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Changes in the Circulation of Tampa Bay Due to Hurricane Frances as Recorded by ADCP Measurements and Reproduced with a Numerical Ocean Model

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ABSTRACT: Hurricane Frances is shown to greatly alter the hydrodynamics within Tampa Bay, Florida, and the exchange of water with the Gulf of Mexico in both observational data and a realistic numerical circulation model of the Tampa Bay estuary. Hurricane Frances hit Tampa Bay on September 5, 2004 with surface winds peaking twice near 22 m s^{-1}. There were three stages to the hydrodynamic effect of Frances on Tampa Bay. The first stage included the approach of Frances up to the first wind peak. The winds were to the south and southeast. During this stage sea level was maintained below mean sea level (MSL) and the residual current (demeaned, detided) was weak. The second stage began as the winds turned to the east and northeast, as the eye passed near the bay, and ended as the second wind peak appeared. During this stage the residual currents were strongly positive (into the bay), raising sea level to 1.2 m above MSL at St. Petersburg. The measured residual circulation peaked at over +0.7 m s^{-1} near the surface. The model shows this velocity peak yielded a maximum volume flux into the bay of +44,227 m^3 s^{-1}, displacing a total volume of 1.5 billion m^3 in just a few hours, about 42% of the bay volume. In the third stage a strong negative flow developed as the wind and sea level relaxed to near normal levels. The ADCP measured a peak outflow of −0.8 m s^{-1} during this time. Model results indicate a maximum flux of −37,575 m^3 s^{-1}, and that it took about 50 h to drain the extra volume driven into the bay by Hurricane Frances.

Introduction

Tampa Bay, centrally located on the west coast of Florida, has a circulation that is three-dimensional and time dependent. Tides, winds, and rivers all have a significant effect on the circulation (Galperin et al. 1992; Weisberg and Zheng 2006b). The bay is approximately 53 km long and has natural channels that follow the main core of the y-shaped estuary with a maximum depth of 27 m north of Egmont Key. The shallower regions of the channels have been dredged to depths of 15 m to facilitate shipping (Zervas 1993). Ocean water from the Gulf of Mexico enters through the mouth located in the southwest portion of Tampa Bay. Freshwater from the north together with saltwater coming from the south produce a horizontal salinity gradient. Estuaries that are vertically homogenous but have strong horizontal salinity gradients have been shown to have baroclinic density-driven flows, which contribute to the mean circulation (Pritchard 1956). Burwell (2001) found that the mean (estuarine) circulation in Tampa Bay appears to be a mix of classical two layer flow over the shipping channels, with denser ocean water flowing in at depth and fresher water flowing out of the bay near the surface and along the relatively shallow sides of the bay.

In September 2004 three hurricanes passed through or near central Florida, each approximately a week apart, bringing high winds and affecting sea level in Tampa Bay (Fig. 1). Changes in the circulation of Tampa Bay resulting from the first hurricane are the focus of this article.

Hurricane Frances made landfall on 5 September near Vero Beach as a category 2 hurricane, causing significant flooding due to its tidal storm surge (Alshiemer 2004; Beven 2004). Hurricane Frances produced two wind peaks in Tampa Bay during its passage (Fig. 1). The first peak was around 20 m s^{-1} to the south-southeast. Between the peaks the winds dipped to 9–10 m s^{-1} as the eye passed nearby. The second wind peak, a few hours after the first, was near 22 m s^{-1} to the northeast (the mean wind speed for July–December 2004 is about 4 m s^{-1}). Rainfall during Hurricane Frances ranged from 5 to 10 cm over southwest Florida, 10 to 15 cm in Manatee and southern Pinellas Counties, 15 to 20 cm in Hillsborough, Hardee, and western Polk Counties, and 20 to 30 cm in Pasco County (SRH 2004). See Sallenger et al. (2006) for more details about Hurricane Frances.

There have been a number of articles examining hurricanes and their effects on different coastal and estuarine systems. Valle-Levinson et al. (2002) studied the response of the lower Chesapeake Bay to Hurricane Floyd and found that approximately

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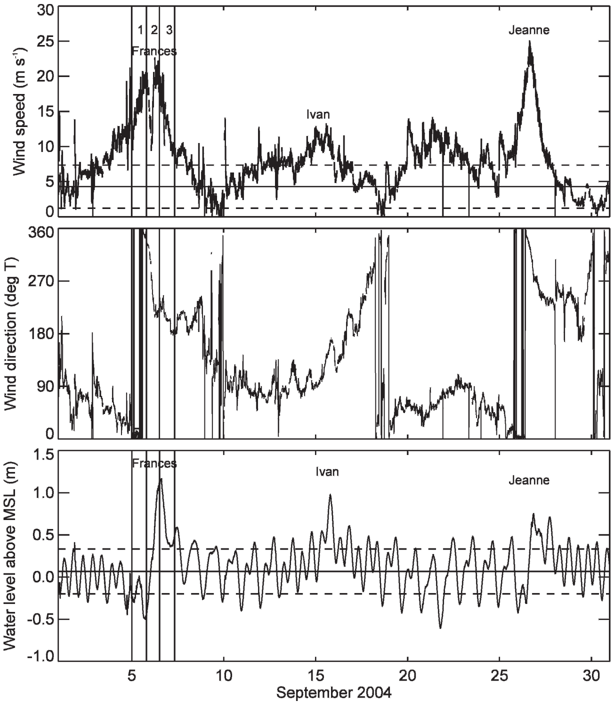

Fig. 1. Measurements taken for September 2004 from NOAA site 8726520 at St. Petersburg, Florida: wind speed for September 2004 (solid), 6-mo model mean of July–December (thin solid), and ± 1σ (dashed), wind direction (degrees True), and hourly water levels relative to mean sea level (solid), 6-mo model mean of July–December 2004 (solid), and ± 1σ (dashed). Vertical lines indicate the three stages of Hurricane Frances described in the text.

one-third of the net outflow was caused by wind forcing and two-thirds by freshwater discharge. Walker (2001) studied the hurricane wind effects on water level, salinity, and sediment transport in the Atchafalaya-Vermilion Bay System in Louisiana. The results demonstrated that remote storm systems can have substantial effects on the physical process that affect the ecological processes in shallow coastal bay systems. Mcleish et al. (1997) recorded currents on the southeast Florida coast as Hurricane Andrew crossed the continental shelf. Forristall (1980) used wind-driven current measurements made during Hurricanes Carmen and Eloise in 1975 and incorporated them into a two-layer model. Comparisons of the model and the storm measurements showed that the model was reasonably accurate. Weisberg and Zheng (2006a) use a finite volume coastal ocean model with flooding and drying capabilities to investigate the storm surge responses for Tampa Bay as well as to simulate Hurricane Charley in the Charlotte Harbor vicinity (Weisberg and Zheng 2005).

The hydrodynamic response of Tampa Bay to the passage of Hurricane Frances is examined in three stages. During the first stage, as Hurricane Frances approached and the wind speed increased to the first peak, water levels fell to about −0.5 m below mean sea level (MSL; Fig. 1). In the second stage the wind speed initially decreased and the water level returned to normal. The wind then increased to the second wind peak and turned to the northeast, further raising the water level to 1.2 m above MSL. In the third stage the winds decreased to normal intensity and the water level decreased to approximately one standard deviation above the mean.

Methods and Results

An Acoustic Doppler Current Profiler (ADCP) located in the shipping channel under the Sunshine Skyway Bridge (27°37′N, 82°39′W), near the mouth of the bay, provides hourly measurements of velocity at several depth fields. This is compared to velocity from a realistic numerical model of the circulation in Tampa Bay (Vincent 2001). Residual circulation is calculated by subtracting the mean and then removing the eight main tidal components for Tampa Bay (M2, K1, O1, S2, P1, N2, Q1, and K2). This is done by doing a least square fit of the sinusoidal function for each period of the tidal components.

The broadband ADCP used in this study is one of three ADCPs that are used in the Physical Oceanographic Real Time System (PORTS). Detailed information on the Tampa Bay PORTS system can be found on the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) website at http://140.90.121.76/tbports/tbports.html. The ADCP (PORTS station t01010) is an RD Instrument with a work horse of 1200 kH. The instrument sits in approximately 17 m of water and has 1-m bins. It has a blanking distance about 44 cm above the 52 cm high instrument, making the first bin about 1 m off the bottom of the bay. The data are telemetered to the University of South Florida every 6 min and are continuously quality controlled by watch standers at the NOAA NOS through dedicated network connections. The axial (along the main axis of the bay) current is calculated by projecting the measured velocity vector onto the local angle (62° from true north). The ADCP was not operational from September 7–24.

The Estuarine and Coastal Ocean Model (ECOM-3D) used in this study was developed by Blumberg and Mellor (1987). It is a version of the Princeton Ocean Model that has been modified and adapted for Tampa Bay applications by Blumberg, Galperin, Vincent, and Burwell (Galperin et al. 1992; Vincent et al. 1997). The model grid consists of 70 by 100 cells in the horizontal and 11 layers in the vertical. The grid is closely aligned to the local axis of the bay, so only the corresponding axial velocity variable is examined. The minimum depth is 1.3 m (MLLW). The internal three-dimensional mode and external two-dimensional mode use a 60-second and 6-second split time step, respectively. This mode splitting separates the external fast surface gravity wave calculation from the internal wave calculation for computational economy (Burwell 2001).

The model has been developed with bay geometry and dynamics. Open boundary conditions are provided by the monthly measured salinity from site 93 (just south of Egmont Key) data collected by the Environmental Protection Commission of Hillsborough County (see Boler 1992 for a discussion). Sea surface elevation was obtained from Egmont Key and Anna Maria Island at the mouth of Tampa Bay from PORTS stations EGK and ANM. The model has a free surface. Winds from the Cut-C Lower Rear Range Marker (CCUT) instrument in the center of the bay (PORTS station m01010) are used uniformly across the model domain. The use of a single wind vector is justified by comparing wind speed and direction from five SEACOOS (Southeast U.S. Atlantic Coastal Ocean Observing System) sites around Tampa Bay. The five sites included Albert Whitted Airport, Clearwater International Airport, Tampa Bay International Airport, MacDill Air Force Base, and Sarasota/Bradenton Airport. The comparisons show that for the month of September the timing and direction of the winds at all sites are alike, even during Hurricane Frances when wind speeds and directions changed drastically over short periods of time. During Hurricane Frances the land based wind speed observations are generally 70% of the CCUT observations and the wind directions have a difference of less than 25° when compared to those from the CCUT tower. Winds from the CCUT site tend to be slightly stronger and at a different direction due to the monitoring site being in the middle of the bay where there are no buildings or other objects to cause obstruction.

Daily precipitation rates from three different sites (Tampa, St. Petersburg, and Sarasota) for 2004 are obtained from the National Weather Service. These are averaged to get a uniform daily precipitation value for the model. Daily stream flows from the U.S. Geological Survey are used to provide river inflow. Daily discharge data from the 4 wastewater treatment plants in Tampa Bay are also included for a total 36 freshwater point sources in the model. Vincent (2001) compared model water levels and salinities to observed data. He found that the model does an excellent job of reproducing water levels all around the bay; the mean absolute error was less than 0.025 m. The mean error for salinity was less than or equal to 0.23 psu, and the model results and data had a positive correlation of about 0.93.

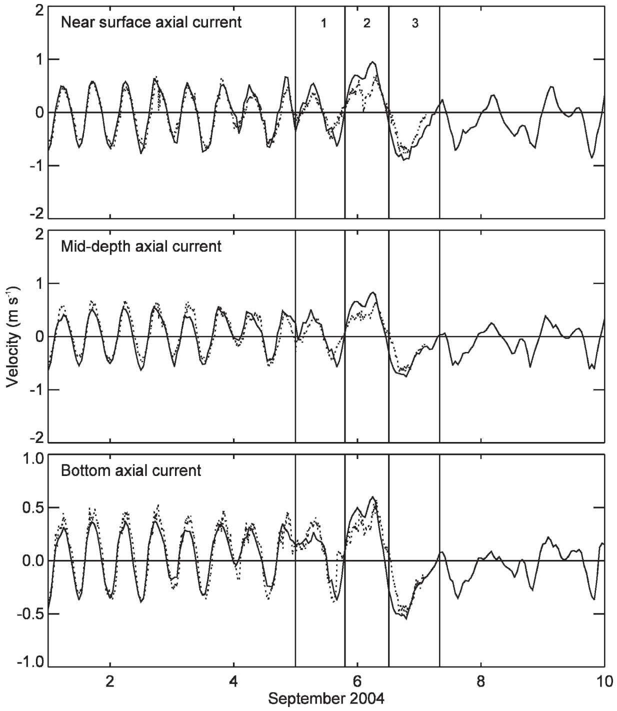

Fig. 2. Instantaneous model (solid line) and ADCP (dotted line) axial current speed in the shipping channel just north of the Sunshine Skyway Bridge. Near surface, mid depth, and near bottom. Vertical lines indicate the three stages of Hurricane Frances described in the text.

The main limitation of the model relevant to the hurricane simulation is the lack of wetting-drying capabilities. During the first stage of Hurricane Frances the strong winds can cause the model elevation to go negative in shallow areas of the bay. To solve this problem the northwest lobe (Old Tampa Bay) of Tampa Bay was given a minimum bathymetric depth of 1.7 m MLLW.

Velocities for the near-surface, mid-depth, and bottom of the bay from the ADCP and model are compared. ADCP bins 2, 8, and 12 are used. Bin 2 is approximately 2 m off the bottom of the bay, bin 8 starts at about 8 m off the bottom, and bin 12 is near the surface approximately 12 m off the bottom. The model depth at the grid cell corresponding to the ADCP site is 10.36 m deep, creating possible mismatches when comparing ADCP data and model results. For the model, levels 5, 6, and 8 were used (at relative depths 0.25, 0.5, and 0.875, respectively). The velocities for the days surrounding Hurricane Frances from the model and ADCP data correspond well to one another (Fig. 2).

During stage 1 the instantaneous surface axial velocity measured by the ADCP shows a prolonged outflow (Fig. 2). During stage 2 instantaneous

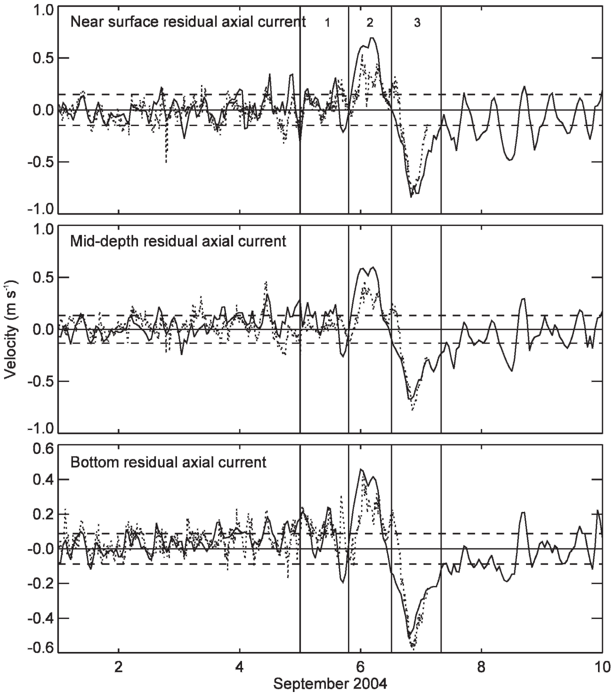

Fig. 3. The same as Fig. 2 except after subtracting the mean and detiding (see text). The 6-mo model mean (thin solid) and ± 1σ (thin dashed). Vertical lines indicate the three stages of Hurricane Frances described in the text.

surface velocity measured by the ADCP reaches a high of about +0.7 m s^{-1}. The winds decrease over the next 24 h to 5–10 m s^{-1} in stage 3, and the surface axial ADCP velocities reverse to a maximum speed near −0.7 m s^{-1} out of the bay. The model shows a similar behavior. The correlation between the model and the ADCP is $r = 0.97$ and the RMS error is 0.12 m s^{-1}. The correlation was calculated from 1 July through 7 September because this time frame had the longest record of continuous ADCP data. In stage 1, the surface residual current is weak in the ADCP and model (Fig. 3), but the model shows significant outflow during the first wind peak. As the wind turns in stage 2, the residual surface current peaks over +0.6 m s^{-1} in the ADCP and +0.7 m s^{-1} in the model. This is rapidly followed by a reversal to −0.8 m s^{-1} in stage 3. Both mid-depth and bottom axial currents show a similar reversal, though the magnitudes decrease with depth.

The mid-depth residual velocity in stages 1 and 2 goes from about −0.2 m s^{-1} and peaks at +0.5 m s^{-1} for the ADCP and +0.6 m s^{-1} for the model as the wind turns to the northeast. During this time the bottom velocity goes from about −0.18 m s^{-1} to a peak of about +0.45 m s^{-1} for both the ADCP and model. In stage 3 the mid-depth velocity reverses and reaches −0.8 m s^{-1} for the ADCP and −0.7 m s^{-1} in the model. The bottom also shows a large reversal to −0.6 m s^{-1} for the ADCP and −0.5 m s^{-1} for the model.

Discussion

Results indicate Hurricane Frances dominants the residual circulation during its passage near Tampa Bay. There were three stages in the variation of the residual current during Hurricane Frances. The first stage began 18 h before the first wind peak as Frances approached Tampa Bay with winds to the south and southeast. During this time sea level was maintained below MSL by the winds. The second stage began as the eye passed nearby and the winds turned to the east and northeast, and the second wind peak occurred. During this stage the residual currents were strongly positive, raising sea level to 1.2 m above MSL at St. Petersburg. In the third stage, after Hurricane Frances left the area, the positive residual flow into the bay was replaced by a strong negative flow within a few hours as the wind and sea level relaxed toward normal levels.

Strong currents in the residual flow associated with Hurricane Frances occurred at all depth levels and were more than three standard deviations above the normal residual current. The model reproduces these observed changes. (There are some differences between ADCP and model velocities, but this might be due to the fact that the ADCP and model depths do not match exactly.) The ADCP measurements during Hurricane Frances are limited to only a single point in space, so the model is used to further examine the changes in the circulation at other locations.

Strong currents during Hurricane Frances occur in the model at the mouth of Tampa Bay and produce significant changes in the volume flux through the mouth of the bay. Integrating the model currents over vertical surfaces in the Egmont and Southwest Passages yields the volume flux through the mouth. The mean volume flux for the second half of 2004 is −2,326 m^3 s^{-1}, indicating a net outflow, most likely due to excess of water from the multiple freshwater sources scattered around the perimeter of the bay. The standard deviation of the mean flux during this time period is 15,036 m^3 s^{-1}, mostly due to tidal currents flowing in and out of the bay. During stage 2 the peak volume flux achieved +44,227 m^3 s^{-1}. In stage 3 the outflow peaked at −37,575 m^3 s^{-1}, but declined rapidly.

The high winds and freshwater input that occur during Hurricane Frances directly affect the circulation of the bay by increasing surface wind stress and freshwater inflow. The changes in circulation produce a significant flushing of Tampa Bay. Integrating the positive volume at the mouth of the bay yields a total volume of 1.5 billion m^3. The model has a total volume of 3.6 billion m^3. Integrating over the next 24 h during the outflow period yields a total volume of -895 million m^3. Progressively integrating as the outflow declines indicates that the additional volume from the large inflow of Hurricane Frances does not fully drain from the bay for 50 h.

A similar result is found with a simple estimate using observed data. From the water level observations at the St. Petersburg gauge, there is a change in water level from -0.51 m at 17:42 Coordinated Universal Time (UTC) on 5 September to a high of 1.17 m at 14:48 on 6 September leading to a water level change of 1.68 m. This value is then multiplied by the surface area of the bay, 1.031×10^9 m^2 (Zervas 1993) and leads to a volume change of 1.73 billion m^3. Dividing the volume change by the mean volume of the bay, 3.81×10^9 m^3 (Zervas 1993), results in an increase of 45% in bay volume. The same calculations can be done to find the decrease in bay volume. Water level reached a minimum of 0.36 m at 2:36 on 7 September, leading to a decrease in bay volume of -836 million m^3 or a 22% decrease. Given the high winds and wave action during this time, it is likely that there was significant mixing of new Gulf of Mexico water entering the bay with water already resident, leading to a significant replacement of bay water and drastically reduced residence time.

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