Tides and Winds, as Simulated using a Finite Volume Coastal Ocean Model

by

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Abstract: The circulation of Tampa Bay is investigated using a high-resolution, three-dimensional, density-dependent, finite volume coastal ocean model (FVCOM) that includes Tampa Bay, the intra-coastal waterway and the inner portion of the west Florida continental shelf. Model performance over the three-month interval, September to November, 2001 is assessed against available tide gauge and velocity profiler data before using the model to describe the circulation as driven by rivers, tides and winds. Because of a mean wind velocity vector directed down the estuary axis we ran a parallel model experiment without winds to distinguish the estuarine circulation by gravitational convection from the mean wind effects. With or without winds, Tampa Bay exhibits a robust, two-layered estuarine circulation that concentrates on the deep channels. The mean outflow at the surface tends to converge on the channels where the free surface elevation is locally minimum. The mean inflow near the bottom also concentrates in the channels where the baroclinic pressure gradient force is largest. Geometry thus guides the mean circulation and salinity distributions. At the Tampa Bay mouth mean outflows exist both in the deeper Egmont Channel and the shallower South Pass, whereas a mean inflow is limited to the Egmont Channel. A residence time based on the Egmont Channel influx is estimated to be about 100 days. Consistent with previous studies we conclude that gravitational convection is a major contributor to the water property distributions of Tampa Bay, and that the FVCOM is suitable for estuary/shelf interaction studies.
1. Introduction

Tampa Bay is the largest of the Florida estuaries and, based on tonnage, it is amongst the largest of the United States ports. Located on the west-central coast of Florida, Tampa Bay consists of four sub-regions: Old Tampa Bay, Hillsborough Bay, and middle and lower Tampa Bay (Figure 1). Like most urban waterways it harbors dual usage by commercial shipping and recreational boaters while accommodating the municipal needs of power generation, fresh water consumption, and the sanitation requirements of a growing population. Such multiple uses are not always consistent with the primordial ecology of this otherwise mangrove and sea grass lined habitat for a variety of recreational and commercial fish. Understanding the fluxes into and out of the bay of both land and coastal ocean derived materials (such as water, salt and nutrients) is essential for forecasting the ecological health of the estuary, both in its present state and in any future altered state. This necessitates a full explication of the Tampa Bay estuary circulation as driven by rivers, tides and winds, which is the goal of our paper.

In the context of estuary classification schemes, Tampa Bay, a drowned river valley abutting the Gulf of Mexico (GOM) and its west Florida continental shelf (WFS), is partially to well-mixed. The axis of the bay is oriented at approximately 62°, and from its mouth at Egmont Key to its head at Hillsborough Bay (Old Tampa Bay) the bay length is about 50 km (55 km). The width of the bay at its midsection is about 15 km, and, with the exception of the dredged shipping channels (generally 15m, but as deep as 25 m at the Egmont Key entrance, and of width 150-400 m), the bay is shallow, with an area-weighted depth of about 4 m [Zervas, 1993]. The surface areas of bay and its encompassing watershed are approximately 1030 km² and 4600 km², respectively [Clark and MacAuley, 1989], and the
volume of the bay is about $4 \times 10^9$ m$^3$. The watershed includes the adjacent Pinellas, Hillsborough and Manatee counties, plus parts of Pasco, Sarasota and Polk counties, and this results in an annual average fresh water flow rate of about 63 m$^3$s$^{-1}$, partitioned amongst the Hillsborough (15 m$^3$s$^{-1}$), Alafia (13 m$^3$s$^{-1}$), Little Manatee (6 m$^3$s$^{-1}$) and Manatee (10 m$^3$s$^{-1}$) Rivers, and with the remaining one third coming from smaller streams, springs and direct land drainage [Lewis and Estevez, 1988].

Similar to most navigable estuaries, the Tampa Bay sea level and current variations are controlled primarily by tides. The tides, propagating from the GOM, are of mixed semi-diurnal and diurnal type. An analysis of sea level at St. Petersburg (Figure 2) shows that about 24% of the variance associates with the semi-diurnal species, 42% with the diurnal species and 31% with longer time scales, mostly of non-tidal origin (by weather and steric effects). The remaining 3% is of higher tidal harmonic and seiche origin. A similar analysis for the axial component of velocity measured in the channel beneath the Sunshine Skyway Bridge (also in Figure 2) shows that 62% of the variance associates with the semi-diurnal species, 33% with the diurnal species and 3% with longer time scales, mostly of non-tidal origin. The remaining 2% is of higher tidal harmonic and seiche origin. With this partition so heavily weighted toward tides and with the fresh water flow rates so low, it is no wonder that most previous model studies of Tampa Bay were based on vertically averaged, density-independent formulations. Nevertheless, Tampa Bay is an estuary, and the fresh water must transit from the river mouths to the GOM. With salinity varying en route from small values at the bay head to about 35 at the bay mouth, an axial pressure gradient force exists that drives a non-tidal, gravitational convection mode of circulation, known as estuarine circulation. It is essential that we consider this persistent, albeit slow estuarine circulation
along with the swifter, oscillatory tidal (and wind driven) currents if we are to understand and quantify the material fluxes through Tampa Bay.

Estuarine circulation studies have their modern origin with the Chesapeake Bay works of Pritchard and colleagues [e.g., *Cameron and Pritchard*, 1963]. Based on river inflows and turbulence mixing rates, estuaries transition from salt wedge (fresh water flowing seaward above a relatively quiescent salt layer) to partially mixed (a two-layered mean circulation with fresher water flowing seaward above saltier water flowing landward and with the fluxes in either layer being much larger than the river flow rates themselves) to well-mixed (still a two-layered circulation, but with more sluggish flows). The basic physics of the estuarine circulation, in which steric sea level and baroclinic adjustment with depth (by the axial salinity gradient) cause an axial pressure gradient force that drives the estuarine circulation in balance with the frictional retarding force by the vertical mixing of momentum, is presented by *Officer* [1976]. Another, more complex formalism, plus a classification scheme, is given by *Hansen and Rattray* [1966]. Since these are based on constant mixing coefficients that in nature are quite variable, it is difficult to fully assess estuarine circulation a priori. Measurements and models with flow dependent mixing formulations are required.

Physical oceanographic measurements for resolving the fully three-dimensional estuarine circulation of Tampa Bay remain sparse. Monthly samples of temperature, salinity, and other environmental variables have been ongoing by the Hillsborough County Environmental Protection Commission (HCEPC) since 1974 [e.g. *Squires et al.*, 1995]. These show a minimum 10 psu salinity difference between Hillsborough Bay and Egmont Key, and this, along with the spatial distribution of the salinity that show highest values
within the channel, led these authors to conclude that gravitational convection is an important mode of circulation for Tampa Bay.

Velocity observations were initiated in 1990 by the NOAA Tampa Bay Oceanography Project [e.g., Zervas, 1993], and some of these continue through the present time. The initial results from these measurements made in the channel beneath the Sunshine Skyway Bridge are reported by Weisberg and Williams [1991]. Along with strong tidal currents they found both wind-induced current fluctuations and a well-defined mean flow attributed to gravitational convection. The wind-induced motions are consistent with findings elsewhere on the importance of both local [Weisberg and Sturges, 1976 and Weisberg, 1976] and offshore [Wang and Elliott, 1978 and Wang, 1979] wind forcing, and the mean flows are substantial.

Numerical modeling of the Tampa Bay circulation began with the two-dimensional, vertically-averaged studies of Ross [1973], Ross et al. [1984] and Goodwin [1980, 1987, and 1989]. These initial simulations were based on the assertion that the baroclinic circulation (by gravitational convection) may be neglected since Tampa Bay is well-mixed. Thus while these models achieved reasonable fidelity with sea level observations and to a lesser degree with the tidal currents, they are incapable of addressing material fluxes over time scales longer than tidal since they omit the mean estuarine circulation by gravitational convection, and their renditions of the wind-driven flows are inherently incorrect. The first attempt at a fully three-dimensional and density-dependent model application for Tampa Bay was by Galperin et al. [1991a, b] who applied the Princeton Ocean Model (POM) of Blumberg and Mellor [1987]. They considered forcing by rivers, tides and winds [the latter in Galperin et al., 1991a] and demonstrated that the baroclinicity related to the horizontal salinity gradient
is sufficient to drive a non-tidal circulation by gravitational convection. By comparing barotropic (with the density field decoupled from the model dynamics) and baroclinic runs with the same model these authors demonstrated the fallacious assumption in the previous Tampa Bay model studies that baroclinicity is unimportant. Eulerian averaged gyre circulations of the type reported in either the Ross or Goodwin studies were noted in the barotropic runs, but these changed markedly in the baroclinic runs, where the mean currents were much larger and spatially dependent on the salinity field. Moreover, the salinity field changed markedly between the barotropic and baroclinic runs, demonstrating that it is the gravitational convection that controls the distribution of salinity (and hence the advection of other material properties) in Tampa Bay. Subsequent to these studies the ECOM-3D model, an outgrowth of POM described by Blumberg [1993], was implemented for Tampa Bay and run in both hindcast analysis and nowcast/forecast modes as part of the NOAA-facilitated Tampa Bay Physical Oceanographic Real-Time System (PORTS) [Vincent et al., 2000]. Although this ECOM-3D model implementation provides very good sea level and tidal current results, it has not undergone detailed non-tidal circulation analyses. Its relatively low grid resolution also limits its ability to assess the effects of headlands, causeways and narrow shipping channels on the circulation, and with the model open boundary located at the bay mouth, it is incapable of addressing the exchanges between Tampa Bay and the GOM.

The present paper presents a high resolution, three-dimensional, time-dependent model simulation of the Tampa Bay estuary forced by rivers, tides and winds. By using the Finite Volume Coastal Ocean Model (FVCOM) of Chen et al. [2003] over a domain that includes Tampa Bay and the inner WFS region we set out to build upon the work of Galperin et al. [1991a, b] in providing an expanded explication of the Tampa Bay circulation, how the
bay interacts with the adjacent GOM, and how the water and salt fluxes are distributed at various cross-sections. Section 2 describes the model and its Tampa Bay configuration. Section 3 gives the boundary and initial conditions. A three-month, fall season model simulation comparison with sea level and current data are provided in section 4 and, on the basis of that comparison, the results of the simulation are presented in section 5. Section 6 provides a set of conclusions and recommendations.

2. Model Description and Configuration

Three-dimensional, time- and density-dependent, prognostic numerical circulation models are now routinely applied to continental shelves, coastal oceans [e.g., Mellor and Ezer, 1991 and Chen et al., 1999] and estuaries [e.g., Blumberg and Pritchard, 1997]. Recent applications to the Charlotte Harbor estuary on the west Florida coast are given by Weisberg and Zheng [2003] and Zheng and Weisberg [2004]. With regard to numerical discretization schemes these models can be sorted into three categories: 1) finite-difference models, such as POM [Blumberg and Mellor, 1987], ECOM-3D [Blumberg, 1993] and ROMS [Haidvogel et al., 2000]; 2) finite-element models, such as QUODDY [Lynch and Naimie, 1993] and ADCIRC [Luetttich and Westerink, 2001]; and 3) finite-volume models, such as FVCOM [Chen et al., 2003]. Finite-difference methods have the advantages of simplicity and computational efficiency, whereas the finite-element methods have the advantage of geometrical flexibility by virtue of unstructured triangular meshes that may be accurately fitted to irregular coastlines and bathymetries.

The FVCOM used here was developed and applied to both coastal ocean and estuary environments by Chen et al., [2003]. It employs an unstructured grid in the horizontal while solving the prognostic equations using finite differences. Similar to POM it has a σ-
coordinate in the vertical, incorporates the *Mellor and Yamada* [1982] level-2.5 turbulence closure sub-model, as modified by *Galperin et al.* [1988] for flow-dependent vertical mixing coefficients, and it uses the *Smagorinsky* [1963] formulation for calculating horizontal mixing coefficients. FVCOM also uses a mode-splitting technique to solve the momentum equations with two distinct time steps for computational efficiency, i.e., external and internal mode time steps to accommodate the faster and slower barotropic and baroclinic responses, respectively.

Unlike the differential discrete schemes employed by both finite-difference and finite-element methods, the FVCOM solves the primitive equations using a flux calculation integrated over each model grid control volume. This allows for the conservation of mass, momentum, energy, salt, and heat in the individual control volumes and over the entire model domain. Since these integral equations are computationally linked by using finite-differences over arbitrarily sized, non-overlapping unstructured grids, the FVCOM combines the attributes of the finite-difference and finite-element methods. Instead of a staggered C-grid (with horizontal velocity components on the sides and scalar variables in the center), FVCOM uses a grid arrangement such that all scalar variables are solved at the grid nodes, whereas velocity is solved at the grid centers. The use of a σ-coordinate in the vertical allows for a free surface and irregular bottom topography mapped onto a regular domain.

The model domain and the non-overlapping unstructured triangular grids are shown in Figure 3. The domain encompasses Tampa Bay, Sarasota Bay, the Pinellas County intracoastal waterway and the adjoining rivers entering Tampa Bay. By arching the open boundary between the coast near Pasco and Sarasota Counties in the north and south, respectively, the model domain also includes a portion of the inner shelf out to about 50 km.
from the bay mouth. Figure 4 provides a zoomed view of the model grid focusing on the Tampa Bay and Pinellas County intra-coastal waterway regions. To our knowledge, this is the first three-dimensional, hydrodynamic model of Tampa Bay that can resolve the intra-coastal waterway and the four bridge causeways. The entire model grid consists of 10701 nodes, with 19562 triangular cells in the horizontal and 11 evenly distributed $\sigma$ levels in the vertical. Horizontal resolution varies from 100 m in the intra-coastal waterway to 300 m in the bay, gradually expanding to 10 km near the open boundary. Vertical resolution varies from 0.1 m to 4 m depending on water depth, as given by the 30 m resolution, NOAA/USGS unified bathymetric/topographic data [Hess, 2001] shown in Figure 5. Based on the CFL condition, computational time steps of 6.6667 s and 20 s are used for the external and internal modes, respectively. For the present study the model is initialized on August 24, 2001 and run to November 30, 2001. The period August 24 to August 31, 2001 is the model ramp-up time, and the model analysis interval is from September 1, 2001 to November 30, 2001.

3. Model Forcing Functions and Initial Conditions

Initializing and forcing an estuary model linked to the coastal ocean remains challenging. Here we describe the approach taken for Tampa Bay.

3.1. Elevation boundary condition

Along with steric effects, estuarine sea level fluctuations are in response to tides $[\eta_r(x,t)]$ and weather (by wind and atmosphere pressure) $[\eta_{sw}(t)]$. How to specify these at the open boundary, so that the model can calculate correct values over the computational interior, is a critical issue. In general, there are two methods for providing elevations at the open boundary. The first is by using observed elevation data and the second is by running a
coarse-grid shelf model to estimate the elevation variations at the open boundary of the estuary model. The first method provides the most accurate information, assuming that the data exist. For a large open boundary as applied here this is not the case (previous Tampa Bay models ended at the bay mouth and used elevations observed there, but this precludes analyses of WFS, bay interactions). Although the second method cannot provide open boundary elevation information as accurately as the first method, it is often more practical and of more general use [e.g., Zheng et al., 2003]. We adopt that method here.

For tides we use the WFS tidal model of He and Weisberg [2002] for which a regional POM model was driven by tidal constituents sampled from the global, data assimilative model of Tierney et al [2000]. By using the harmonic constants from the eight primary astronomical tidal constituents (M₂, S₂, N₂, K₂, O₁, K₁, P₁, and Q₁) these authors accounted for more than 95% of the WFS tidal variance and with very good fidelity when quantitatively gauged against available coastal sea level and offshore velocity profiler data. Here we further interpolate the He and Weisberg [2002] harmonic constants onto the open boundary of the Tampa Bay model, and following Foreman [1977] we provide hourly tidal elevation \( \eta_r(x,t) \) at the open boundary nodes for the fall 2001 period modeled.

For winds we must consider both the local set-up by the wind stress acting on the model domain free surface and the effects of the wind stress acting over the larger scale coastal ocean outside the model domain. In the present Tampa Bay model we use an empirical relationship for the larger scale coastal ocean effects derived from a ten-year analysis of NOAA tide gauge and wind data from Clearwater and St. Petersburg, FL and from NBDC Buoy 42036 and Venice, FL [Y. Liu, personal communication, 2005]. Results show that for downwelling-favorable winds, sea level increases when the wind direction
resides within the range of 110º and 230º, with maximum response occurring at 170º, while for upwelling-favorable winds, sea level decreases when the wind direction resides within the range of -30º and 90º, with maximum response occurring at 30º. Given this analysis, the wind-induced subtidal sea level elevation fluctuations at the open boundary are estimated from:

$$\eta_M(t) = \begin{cases} 
\alpha * 8.0 * |\vec{v}_w| * \sin\left(\frac{\theta_w - 110}{120} \cdot \pi\right) & \text{when } 110 \leq \theta_w \leq 230 \\
-\alpha * 8.0 * |\vec{v}_w| * \sin\left(\frac{\theta_w + 30}{120} \cdot \pi\right) & \text{when } -30 \leq \theta_w \leq 90
\end{cases}$$

(1)

where $|\vec{v}_w|$ and $\theta_w$ are wind speed and wind direction, respectively, and $\alpha = 0.0025$ is a parameter determined by sensitivity studies. The resulting elevation $[\eta(x,t)]$ at the open boundary is expressed as:

$$\eta(x,t) = \eta_t(x,t) + \eta_M(t)$$

(2)

3.2 Temperature and salinity boundary conditions

Typical of estuarine studies we hold temperature constant at 20º C based on the assumption that the baroclinic forcing in the Tampa Bay is mainly determined by the salinity gradient rather than by the temperature gradient variations. When the salt flux is directed out of the computational domain, the salinity is calculated from the salt equation by applying a second-order upwind differential scheme, whereas when the salt flux is directed into the computational domain, the salinity is specified to be 35 psu, a typical value for the inner shelf.

3.3. River inflows

Some 70% of the Tampa Bay fresh water inflows are from the Hillsborough, Alafia, Little Manatee and Manatee rivers. The remaining 30% comes from creeks, streams,
marshes, canals, wastewater treatment plants and springs. To accommodate these sources fresh water is distributed amongst 39 grid nodes (Figure 1) and injected into the computational domain as a volume flux boundary condition using the method of Chen et al. [2003]. Daily discharge data at these node positions for the August 24 through November 30, 2001 period are from the Tampa Bay PORTS Program [S. Meyers and M. Luther, personal communication, 2004]. Time series for the combined flows into Old Tampa Bay, Hillsborough Bay and the remainder of Tampa Bay are shown in Figure 6. Our simulation interval is one of low fresh water inflows (~25 m³ s⁻¹) immediately following the period of highest fresh water inflows (~250 m³ s⁻¹). However, given the lengthy flushing time for the bay the simulation is conducted during a time of moderately large horizontal salinity gradient and hence baroclinic pressure gradient.

3.4. Meteorological forcing functions

Spatially uniform wind stress and air pressure are used over the computational domain. Hourly wind speed, direction and air pressure data collected at the Tampa International Airport are applied from August 24 to November 30, 2001, with wind data gaps (September 5 - 17 and November 7 –10) filled using the six-hourly NCEP reanalysis (EDAS) product sampled at the nearest Tampa Bay grid point. The air pressure data are used to adjust the observed sea level for comparison with the model simulated sea level since for this study air pressure is held constant at the September to November mean value.

3.5. Initial conditions

The initial values of elevation and velocity are specified as zero throughout the computational domain. By running a separate, lower resolution WFS FVCOM model for the spring and summer seasons that includes the Tampa Bay and Charlotte Harbor estuaries
(unpublished) we obtained the horizontal salinity distribution for this higher resolution Tampa Bay simulation spun up with the Figure 6 river inflows. We applied this initial salinity distribution as a vertical average on August 24, 2001 and used the first week of the model run for the vertically averaged salinity to readjust along with the sea level and velocity fields under forcing by rivers, tides, and winds. By doing this we found that one-week was a sufficient interval for the Tampa Bay model spin up since the axial salinity gradient was already established from the prior river inflows to the lower resolution WFS FVCOM model.

4. Comparisons between Model Simulations and Observations

The most abundant data set available for comparison with the model simulation is that of sea level. Velocity and salinity data are more limited. Three types of comparisons are shown (each for the purpose of establishing some degree of model validity to justify the model analyses of section 5): hourly times series, low-pass filtered time series, and record length means. For sea level we use data from the tide gauges at St. Petersburg, Port Manatee, Egmont Key, Anna Maria, Clearwater Beach and Mckay Bay. For velocity we are limited to one acoustic Doppler current profiler (ADCP) record sampled within the deep shipping channel beneath the Sunshine Skyway Bridge. The station locations are shown in Figure 1. Salinity data are limited to coarsely sampled monthly composites from near-surface, near-bottom and middle depths. A comparison is made in section 5 between the near-surface and near-bottom salinities observed and simulated.

4.1. Sea level

Time-series comparisons between hourly observed and modeled sea levels are shown in Figure 7, along with the hourly wind velocity vectors used to force the model. Visually
we see agreement in both amplitude and phase at all six stations, and we note that the amplitude agreements are best when the winds are light. The model also reproduces the neap/spring tide cycle. This demonstrates a degree of validity in the use of only eight tidal constituents for Tampa Bay. It is noted that we also tried limiting the simulation to the four primary tidal constituents: $M_2$, $S_2$, $K_1$, and $O_1$, but this resulted in phase errors deemed to be too large (up to 2 hr).

Quantitative comparisons based on regression analyses are given in Table 1. The lowest correlation coefficient (0.85) and the maximum $rms$ error (12.1 cm, or about 9.6% of the tidal range) occur at the Anna Maria station located near the bay mouth. For the St. Petersburg and Port Manatee stations located at mid-bay, the correlation coefficients exceed 0.90 and the $rms$ errors are less than 10.0 cm. The slight increase in $rms$ error at McKay Bay (12.0 cm) is not surprising since the McKay Bay tide gauge is located in a narrow channel connecting Hillsborough Bay and Mckay Bay that is not resolved in this model.

Similar visual and quantitative comparisons are shown in Figure 8 and Table 2, respectively, for low pass filtered times series (using a 36 hr cut-off to distinguish the weather from the tide-induced sea level variations). Included in Figure 8 are the low-pass filtered wind velocity vectors and air pressure. The sub-tidal sea level variations are similar at all stations and visual correlations with the wind velocity vectors and air pressure are clear. For example, for the period October 9-11, the winds are downwelling-favorable and sea level increases by about 35 cm, whereas from October 13-19, the winds are upwelling-favorable and sea level decreases by about the same amount. The effect of air pressure is seen in the October 29-31 period when, despite the wind being upwelling-favorable, sea level actually increases as the air pressure drops. Overall, the means of the correlation coefficients (0.81)
and the \textit{rms} errors (7.5 cm) for these 36-hr low-pass filtered sea level time series demonstrate that the discrepancies between the observed and modeled sea levels are primarily the result of the weather-induced sub-tidal motions, as opposed to the tidal motions. This is as expected since the tides are deterministic and well specified, whereas the winds and atmospheric pressure are stochastic and only approximately specified (by spatially constant values over the entire computational domain).

To further quantify the tidal simulation veracity we compare harmonic analyses for the principal semi-diurnal, \( M_2 \), and diurnal, \( K_1 \), tide constituents of Tampa Bay (Table 3). The agreements between observed and modeled amplitudes and phases at the six stations considered are very good. For \( M_2 \) the amplitudes are generally within 1-2 cm, with the outlier being 3.2 cm, and the phases are generally within 0-4º (0-8 min), with the outlier being 11.5º (24 min). For \( K_1 \) the amplitudes are all within 1 cm and the phases are generally within 2-4º (8-16 min), with the outlier being 7.6º (30 min).

\textbf{4.2. Current velocity}

The two Tampa Bay PORTS Program ADCP stations relevant to our study are located in the deep shipping channel beneath the Sunshine Skyway Bridge and at the turning point to the Port Manatee channel located about 7 km to the northeast of the Sunshine Skyway Bridge. For the simulation period, the ADCP at the Port Manatee channel was out of operation leaving us with one point for comparison, but nevertheless an excellent one since it is located where the salinity gradient and the mean circulation by gravitational convection are well established. Given the depth of the channel there are a total 12 non-contaminated 1 m data bins distributed over the water column from 1 m above the bottom to 4 m below the mean surface.
After rotation for the axial and co-axial components of velocity in both the model and the observations comparisons for these components are shown in Figure 9 at three observational depths: near-surface (defined as the first good bin 4 m below the surface), mid-depth (the middle bin), and near-bottom (1 m above the bottom). Since the model employs a $\sigma$-coordinate in the vertical we sample it at the $\sigma$-layer most closely matching the data sample depth. As with sea level the visual comparison for the hourly velocity component times series are very good. Both the observations and model show that the axial current amplitudes decrease with depth from nearly 100 cms$^{-1}$ near the surface to 70 cms$^{-1}$ near the bottom. Using a vector time series regression for quantifying the agreements we find the vector correlation coefficients, vector orientation differences and vector regression coefficients between the modeled and observed currents at these three depths to be: 0.91, -0.93º and 0.95 at the near-surface; 0.92, 0.99 º and 0.99 at mid-depth, and 0.92, 2.93 º and 0.99 at the near-bottom, respectively.

Although we can only compare modeled and observed currents at one station, such good agreements over all depths coupled with the agreements of sea level over the entire computational domain suggest that our model strategy for Tampa Bay is justifiable, including the manner in which we specify the open boundary values. Further improvements will require higher resolution time and space dependent wind and atmospheric pressure fields and/or the use of data assimilation to correct open boundary value errors. For the purposes here, however, data assimilation is not desirable since our goal is to explicate the circulation over various time and process scales, requiring conservation over the entire record, as contrasted with the incremental adjustments that are made through assimilation.
Low-pass filtering the velocity data the same way as for the sea level reveals the relative magnitude differences between the tidal and sub-tidal currents (Figure 10). The sub-tidal currents are an order of magnitude smaller than the tidal currents, their fluctuations appear to be driven by the winds and there exists a depth dependent record length mean distribution. Repeating the vector regression analyses for these low-pass filtered time series results in vector correlation coefficients, vector orientation differences and vector regression coefficients between the modeled and observed currents at these three depths to be: 0.72, -1.61° and 0.77 at the near surface; 0.86, 4.04° and 0.81 at mid-depth, and 0.92, 6.32° and 0.96 at the near bottom, respectively.

Averaging over the entire three-month record length to filter the synoptic scale weather fluctuations we compare the mean vertical profiles modeled and observed in Figure 11. Three sets of record length mean profiles are given: 1) the observations (between 1 m off the bottom and 4 m from the surface) extrapolated to the surface by using the shear between the last three data points, 2) the modeled profile driven as already explained and 3) the modeled profile driven only by rivers and tides. For comparison here we consider 1) and 2) only; 3) will be discussed in section 5. Near the bottom the observed and modeled profiles nearly overlap one another. Mid-way up the water column they begin to diverge with a maximum offset of about 2 cms⁻¹ near the surface. This near surface discrepancy may be due to the linear extrapolation of the data as there are not actual current observations above 4 m depth. The model shows a classical two-layered estuarine circulation, and with allowance for the extrapolation to the surface the observations parrot this finding. The local maximum inflow is observed and modeled to be about 6 cms⁻¹ at about 12 m depth. The transition from inflow to outflow occurs at about 4-5 m depth. Near the surface the model outflow is also
around 6 cm$^{-1}$, whereas the extrapolated observed outflow is about 4 cm$^{-1}$. The case without wind was run to confirm that this profile is due to gravitational convection as opposed to a mean wind. The record-length mean wind (directed out of the estuary in this simulation) does shift the profile, as expected, but the finding that gravitational convection establishes an estuarine circulation pattern is inescapable. This finding with FVCOM parallels that of Galperin et al. [1991a, b] with POM so the result is insensitive to the model structure. Moreover, the observed profile for this September to November 2001 period parallels that of Weisberg and Williams [1991] for a similar interval in 1990 so regardless of the model the mean velocity profile is a robust finding of the observations.

5. The Circulation of Tampa Bay as Inferred from the Model

Given a degree of model veracity established through observations and model simulation comparisons we now set out to describe the Tampa Bay circulation as inferred from the model. In this section we sequentially consider the simulation of tides; the residual circulation resulting from tides alone; the record-length mean circulations, salinity distributions and sea level shapes resulting from forcing by 1) rivers, tides and winds, and 2) rivers and tides and the fluxes of water and salt at selected sections throughout the bay.

5.1. Tides

The linear least squares harmonic analysis method of Foreman [1977] is used to compute the amplitudes and phases for the eight primary tidal constituents throughout the computational domain for this three-month simulation. Shown in Figure 12 are the amplitude and phase distributions for the two principal constituents, M$_2$ and K$_1$. Over the inner shelf, the semi-diurnal M$_2$ tide propagates from south to north paralleling the coastline,
with amplitude increasing from 15 cm in the south to 24 cm in the north and with a phase lag about 15º (31 min). In contrast with M2 the K1 tide has a spatially uniform distribution for both amplitude and phase over the inner shelf. These results are consistent with He and Weisberg [2002].

As these tide waves propagate into Tampa Bay through Egmont channel and South Pass the amplitudes of the M2 and K1 constituents first decrease by 1 cm and 0.5 cm, respectively, before increasing farther up the estuary in Old Tampa Bay by 10 cm and 2.5 cm, respectively. This initial decrease followed by an increase in amplitude is similar to the findings in Charlotte Harbor [Zheng and Weisberg, 2004]. The initial decrease is due to a combination of channel constriction (the Bernoulli effect) and dissipation within the relatively narrow channels, and the subsequent increase is due to the constructive interference between the incoming and the reflected (at the estuary’s head) tidal waves. The phase variations from the Tampa Bay mouth to the estuary’s head are about 90º (~3.1 hrs) for M2 and about 40º (~2.8 hours) for K1, respectively. These phase lags are slightly longer than those implied for a gravity wave propagating at speed of $\sqrt{gh}$, which, with $h$ being the mean Tampa Bay depth implies 2.3 hrs. This increased propagation time is consistent with frictional losses [Friedrichs and Madsen, 1992].

5.2. Tide-induced residual circulation

The previous vertically-averaged, two-dimensional models of Ross and Goodwin considered tidal residual flows either as pathways for material transports, or as mechanisms for trapping materials at given locations. Galperin et al. [1991a, b] identified the flaw in these arguments, but given the complex topography, the bridge causeways and multiple inlets, it is interesting to consider the distributions of tidal residuals with a high-resolution
model. Shown in Figure 13 is a tidal residual surface current map for the lower part of the bay based on the M$_2$ tide only (no rivers, winds or other tide constituents). The patterns are very complex and replete with eddies. While these Eulerian mean vectors are small relative to the tidal currents themselves, they do map out the topographic influences of the bridge causeways, the deep channels, the inlets and the shoals. Inferences can be made on convergences and divergences that may or may not be associated with sediment erosion/accretion (all of the shoals around Egmont Key and South Pass for instance and the fact that Egmont Key is presently eroding) or biological accumulations. The point here is not to speculate, but rather to highlight the possibility of using high resolution estuary models such as this with full physics, not just M$_2$ tides, for exploring either the sub-regional consequences of complex flow fields or how engineering alterations may modify the flow fields. This figure also highlights the fact that our model simulation includes the entire Pinellas Co. intra-coastal waterway and its communication through the various inlets with the inner shelf that are not reported on herein.

5.3. Record-length mean circulation, salinity distribution, and sea surface shape

We now consider the record length mean distributions, or the non-tidal estuarine circulation, determined either by rivers and tides, or by rivers, tides and winds. The goal is to describe the estuarine circulation by gravitational convection, and to separate out what may be wind effects from the purely gravitational effects in this particular simulation interval, where retrospectively there is a mean wind vector directed down the estuary axis. Thus we consider two independent model runs, one with and one without winds, and we present results for the three-month record-length averages for each of these.
We begin with the shape of the mean sea surface (Figure 14). The left hand panel is the case of forcing by rivers, tides and winds; the middle panel is the case of forcing by rivers and tides only and the right hand panel is the difference, attributable to the winds.

From Figure 8 recall that for this simulation interval there is a record-length mean wind velocity of 3.4 ms$^{-1}$, directed toward 245º, or essentially down the Tampa Bay axis toward the GOM. Retrospectively, we might surmise that this along axis wind could add constructively to the circulation by gravitational convection and hence it is necessary to distinguish between these two effects. Consider the sea surface elevation differences along the bay axis from the head of Hillsborough Bay to the mouth at Egmont Key. With wind the sea surface is lower at the head than at the mouth by about 3 cm; without wind it is higher at the head than at the mouth by about 3 cm, and upon taking the difference we see a very regular linear slope due to the wind of 6 cm. Thus the center panel is the sea surface elevation distribution arising from the baroclinic adjustment of the sea surface to the bay’s salinity distribution. The down bay axis surface pressure gradient is what drives the upper layer estuarine circulation. Note further that the surface pressure gradient force is largest in the middle and lower regions of Tampa Bay and that the sea surface is concave, with the relative minimum located over the deepest water centered on the channel axis. This implies that the non-tidal estuarine circulation should converge on and be strongest along the channel axis.

These inferences are borne out by the near-surface record-length mean currents shown in Figure 15. With wind we see relatively strong currents everywhere and directed more or less in the direction of the wind, even over the shallow inner shelf. Without wind we see a pattern indicative of gravitational convection, with the largest currents flowing along
the channel axes (refer to the Figure 5 topography to better appreciate the complexity of these mean surface currents). The difference plot shows that the largest wind-driven, near-surface currents are on the sides of the estuary where shallow water allows the wind stress to overwhelm the opposing pressure gradient force. So while the mean wind adds to the gravitational convection to increase the outflows of the near-surface currents, the inflows in the deepest waters are primarily those of the gravitational convection.

Comparable findings are seen in the near-bottom mean circulation distributions of Figure 16. Unlike the surface the mean near-bottom flows are directed into and toward the head of the estuary. The mean wind increases these inflows, but mostly away from the channel where the inflows are primarily by gravitational convection. This is a baroclinic consequence of increasing depth since the baroclinic contribution to the pressure gradient force is due to the vertical integral of the horizontal salinity gradient, and this integral is largest in the channel. In combination Figures 15 and 16 help to explain the previous findings in Figure 11. Here we see a shift to the right (more inflow and less outflow in the channel) due to the mean winds being directed down channel. Quantitatively, the wind effect shifts the nodal point of the two-layered circulation to be shallower by about 1 m and it increases the inflow by about 2 cm s\(^{-1}\). The effect of the wind at depth is larger than at the surface for two reasons. The first is kinematical. Since the return flow for the down-estuary wind transport must concentrate over a narrower cross section (the area of deep water is less than the area of shallow water) the speed at depth must be larger than at the surface, similar to the findings for Narragansett Bay by Weisberg [1976]. The second is dynamical. The wind-induced outflow must flow against an adverse pressure gradient by the surface tilt (Figure 14), whereas this same barotropic pressure gradient reinforces the bottom inflow.
These wind effects are consistent with the Great Lakes findings of Csanady [1973] and the Delaware Bay findings of Wong [1994] and Wong and Moses-Hall [1998]. The dynamics argument advanced by these authors is that for uniform surface slope, decreasing depth necessitates decreasing surface to bottom stress differential. In shallow water turbulent mixing by wind stress penetrates to the bottom causing a unidirectional flow and hence minimum stress differential. As depth increases the flow direction can reverse with depth causing an increased stress differential. By assuming that the sectionally-averaged bottom stress is much less than the surface wind stress these authors arrive at analytical solutions under idealized geometries that are consistent with our findings here, namely that in shallow water the wind-induced flows tend to be downwind, whereas in deeper water the flows at depth may be directed upwind.

By altering the non-tidal circulation the mean winds also alter the non-tidal salinity distributions as shown in Figures 17 and 18 for the near-surface and near-bottom levels, respectively. Either with or without wind the near-surface salinity distributions show a preference for the deep channel with salinity isoline maxima being located in the channel consistent with Galperin et al. [1991a, b]. Without wind, the surface intrusion of high salinity water over the deep channel is due to the effect of the up-estuary advection of high salinity water near the bottom by gravitational convection coupled with the turbulent mixing of this water upward by tidal friction. The mean wind in this case enhances both the up-estuary advection (Figure 16) of high salinity water and the vertical mixing, leading to an increase of salinity, which is very clear from the difference map. However, by increasing mixing it also decreases the horizontal salinity gradient. These findings are consistent with those of Zheng and Weisberg [2004] for the Charlotte Harbor estuary using the ECOM-3d
model so again we point out that the results are not model dependent. In the present scenario the mean wind forcing increases the near-surface salinity in Hillsborough Bay by about 2 psu and at the bay mouth by about 0.2 psu. The salt increase inside the bay is at the expense of salt loss on the inner shelf, where just outside the bay we see a salinity decrease of up to 0.6 psu. The near-bottom salinity distributions parallel those of the near-surface except that the channels are much more discernable due to the funneling of the deep ocean waters through the deep channels, consistent with the model and observation findings of Galperin et al. [1991a, b] and Squires et al. [1995], respectively.

Salinity data for comparison with the model simulation are available from the HCEPC hydrographic sampling program. Shown in Figure 19 (for comparison with Figures 17 and 18) are the coarsely sampled near-surface and near-bottom salinity for November 2001. The observed salinity contours closely match those simulated. Given the errors inherent in coarse sampling (due to aliasing by tides, winds and river inflow fluctuations) there is no significant difference between these observed and simulated salinity distributions. The October data (not shown) are very similar to the November data so averaging those together would not make a noticeable difference. We did not do this since each month has data gaps and samples at somewhat different locations.

5.4. Fluxes

In this subsection we investigate the fluxes of water and salt through various Tampa Bay cross sections and demonstrate that the FVCOM conserves mass over long simulation intervals. While tides are responsible for the ebb and flow of materials over a tidal excursion length scale and that under certain conditions tidal rectification can result in large net transports, it is generally recognized that gravitational convection is an important mode of
estuarine material transport. Three cross sections are considered: Middle Tampa Bay, Hillsborough Bay, and the bay mouth (Figure 4). In each case we investigate the mean flux distributions of water and salt by taking the scalar product between the velocity vector (either multiplied by salinity or not) and the unit vector normal to the differential cross section. Along with these cross sections we also look at an along estuary section aligned with the channel axis (Figure 4).

The Middle Tampa Bay (Figure 20) and Hillsborough Bay (Figure 21) cross sectional distributions are similar. The mean volume (velocity) and salt flux distributions show two-layered structures with net seaward atop net landward transports, but with the landward transports showing preference for the deep channels. The shapes of the isolines are informative since the upward bowing of the isolines at the channels reflect the downward bowing of the free surface there, indicative of the baroclinic adjustment of the pressure and density fields.

As in the previous figures of this section we consider the cases with and without mean wind forcing. At the Middle Tampa Bay cross section we resolve two different channels, one emanating from St. Petersburg and the other being the main shipping channel connecting with Hillsborough Bay and Old Tampa Bay. It is only within these channels that a two-layered circulation is seen, demonstrating the importance of high resolution for modeling Tampa Bay. Over the shallower regions outside the channels the flow is directed out of the estuary at all depths. The salinity isolines also show that it is only in the channels that there exists appreciable vertical stratification, as tide and wind mixing is adequate to vertically mix the shallow regions. The richness in structure in the velocity, salinity and salt flux distributions clearly shows that the use of a depth-averaged model for Tampa Bay is
inadequate for assessing material transports. With the wind in this case being directed down the estuary axis both the volume and salt fluxes through these estuary cross sections are elevated over the no wind forcing case, similar to what we discussed earlier. Nevertheless, the patterns are largely unaltered, again providing emphasis to the importance of gravitational convection.

The section across the mouth of Tampa Bay shows the Egmont Channel and South Pass that are separated by Egmont Key (Figure 22). Egmont Channel is the deep shipping lane and South Pass, in comparison, is relatively shallow. For the cases either with or without winds we see that volume and salt fluxes are directed seaward throughout South Pass, whereas Egmont Channel has a two-layered flow. The implication is that Tampa Bay is ventilated by Egmont Channel, on average, not by South Pass. Interestingly the position of maximum inflow is neither at the bottom nor on the right hand side (looking into the bay). This is a consequence of the channel topography, which bends in the vicinity of the mouth and which is also characterized by a deep hole limited in extent to the vicinity of the mouth. High resolution is once again emphasized and future model simulations should increase this even further.

Along the deep channel axis (Figure 23) we see a classical two-layered structure from the Tampa Bay mouth to Hillsborough Bay. The intensity increases downstream as expected since the entrainment increases downstream, and it is also noted that both the flow and the salinity intrusion are increased by the down estuary mean winds.

6. Conclusions
The circulation of Tampa Bay was simulated and diagnosed for the three-month interval, September to November 2001, using the FVCOM of Chen et al. [2003] forced by realistic river, tide and wind data. Despite Tampa Bay being a major metropolitan estuary of significant commercial and recreational value, and housing the first of the NOAA PORTS Programs, there are very few descriptions of the circulation based on either observations or models. Our paper follows up on the observational and modeling studies of Weisberg and Williams [1991] and Galperin et al., [1991a, b], both of which emphasized the estuarine nature of Tampa Bay and the need for fully three-dimensional, density dependent studies of the material (salt, nutrients, etc.) fluxes in order to better understand the bay’s ecology and alterations that might occur from anthropogenic influences. While the PORTS Program has continued to maintain the observations initiated in 1990 and developed a nowcast/forecast model system (to be reactivated; M. Luther, personal communication, 2005), there remained a need for more complete discussions of the circulation, especially the gravitational convection, and for how Tampa Bay communicates with the adjacent GOM. Our goal was to provide these through the use of the high-resolution FVCOM. This is the first time that a finite volume model has been applied to the three-dimensional, density dependent circulation of Tampa Bay – our previous (constant density) FVCOM applications to Tampa Bay were for hurricane storm surge simulation using the model’s flooding and drying capabilities (Weisberg and Zheng, in preparation).

The model domain extends some 50 km into the GOM and it takes advantage of the FVCOM’s unstructured grid to resolve the intra-coastal waterway (not reported on herein), the deep shipping channels and the bridge causeways, all of which impact the circulation. It is initialized by a salinity distribution arrived at from a separate, larger scale, lower resolution
FVCOM simulation of the WFS inclusive of Tampa Bay and Charlotte Harbor, and it is forced by eight primary tidal constituents, spatially uniform local winds and atmospheric pressure (with an empirical wind/sea level relationship also applied at the open boundary) and river inflows at 39 grid nodes. Model simulations were compared with sea levels at six tide gauges and with a velocity profile (by ADCP) from the shipping channel beneath the Sunshine Skyway Bridge to demonstrate the veracity of the model simulation and the legitimacy of the open boundary specifications. While the variances of all quantities are largely tidal, the effects of winds and rivers are important in Tampa Bay. Long under appreciated for Tampa Bay is the non-tidal estuarine circulation by gravitational convection that results in a two-layered structure with surface (bottom) outflow (inflow) of relatively fresher (saltier) water. With the mean wind vector directed down the estuary axis our simulation interval was also one in which the wind effects were additive to the gravitational convection so we performed a parallel analysis with rivers and tides only to separate the two drivers. Subtracting one simulation from the other showed how the gravitational convection and the winds each impact the record length mean sea surface, currents and salinity distributions.

For the gravitational convection the two-layered circulation shows preference for the deep channels, versus the shallow sides. Since the sea surface tends to adjust baroclinically with the density (salinity) field we find a convergence of the surface circulation on the channels where sea surface tends to be concave. Similarly, we find that the inflow is centered on the channels since the baroclinic portion of the along-axis pressure gradient force is largest there. Complex geometry leads to complex flow patterns and net fluxes that are apportioned differently across different cross sections. For instance, at the Tampa Bay
mouth, Egmont Key separates a region of outflow to the south from a region of combined inflow and outflow within the main shipping channel to the north. The position of maximum inflow is also influenced by the channel geometry. At mid-bay where there are two channels, one from St. Petersburg and the other the main shipping channel, a two-layered circulation exists in both of these channels with the flow between them being unidirectional and out of the estuary. Paralleling these flow complexities are the related spatial variations in the salinity field. A comparison between the simulated mean near-surface and near-bottom salinity fields with the November 2001 observations by the HCEPC supports the validity of the simulated salinity fields and the model initialization procedure employed.

Lagrangian pathway analyses (not shown) suggest that particles limited to the surface take very straight-forward routes systematically leading to their egress onto the WFS, whereas particles at depth change their vertical positions and hence encounter varied flow regimes making their journeys much less predictable. This raises interesting questions about fish larvae pathways and the mechanisms of estuary flushing for future study. Simple volume flux estimates of flushing based on the bay volume and the inflow of new GOM water through Egmont Channel (Figure 22) suggest a residence (e-folding) time of about 100 days, which is much shorter than residence times by fresh water inflow alone. However, it must be recognized that residence times can be estimated by many different methods and their determinations remain challenging (e.g., Burwell et al., 2000).

Also challenging is the technique for linking the estuary with the adjacent coastal ocean. Here we used a combination of deterministic and empirical relationships to estimate the sea level on the shelf. A more accurate way to model an estuary is to provide observed boundary values right at the bay mouth, but this precludes investigations on the interactions
between the estuary and the shelf. The approach taken here is an initial, expedient one.

While satisfactory for our purposes here, further improvements may be obtained by formally nesting an estuary model into a shelf model or using data assimilation to correct for open boundary value errors. With the FVCOM shown to be a viable tool for Tampa Bay studies future work will be directed toward such improvements along with increased horizontal resolution to better resolve the channels and other complex topography.

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References


Ross, B. E. (1973), The hydrology and flushing of the bays, estuaries, and nearshore areas of the eastern Gulf of Mexico, In: *A summary of knowledge of the eastern Gulf of Mexico*, St. Petersburg, Florida.


### Table 1: Statistical assessments of model performance for instantaneous sea level

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### Table 2: Statistical assessments of model performance for 36-h low-pass filtered sea level

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Table 3: Comparisons of $M_2$ and $K_1$ tidal harmonic constants

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Fig. 1: The Tampa Bay estuary and the adjacent West Florida Shelf. Filled circles denote the tidal gauge stations; filled square the ADCP station; and filled triangles the river inflow locations. Labels are provided for the various regions discussed in the text.

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Fig. 11: Three-month mean axial velocity component profile comparisons sampled beneath the Sunshine Skyway Bridge. Filled circles denote the observations; filled triangles the rivers, tides, and winds model-simulation; and filled diamonds the rivers and tides model simulation. The open circles extend the observations to the surface by linearly extrapolating the nearest three data points.

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Fig. 22: Same as Figure 20, except for the Tampa Bay mouth cross section (III).
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Fig. 2

I: non-tidal forcing

II: diurnal tides

III: semi-diurnal tides

Variance = 0.062 m²

Variance = 0.223 m² s⁻²
I: Middle Tampa Bay section  
II: Hillsborough Bay mouth  
III: Tampa Bay mouth  
IV: Along deep channel section
Fig. 6
Fig. 7
$u_{mean} = -3.1 \text{ m} \cdot \text{s}^{-1}$ $v_{mean} = -1.5 \text{ m} \cdot \text{s}^{-1}$
Fig. 9
Fig. 10
Fig. 12
Fig. 13
Surface non-tidal current

With wind

Without wind

Difference

20 cm/s
Fig. 16

Near bottom non-tidal current

With wind

Without wind

Difference
Surface non-tidal salinity

With wind

Without wind

Difference

Fig. 17
Near bottom non-tidal salinity

With wind

Without wind

Difference

Fig. 18
Middle Tampa Bay Section

With wind

Without wind

Salt Flux (psu cm/s)

Velocity (cm/s)

Salinity (psu)

With wind

Middle Tampa Bay Section

Without wind

Salinity (psu cm/s)

Velocity (cm/s)

Salinity (psu)

With wind

Middle Tampa Bay Section

Without wind

Salinity (psu cm/s)

Velocity (cm/s)

Salinity (psu)

With wind

Middle Tampa Bay Section

Without wind

Salinity (psu cm/s)

Velocity (cm/s)

Salinity (psu)

With wind

Middle Tampa Bay Section

Without wind

Salinity (psu cm/s)

Velocity (cm/s)

Salinity (psu)

With wind

Middle Tampa Bay Section

Without wind

Salinity (psu cm/s)

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Without wind

Salinity (psu cm/s)

Velocity (cm/s)

Salinity (psu)

With wind

Middle Tampa Bay Section

Without wind

Salinity (psu cm/s)

Velocity (cm/s)

Salinity (psu)

With wind

Middle Tampa Bay Section

Without wind

Salinity (psu cm/s)

Velocity (cm/s)

Salinity (psu)

With wind

Middle Tampa Bay Section

Without wind

Salinity (psu cm/s)

Velocity (cm/s)

Salinity (psu)

With wind

Middle Tampa Bay Section

Without wind

Salinity (psu cm/s)

Velocity (cm/s)

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With wind

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Without wind

Salinity (psu cm/s)

Velocity (cm/s)

Salinity (psu)

With wind

Middle Tampa Bay Section

Without wind

Salinity (psu cm/s)

Velocity (cm/s)

Salinity (psu)

With wind

Middle Tampa Bay Section

Without wind

Salinity (psu cm/s)

Velocity (cm/s)

Salinity (psu)
Fig. 21

Hillsborough Bay Section

With wind

Without Wind

Distance (km)

Depth (m)

Salt Flux (psu cm/s)

Velocity (cm/s)

Salinity (psu)

0.0
15
12
9
6
3
0
-2
-4
-6
-8
8
6
4
2
0
-50
-100
-150
-200
0.0
15
12
9
6
3
0
-2
-4
-6
-8
8
6
4
2
0
-50
-100
-150
-200
0.0
Fig. 22
Fig. 23