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Hurricane Storm Surge Simulations for Tampa Bay

ROBERT H. WEISBERG* and LIANYUAN ZHENG

College of Marine Science, University of South Florida, 140 7th Avenue South, St. Petersburg, Florida 33701

ABSTRACT: Using a high resolution, three-dimensional, primitive equation, finite volume coastal ocean model with flooding and drying capabilities, supported by a merged bathymetric-topographic data set and driven by prototypical hurricane winds and atmospheric pressure fields, we investigated the storm surge responses for the Tampa Bay, Florida, vicinity and their sensitivities to point of landfall, direction and speed of approach, and intensity. All of these factors were found to be important. Flooding potential by wind stress and atmospheric pressure induced surge is significant for a category 2 hurricane and catastrophic for a category 4 hurricane. Tide, river, and wave effects are additive, making the potential for flood-induced damage even greater. Since storm surge sets up as a slope to the sea surface, the highest surge tends to occur over the upper reaches of the bay, Old Tampa Bay and Hillsborough Bay in particular. For point of landfall sensitivity, the worst case is when the hurricane center is positioned north of the bay mouth such that the maximum winds associated with the eye wall are at the bay mouth. Northerly (southerly) approaching storms yield larger (smaller) surges since the winds initially set up (set down) water level. As a hybrid between the landfall and direction sensitivity experiments, a storm transiting up the bay axis from southwest to northeast yields the smallest surge, debunking a misconception that this is the worst Tampa Bay flooding case. Hurricanes with slow (fast) translation speeds yield larger (smaller) surges within Tampa Bay due to the time required to redistribute mass.

Introduction

The recent assaults by major hurricanes on the northern Gulf of Mexico, including Ivan, Dennis, Katrina, and Rita in September 2004 and June, July, August, and September 2005, respectively, left no doubt as to the vulnerability the southeastern United States to hurricanes. Among the most damaging aspects of hurricanes are the winds and flooding. Coastal flooding includes the effects of storm surge, freshwater accumulations, and wave breaking and run up. Of these flooding effects, the storm surge is the major culprit. It is also what the wave effects depend on since, without surge, waves do not come in contact with coastal structures any more than normal. So while wave run up adds to the overall storm surge it would not be a major factor without the sea level increase induced by wind stress and atmosphere pressure. Here we examine the potential for such hurricane storm surges in the Tampa Bay, Florida, vicinity.

Tampa Bay, located on the central west Florida coast (Fig. 1), is comprised of Pinellas, Hillsborough, and Manatee Counties, the first two of which are among the most populous counties in Florida. Tampa Bay is also the 4th largest of the U.S. ports, when ranked by tonnage. Its potential vulnerability to storm surge is manifested in its low-lying surroundings. Figure 2 shows the subaerial configurations under uniform rises of sea level by 1.5 and 6 m above mean water. The 1.5 m level is essentially a state of no flooding. The 6 m level shows that much of the Tampa Bay surroundings are inundated. A 6 m storm surge is certainly within the range of possibilities for the Gulf of Mexico as demonstrated by the hurricanes mentioned above. Fortunately, Tampa Bay has not been struck by a major hurricane since 1921. Historical hurricane storm tracks also show that fewer storms recurve into the central west Florida coastline than hit the east coast of the U.S. or points farther west in the Gulf of Mexico. Tampa Bay will inevitably experience another hit, and a better understanding on how surge might evolve is necessary for emergency preparedness.

Hurricane storm surge entails a redistribution of water mass. Wind stress acting on the sea surface, when confronted by a rigid boundary, causes water to accumulate along that boundary such that the pressure gradient force associated with the surface slope, times the water depth, tends to balance the difference between the wind and bottom stresses. This tendency results in a spatially inhomogeneous surge evolution so that the Fig. 2 inundation is not realizable. Since this evolution entails a complex, three-dimensional, time-dependent, nonlinear process dependent on local geometry relative to the hurricane winds, it is necessary to model the surge evolution. The National Oceanic and Atmospheric Administration (NOAA) uses the Sea, Lake and Overland Surges from Hurricanes (SLOSH) model of Jelesnianski et al. (1992) to simulate storm surge for all U.S. coastal regions, and it is the output from

* Corresponding author; tele: 727/553-1568; fax: 727/553-1189; e-mail: Weisberg@marine.usf.edu

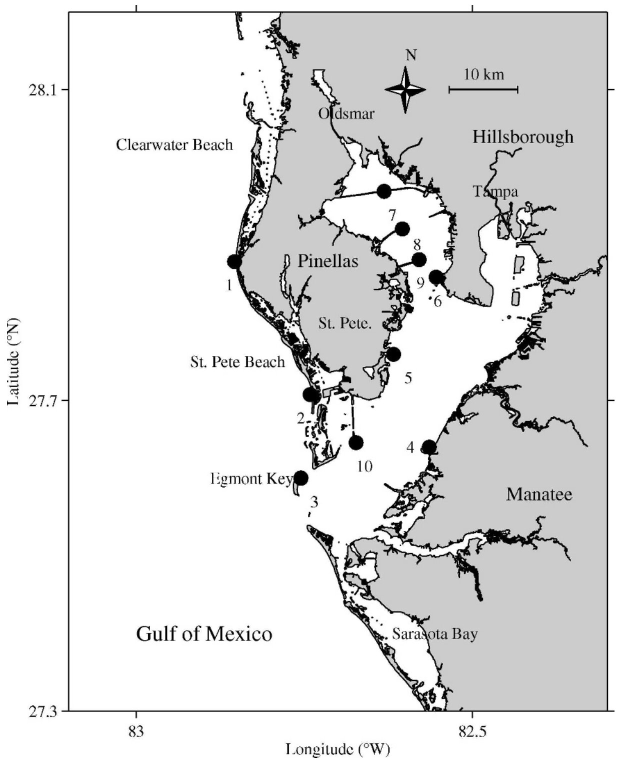

Fig. 1. The Tampa Bay estuary and the adjacent west Florida shelf. Filled circles denote the locations sampled as discussed in the text.

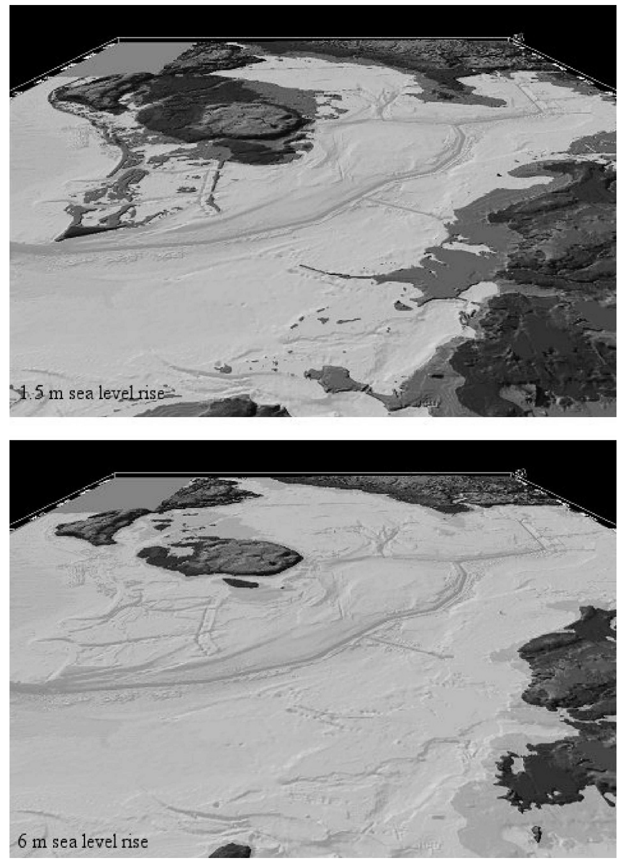

Fig. 2. Subaerial configurations for the Tampa Bay region under uniform rises of sea level by 1.5 m and 6 m above mean water (from the merged NOAA-USGS bathymetric-topographic Tampa Bay demonstration project data set; Hess 2001).

SLOSH that is routinely used by local emergency managers for evacuation guidance. Although SLOSH performs well, its use has drawbacks. The routine dissemination of SLOSH results provides only the worst case of flooding, regardless of landfall location. Such dissemination may be misleading since, depending on landfall location, sea level can be either set up or set down. SLOSH for Tampa Bay has relatively coarse resolution (about 2 km) so it cannot accurately resolve the region's bathymetry and elevations, particularly for the Pinellas County barrier islands, intracoastal waterway, and other subtle, but important, features.

Recent advancements in estuarine and coastal ocean modeling provide new tools for assessing hurricane storm surge potential. Three elements are required. The first is a suitable, high-resolution model, including provisions for flooding and drying. The second is a high-resolution bathymetric and topographic data set, on which to position the model grid. The third is an accurate specification of the surface wind and atmospheric pressure fields required to drive the model. These are described in the next section. The third section provides a baseline simulation for Tampa Bay and explores the sensitivities of the storm surge responses to the point of landfall, the direction and speed of approach, and the storm intensity. The last section summarizes the paper, provides a set of conclusions, and offers recommendations on future hurricane storm surge modeling.

Model Description and Configuration

Storm Surge Model

We use the time-dependent, three-dimensional, primitive equation, finite-volume coastal ocean model (FVCOM) of Chen et al. (2003). It incorporates the Mellor and Yamada (1982) level 2½ turbulence closure submodel modified by Galperin et al. (1988) and the Smagorinsky (1963) formulation to parameterize flow-dependent vertical and horizontal mixing coefficients, respectively. A σ-coordinate transformation is used in the vertical to accommodate irregular bathymetry, and a nonoverlapping unstructured triangular grid is used in the horizontal to accurately fit complex coastlines, headlands, and structures. FVCOM solves the primitive equations by using a flux calculation integrated over each model grid control volume. This ensures mass, momentum, energy, salt, and heat conservation in the individual control volumes and over the entire computational domain. Similar to the Princeton Ocean Model of Blumberg and Mellor (1987), a mode-splitting method with external and internal mode time steps to accommodate the faster and slower barotropic and baroclinic responses, respectively, is used for computational efficiency. FVCOM also includes provision for flooding and drying, a critical element of storm surge simulation (e.g., Hubbert and McInnes 1999). For storm surge simulations we added the Holland (1980) representations for the wind and pressure distributions of a prototypical hurricane.

With Boussinesq and hydrostatic approximations, the primitive equations of momentum and (water) mass conservation are:

$$\frac{\partial(Du)}{\partial t} + \frac{\partial(Du^2)}{\partial x} + \frac{\partial(Duv)}{\partial y} + \frac{\partial(u\omega)}{\partial \sigma} - fDv = -gD\frac{\partial(\eta - \eta_a)}{\partial x} - \frac{gD^2}{\rho_0}\int_\sigma^0 \left[\frac{\partial \rho}{\partial x} - \frac{\sigma}{D}\frac{\partial D}{\partial x}\frac{\partial \rho}{\partial \sigma}\right] d\sigma + \frac{\partial}{\partial \sigma}\left[\frac{K_m}{D}\frac{\partial u}{\partial \sigma}\right] + F_u \quad (1)$$

$$\frac{\partial(Dv)}{\partial t} + \frac{\partial(Duv)}{\partial x} + \frac{\partial(Dv^2)}{\partial y} + \frac{\partial(v\omega)}{\partial \sigma} + fDu = -gD\frac{\partial(\eta - \eta_a)}{\partial y} - \frac{gD^2}{\rho_0}\int_\sigma^0 \left[\frac{\partial \rho}{\partial y} - \frac{\sigma}{D}\frac{\partial D}{\partial y}\frac{\partial \rho}{\partial \sigma}\right] d\sigma + \frac{\partial}{\partial \sigma}\left[\frac{K_m}{D}\frac{\partial v}{\partial \sigma}\right] + F_v \quad (2)$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial(Du)}{\partial x} + \frac{\partial(Dv)}{\partial y} + \frac{\partial \omega}{\partial \sigma} = 0, \quad (3)$$

where u, v, and ω are the x, y, and σ velocity components; f is the Coriolis parameter; g is the gravitational acceleration; K_m is the vertical eddy viscosity; ρ_0 is the reference density; ρ is the perturbation density; $D = H + \eta$ is the total water depth where η and H are the surface elevation and reference depth below the mean sea level, respectively; η_a is the sea level displacement induced by the atmospheric pressure perturbation's inverted barometer effect; and F_u and F_v are the horizontal momentum diffusion terms.

The surface and bottom boundary conditions for momentum are

$$\frac{\rho_0 K_m}{D}\left(\frac{\partial u}{\partial \sigma}, \frac{\partial v}{\partial \sigma}\right) = (\tau_{sx}, \tau_{sy}) \text{ and } \omega = 0 \text{ at } \sigma = 0 \quad (4)$$

$$\frac{\rho_0 K_m}{D}\left(\frac{\partial u}{\partial \sigma}, \frac{\partial v}{\partial \sigma}\right) = (\tau_{bx}, \tau_{by}) \text{ and } \omega = 0 \text{ at } \sigma = -1, \quad (5)$$

where (τ_{sx}, τ_{sy}) and (τ_{bx}, τ_{by}) are wind stress and bottom stress components, respectively. At the open boundary, sea surface elevation is calculated by applying a radiation boundary condition using a gravity wave propagation speed, $\sqrt{gh}$, where h is the water depth. The horizontal velocity components, evaluated at the grid cell centers, are calculated directly from Eqs. 1 and 2 without the vertical and horizontal diffusion terms.

Prototypical Hurricane Model

For the prototypical hurricane storm surge responses investigated here, the radial distributions of wind and atmospheric pressure relative to the storm center and the maximum wind speed are specified following Holland (1980), such that:

$$V_w = \sqrt{\frac{AB(P_n - P_c)\exp(-A/r^B)}{\rho_a r^B} + \frac{r^2 f^2}{4}} - \frac{rf}{2} \quad (6)$$

$$P = P_c + (P_n - P_c)\exp(-A/r^B) \quad (7)$$

$$V_m = \sqrt{(B/\rho e)(P_n - P_c)}, \quad (8)$$

where r is the radial distance from the hurricane center; V_w and P are the wind speed and atmospheric pressure as functions of r; ρ_a is the air density; P_n and P_c are the ambient atmospheric pressure and hurricane central atmospheric pressure, respectively; V_m is the maximum wind speed; e is the natural logarithm base; and A and B are storm scale parameters related by $A = (R_{max})^B$, where R_{max} is the radius of maximum winds.

Wind stress is computed from:

$$\vec{\tau} = C_d \rho_a |\vec{V}_w| \vec{V}_w, \quad (9)$$

where C_d, a drag coefficient dependent on wind speed, is given by Large and Pond (1981):

$$C_d \times 10^3 = \begin{cases} 1.2 & |\vec{V}_w| \geq 11.0 \text{ m s}^{-1} \\ 0.49 + 0.065|\vec{V}_w| & 11.0 \text{ m s}^{-1} \leq |\vec{V}_w| \leq 25.0 \text{ m s}^{-1} \\ 0.49 + 0.065 \times 25 & |\vec{V}_w| \geq 25.0 \text{ m s}^{-1} \end{cases} \quad (10)$$

Model Configuration

While storm surge is manifested locally, continental shelf circulation physics allow for remote effects. Consequently the model domain must be large enough to contain the spatial extent of the storm and the accumulation of surge response due to nonlocal excitation. The domain must also be large enough such that different storm progression scenarios can be explored.

The model domain extends from the Mississippi River delta in the north to the Florida Keys in the south, with an open boundary arching in between. The grid resolution increases from the open boundary toward the west Florida coast, with the highest resolution (of about 100 m) centered on the Pinellas County Intracoastal Waterway and St. Pete Beach (SPB) to resolve the barrier islands. The resolution within Tampa Bay is less than 300 m, whereas the resolution along the open boundary diminishes to about 20 km. For the west Florida coastal region the model domain transitions across the land-sea interface and extends to the 8 m elevation contour. This transition allows us to include a flooding-drying algorithm in the model, a detailed discussion of which is given by Chen et al. (2004). Here we use a flooding threshold depth of 10 cm.

A total of 88,400 triangular cells with 44,713 nodes comprise the horizontal, and 11 uniformly distributed σ-coordinate layers comprise the vertical. The model grid is superimposed on a joint NOAA–U.S. Geological Survey (USGS) bathymetric-topographic data set that in the Tampa Bay vicinity has a 30 m resolution (Hess 2001). Since most of the populated regions have seawalls and these seawalls are at a nominal height of 1.2 m above mean sea level, we set the minimum land elevation as 1.2 m, which means that a minimum 1.3 m surge (the sum of the seawall height and threshold value) is required to cause flooding in this model.

Based on Courant-Friedrichs-Levy numerical stability condition, the computational time steps of 1 and 10 s are used for the external and internal modes, respectively. Temperature and salinity are specified to be constant at 20°C and 35 psu, respectively. Sea level elevation (storm surge) in this model is controlled by wind stress and atmospheric pressure. The effects of tides, rivers, steric (density change) effects, and wave run up are not modeled. These all occur in nature, and they would be additive to what we present on the basis of winds and atmospheric pressure.

According to Eqs. 6, 7, and 8, Fig. 3 shows the distributions of air pressure and wind speed as a function of radial distance from the hurricane center for category 2 and 4 hurricanes (with center pressure $P_c = 961$ mb for category 2 and $P_c = 935$ mb for category 4). Based on these distributions, Fig. 3 also shows the spatial structure, relative to the computational domain, for the surface winds of such a prototypical category 2 hurricane, when the hurricane center is located near the shelf break. This demonstrates the need for a large enough computational domain in order to translate a prototypical hurricane from the deep ocean to the coast.

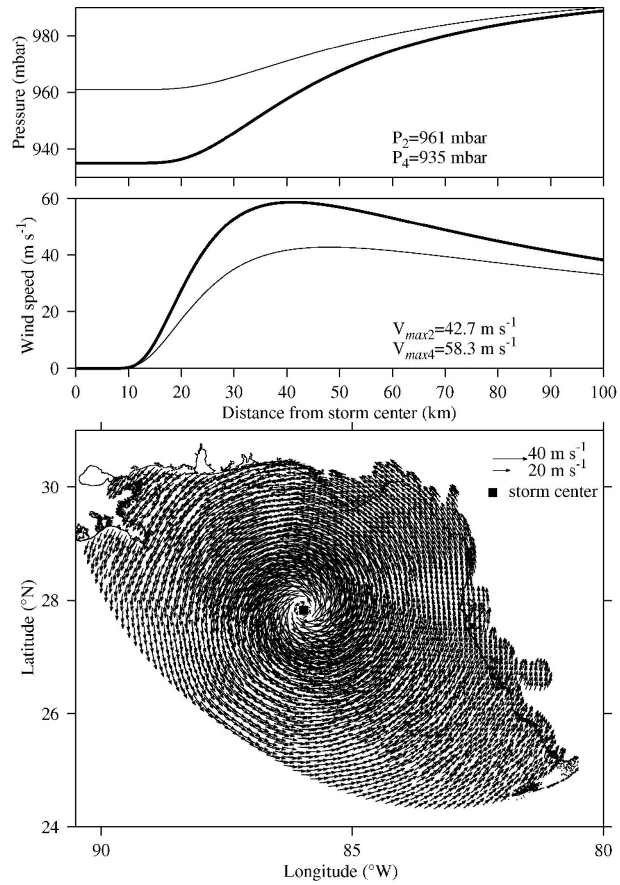

Fig. 3. Profiles of atmospheric pressure and wind speed as functions of radial distance from the storm center for a prototypical category 2 (thin) and category 4 (thick) hurricane, followed by the spatial structure of the winds for such (Holland 1980) prototypical category 2 hurricane positioned within the model grid. P and V_{max} represent the central pressures and maximum wind speeds, and subscript 2 and 4 are for category 2 and 4 hurricanes, respectively.

To establish the utility of our approach (FVCOM with flooding and drying driven by prototypical hurricane wind and pressure distributions) we refer to the realistic Hurricane Charley storm surge simulation for the Charlotte Harbor, Florida, region gauged against observed data by Weisberg and Zheng (2006a). As a further demonstration on the use of FVCOM for the Tampa Bay circulation in response to buoyancy, tides, and winds under more normal, everyday conditions, also quantitatively

TABLE 1. Summary of 11 proposed hurricane experiment scenarios.

Track	Intensity	Landfall Location	Approaching Direction	Moving Speed (m s^{-1})
E_1	Category 2	Indian Rocks Beach	From west to east	5
E_2	Category 2	Sarasota	From west to east	5
E_3	Category 2	Bay mouth	From west to east	5
E_4	Category 2	Tarpon Springs	From west to east	5
D_2	Category 2	Bay mouth	From southwest to northeast	5
D_3	Category 2	Tarpon Springs	From southwest to northeast	5
D_4	Category 2	Parallel coastline	From northwest to southeast	5
D_5	Category 2	Parallel coastline	From southeast to northwest	5
S_2	Category 2	Indian Rocks Beach	From west to east	10
S_3	Category 2	Indian Rocks Beach	From west to east	2.5
I_2	Category 4	Indian Rocks Beach	From west to east	5

gauged against observations, we refer to Weisberg and Zheng (2006b).

Storm Surge Simulations for Tampa Bay

Hurricane storm surge is sensitive to intensity (Saffir-Simpson scale category), point of landfall, direction of approach, and speed of approach, as well as to the hurricane's dimension (eye radius, or radius to maximum winds). To investigate these sensitivities we ran different scenarios in which these factors were varied.

Scenarios

Eleven hurricane scenarios are considered (Table 1). Figure 4 shows seven different storm tracks. Four of these, E_1, E_2, E_3, and E_4, are for storms approaching from west to east, making landfall at locations bracketing the Tampa Bay mouth. Three of these, D_2, D_4, and D_5, are for storms approaching from different directions, and D_3 is parallel to D_2.

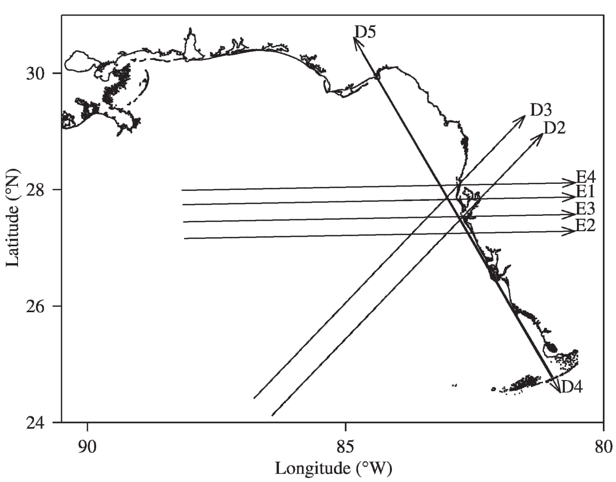

Fig. 4. The eight different storm tracks considered. E_1, E_2, E_3, and E_4 are for eastward moving hurricanes making landfall at Indian Rocks Beach, Sarasota, Tampa Bay mouth, and Tarpon Springs, respectively. Tracks D_2, D_3, D_4, and D_5 are for hurricanes paralleling the axis of the bay or paralleling the coastline from the northwest or the southeast, respectively.

For E_1, E_2, E_3, and E_4 we consider category 2 hurricanes translating at 5 m s^{-1}, making landfall at Indian Rocks Beach (IRB), Sarasota, Tampa Bay mouth, and Tarpon Springs, respectively. For D_2, D_3, D_4, and D_5 we consider category 2 hurricanes translating at 5 m s^{-1}, either traveling parallel to the axis of the bay from the southwest (D_2 and D_3) or parallel to the coastline from the northwest (D_4) or southeast (D_5). Table 1 also identifies S_2 and S_3, which are the same as E_1, but with different translation speeds of 10 and 2.5 m s^{-1}, respectively. Table 1 identifies I_2, which is the same as E_1, but for a category 4 hurricane.

For categories 2 and 4, we use nominal center pressures of 961 and 935 mb, respectively, and maximum wind speeds and eye radii (Fig. 3) of 42.7 m s^{-1} and 48 km for category 2 and 58.3 m s^{-1} and 41.1 km for category 4. For these scenarios, once set, the storm specifications are held constant. To apply these as model boundary conditions we update the wind and pressure fields with each time step.

Results

Sensitivity to Landfall Location

The baseline run to which all other simulations are compared is E_1, a category 2 hurricane, approaching from the west at 5 m s^{-1}, making landfall at IRB and proceeding east across the bay until it exits the computational domain. Planar view elevation snapshots taken at different times in the simulation are given in Fig. 5. These frames show the elevations at hours 24, 28, 29, 30, 32, and 36 from the initiation of the simulation, and show the surge in relation to the storm location as it approaches and passes over the bay. The asterisk is the IRB landfall site and the closed circles denote the storm center. As the hurricane moves eastward from its initial location (about 520 km west of IRB) we initially see a small sea level rise at the storm center due to the inverted barometer effect. By hour 24, when the storm center is located about 90 km west of IRB, the surge in the vicinity of

Tampa Bay is more than 1 m, since a southerly, alongshore-directed, downwelling-favorable wind stress begins to affect the coast, with its associated onshore Ekman transport. By hour 28, one hour before the storm makes landfall, the winds shift to onshore (offshore) south (north) of the hurricane center, and the direct effect of these winds piles water up (sets water down) against a windward (leeward) shoreline. Sea levels south of hurricane center, including those of Tampa Bay, SPB, and Sarasota Bay, continue to rise as the sea surface slopes up with the tendency for the pressure gradients by the surface slope to balance the stress of the wind on the sea surface. Maximum elevations of 3.5 m occur over large areas on the eastern side and the upstream ends of Old Tampa Bay and Hillsborough Bay, leading to flooding there. Regions north of the storm center, such as Clearwater Beach, experience a sea level set down of up to 1 m (Fig. 5) due to offshore-directed winds.

Sampling the model at the Courtney Campbell Causeway (CCC), the Howard Frankland Bridge (HFB), and the Gandy Bridge (GB) shows inundation there. Similarly parts of SPB are flooded. By hour 30, one hour after the storm makes landfall, the center is located on the Pinellas County peninsula west of Old Tampa Bay, but east of the coast. The winds within the bay continue to pile water up, with surge heights as high as 4 m at the upper reaches of Hillsborough Bay. The winds over the entire coastal ocean are now northerly and upwelling-favorable, with offshore Ekman transport causing a pronounced sea level set down along the coast, which dries the barrier island beaches.

As the storm continues eastward and eventually passes Tampa Bay the winds over the bay reverse direction. By hour 32 we see a rapid sea level set down inside the bay (by as much as 2.5 m) over those regions that had been flooded. With the winds now directed toward the east side of the bay, the region of flooding shifts to Manatee County. By hour 36, when the storm center is about 130 km east of the landfall location, the winds over the bay are much weaker and sea levels are returning to normal. In particular, the three bridge causeways, which had previously been flooded, reappear.

Time series of the model-simulated sea level sampled at IRB, SPB, Egmont Key (EK), Port Manatee, St. Petersburg (SP), Port of Tampa, CCC, HFB, GB, and the Sunshine Skyway Bridge (SSB) are shown in Fig. 6, the locations for which are shown in Fig. 1. At the gulf coast locations (IRB, SPB, and EK) the sea levels begin to rise around hour 15. The subsequent storm-induced variation proceeds rapidly with the movement of the storm itself such that by hours 29.5, 31, and 38 sea level displacements become negative at IRB, SPB, and EK, respectively. In between this 14.5 to 23 h interval the maximum surge amplitudes are about 0.7, 1.9, and 1.2 m at IRB, SPB, and EK, respectively. The smallest surge occurs at IRB since the wind speed is weakest there when the hurricane makes landfall. Despite the wind speed at EK being larger than at SPB, the surge at SPB exceeds that at EK because of the geometry. SPB is along a continuous barrier island, while EK is at the bay mouth so water must accumulate at the former, whereas it can flow past the latter. Surge is a very localized phenomenon on the basis of the storm attributes relative to the regional geometry, a finding that will be a repeated theme of these simulations.

The evolution of sea levels inside the estuary exhibit similar behavior, with sea levels rising after hour 15, reaching maxima around hour 30 (one hour after IRB landfall), and becoming negative by around hour 38. Storm surge generally increases from the bay mouth to the upper reaches of the bay, with maximum values exceeding 3.2 m at CCC (Fig. 6) and beyond, versus about 1.5 m at the SSB. Rather than a wall of water, as often described by news reporters, storm surge entails the tendency for the pressure gradient force by the sea surface slope to balance the stress of the wind on the sea surface. The faster the storm moves the quicker the surge evolves, but since a finite amount of time is required to transport water in order to build the slope, faster moving storms can result in smaller surges. Given that storm surge equates with surface slope the farther upslope the location the larger the surge; the upper reaches of the bay show larger surge heights than either the barrier islands or the bay mouth. It is also noted that the largest rate of rise of sea level (south of the storm) coincides with the strongest winds at the time of landfall.

We next consider the results from E_2, for which all specifications are the same as for E_1, except the hurricane makes landfall at Sarasota to the south of Tampa Bay. We again refer to Fig. 6 for time series representations of the model-simulated sea levels sampled at selected locations on the barrier beaches, within the bay, and at the bridge causeways. The surge magnitudes for the Tampa Bay

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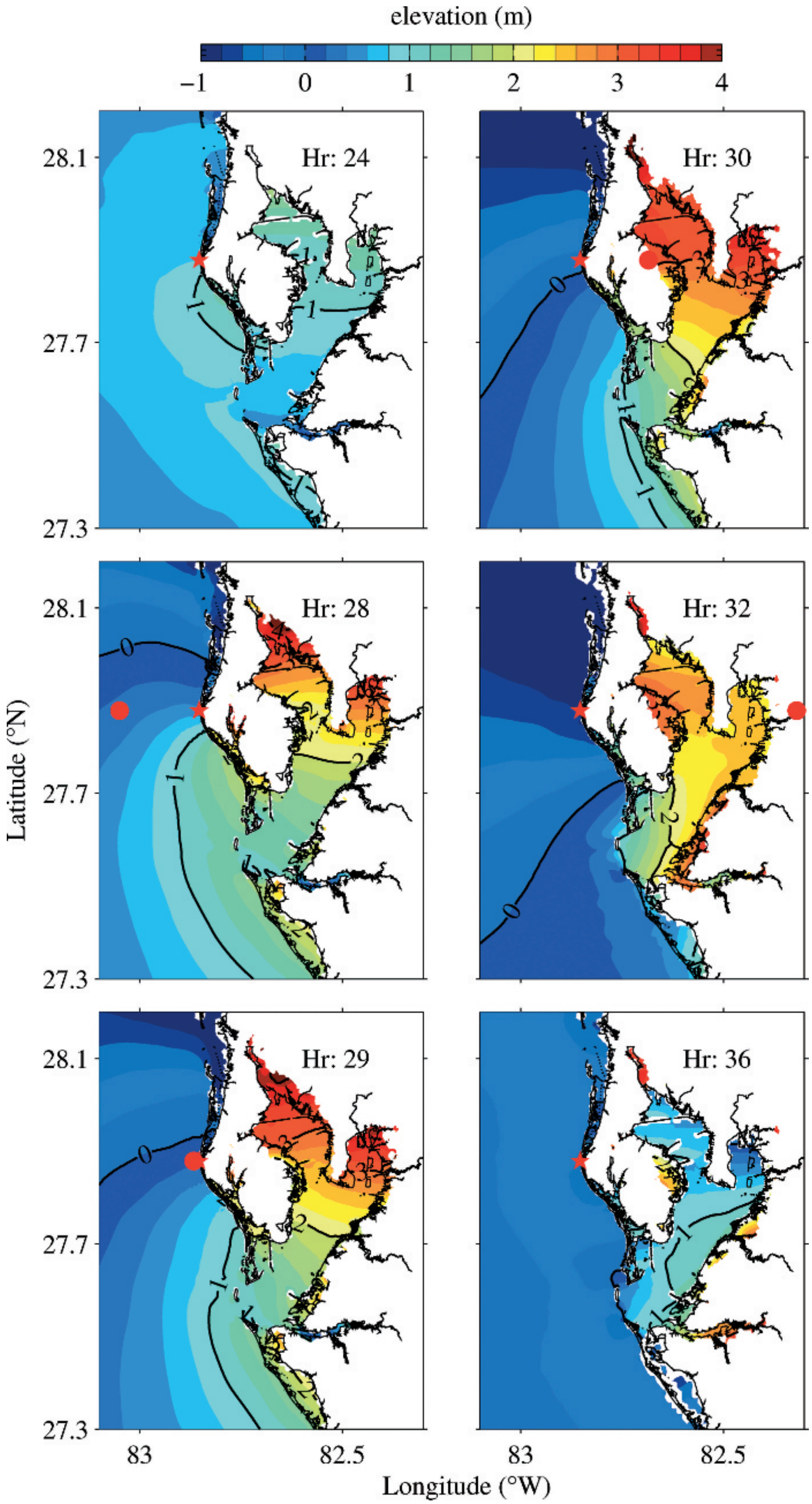
Fig. 5. Planar view of model-simulated elevation snapshots at hours 24, 28, 29, 30, 32, and 36 for a prototypical category 2 hurricane, approaching from the west at 5 m s^{-1} and making landfall at Indian Rocks Beach. The asterisk denotes the landfall location. The filled circles denote the location of storm center. The bold lines are elevation contours at 1-m intervals.


elevation (m)
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0
1
2
3
4
Hr: 24
Hr: 30
Hr: 28
Hr: 32
Hr: 29
Hr: 36
28.1
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Latitude (°N)
83
82.5
Longitude (°W)

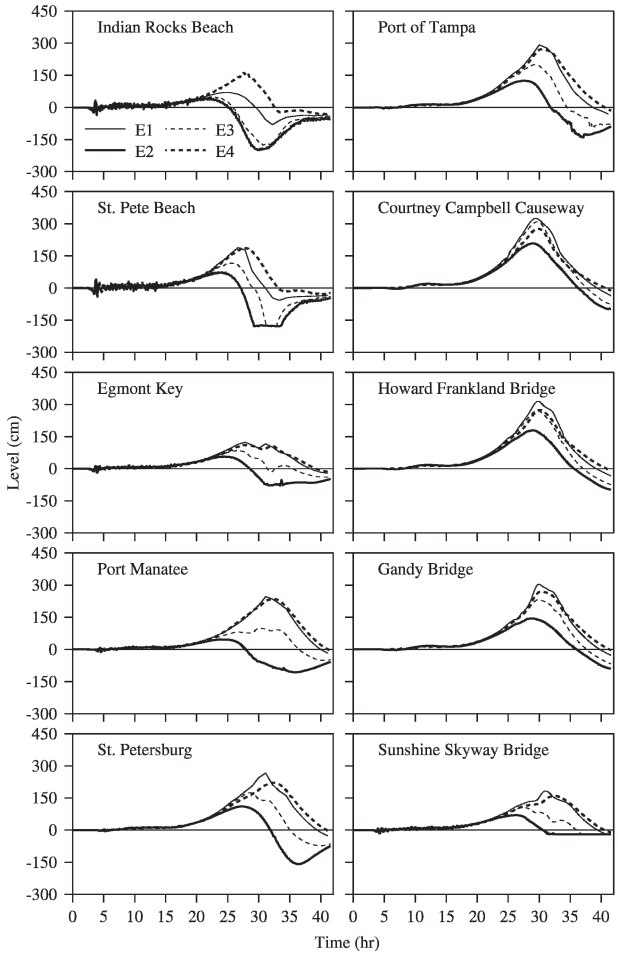

Fig. 6. Time series of model-simulated elevations sampled at Indian Rocks Beach, St. Pete Beach, Egmont Key, Port Manatee, St. Petersburg, Port of Tampa, Courtney Campbell Causeway, Howard Frankland Bridge, Gandy Bridge, and Sunshine Skyway Bridge (from top left to bottom right) for category 2 hurricanes, approaching from the west at 5 m s^{-1} and making landfall as described in Fig. 4 for E_1 (solid), E_2 (bold solid), E_3 (dashed), and E_4 (bold dashed).

vicinity are much less for E_2 than for E_1 since the winds are generally directed offshore to the north of the landfall point. With the cyclonic rotation of the winds around the storm center, the west side of the bay is still susceptible to onshore winds so we see surge heights of about 2.2 m at CCC and 0.7 m at SSB. The differences in surge times are due to the differences in time for which the winds are directed in a surge-favorable manner. For the Pinellas County beaches, very little surge occurs because the winds are directed offshore after the initially downwelling-favorable winds in advance of landfall. At SPB, after the small Ekman transport-induced sea level rise we see a set down of sea level sufficient to completely dry the point (slightly offshore) at which the model is sampled. Similarly all of the other points sampled within the bay eventually show a set down of sea level through the course of this simulation. While the Sarasota vicinity is outside the scope of the present paper, the model also provides (lower resolution) simulations for that region.

E_3 is similar to E_1 and E_2 except that for the point of landfall being at the Tampa Bay mouth midway in between the points of landfall for E_1 and E_2. Referring to Fig. 6 we see that the surge time series lie in between those of E_1 and E_2, as expected.

E_4 addresses the question of what happens in the Tampa Bay vicinity as the point of landfall moves farther north, in this case to Tarpon Springs, located about 70 km north of the bay mouth. Maximum surge heights increase slightly at IRB and SPB, but they are slightly smaller inside the bay (Fig. 6). These differences are explainable on the basis of the wind distribution relative to the points sampled. Surge heights with the bay are smaller since the winds at the bay mouth are smaller.

When the hurricane approaches from west to east with constant translation speed, the storm surges in the Tampa Bay vicinity are dependent upon the point of landfall. Landfall to the north of the bay mouth results in larger surge than landfall at or to the south of the bay mouth. Maximum surges within the bay correspond to situations for which landfall occurs sufficiently north of the bay mouth such that the maximum winds at the eye wall are situated at the bay mouth. In this set of examples the IRB point of landfall generally results in the largest surge heights. Surge heights generally begin to diminish as the landfall point proceeds farther north. From Fig. 3 we see that large winds for a prototypical hurricane can persist for large distances beyond the eye radius. So, for instance, while a hurricane that makes landfall 150 km north at Cedar Keys might not produce hurricane force winds over Tampa Bay, the potentially tropical storm force winds would still result in elevated sea levels.

Sensitivity to Direction of Approach

We now consider the direction of approach for prototypical category 2 hurricanes identical to E_1 (with translation speed of 5 m s^{-1}), but instead of approaching IRB from the west, we direct one hurricane up the Tampa Bay estuary axis from southwest to northeast (D_2), direct a second one parallel to D_2, but displaced by a radius to maximum winds to the northwest (D_3), and direct two others parallel to the coastline, either from northwest to southeast (D_4) or from southeast to northwest (D_5). For D_4 and D_5, the hurricane center is located about 3 km offshore as it passes the bay mouth at hour 20.

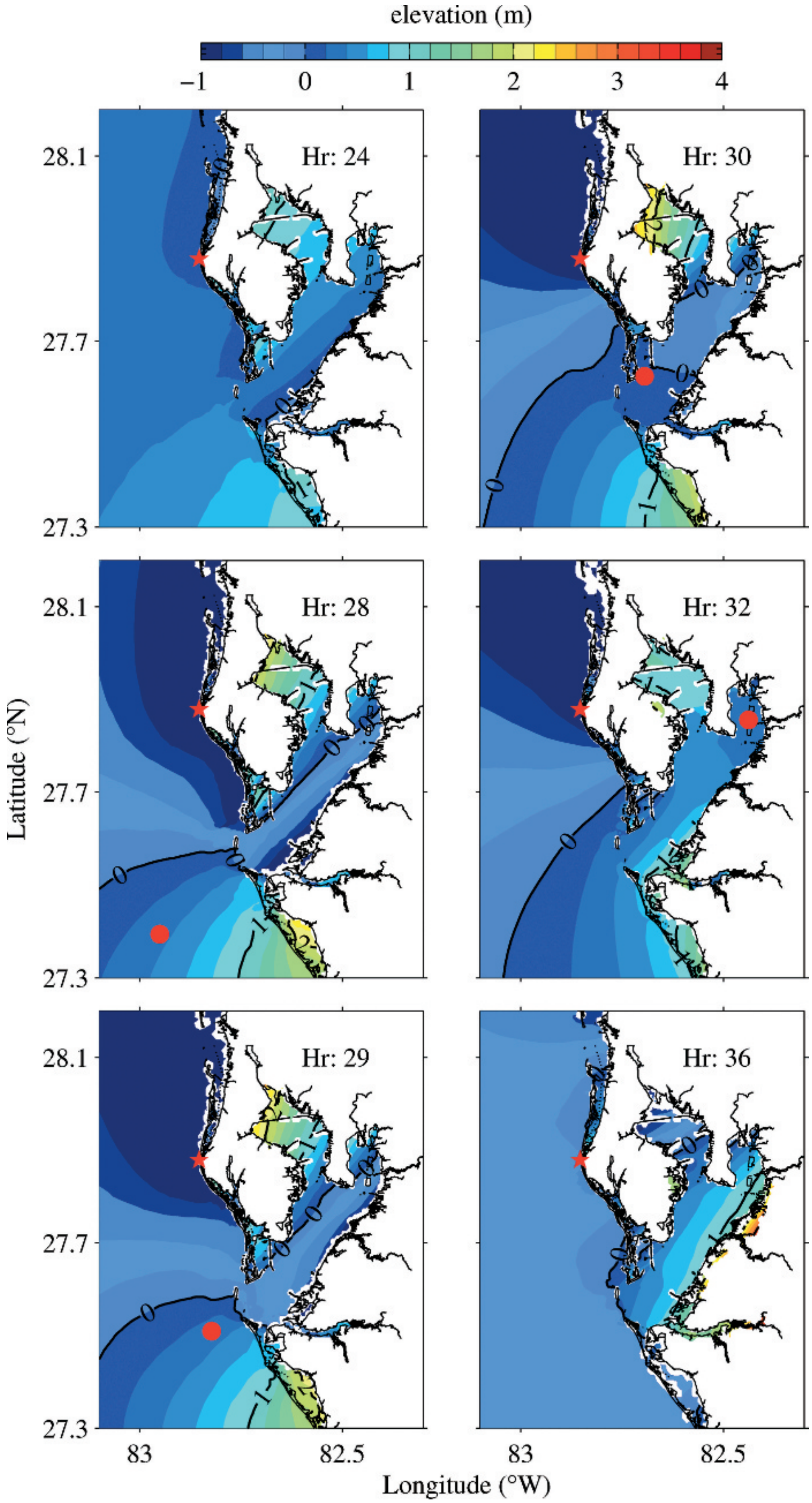

Fig. 7. Same as Fig. 5, except for a category 2 hurricane traveling up the axis of the bay at 5 m s^{-1}.

Similar to Fig. 5, Fig. 7 shows planar views of the D_2 model-simulated elevations for hours 24, 28, 29, 30, 32, and 36. Prior to hour 24, the winds along the coast were downwelling-favorable and sea level had generally increased due to onshore-directed Ekman transport. By hour 24, when the storm center is located about 100 km southwest of the bay mouth, offshore directed winds some distance to the north of the bay mouth are beginning to set sea level down, whereas onshore winds to the south are adding to the sea level set up there. Within the bay we see sea level beginning to set down on the eastern shore while setting up on the western shore. By hour 28 a substantial sea level depression (set up) is seen to the north (south) of the bay mouth. Inside the estuary there now exists a substantial across-bay sea level slope with some drying occurring along the eastern shore driven by an across bay-directed wind stress. Local surge maxima are building both in Sarasota Bay and Old Tampa Bay where the winds are directed onshore. These conditions continue to build through the time in which the storm center enters the bay (between hours 29 and 30). Once the storm center is in the bay, the winds along the coast are directed either offshore (north of the bay) or along shore toward the southeast (near the bay mouth) such that water is transported offshore, lowering sea level outside Tampa Bay and in Sarasota Bay. By hour 32, with the storm center in Hillsborough Bay, water is being driven out of Old Tampa Bay and onto the eastern shore of Tampa Bay. By hour 36 these across bay transports result in flooding along the eastern shore and drying in Old Tampa Bay and also in Sarasota Bay.

Time series representations of these directional sensitivity experiments are provided in Fig. 8, using the same format as in Fig. 6. When compared with E_1 we see that the positive portions of the storm surge inside the bay simulated for D_2 are much less, whereas the negative portions are much larger, particularly along the coast at IRB, SPB, and EK. The D_2 surge heights at the bridge causeways are much less than those for E_1. The folklore often expressed by media reporters that a hurricane passing directly up the bay is the worst case is shown to be false. To the contrary, at least with regard to storm surge, three factors tend to mitigate large flooding. In advance of the storm arriving at the bay mouth, while the winds are directed alongshore and are downwelling-favorable, the Ekman transport related sea level set up is much less than the set up due to onshore directed wind stress. Once the storm center is in the bay, the strongest winds are directed across the bay, so instead of driving coastal ocean water into the bay these winds redistribute water across the bay. Once the storm center is in the bay, the sea levels along the coastal ocean are being set down, forcing water out of the bay.

By translating the D_2 track line northwestward, the winds at the mouth of the bay become oriented up the axis of the bay throughout the storm evolution, and the D_3 surge is much larger than that for D_2. Relative to E_1, D_3 results in a comparable surge height, either higher on the Hillsborough Bay side or slightly lower on the Old Tampa Bay owing to the different orientations of these Tampa Bay segments. Because of these orientation differences it is difficult to define a worst case direction since what may be the worst case for one segment of the bay may not be for another.

The comparisons between storm surge simulations for hurricanes paralleling the coastline from northwest to southeast (D_4) and from southeast to northwest (D_5) are also revealing. Relative to E_1, D_4 and D_5 result in larger and smaller positive surge heights, respectively. For locations both inside and outside Tampa Bay we see opposite evolutions in surge height for these two different directions of shore parallel storm movement. One causes a sea level set up, while the other causes a set down. The explanation lies with the initial set up or set down as these storms approach the bay mouth. For D_4 the winds are directed onshore in advance of the storm so sea level is continually rising as the storm approaches. For D_5 the winds are directed offshore in advance of the storm so sea level is continually falling as the storm approaches. The initial conditions for the largest part of the surge responses are different among these two cases. At CCC the D_4 (D_5) generated surge is about 0.4 m higher (1.5 m lower) than that of E_1 (see Fig. 8). Also along the Pinellas County beaches the D_4 generated surge heights tend to be slightly larger than those of E_1.

Tampa Bay vicinity storm surges are sensitive to the direction of storm approach. While no storm scenario is a good one, the translation of a hurricane directly up the axis of the bay is the best of the worst cases with regard to storm surge. This storm scenario results in a redistribution of water from within the bay, as contrasted with additional coastal ocean water being transported into the bay. D_2 is a hybrid case between point of landfall and direction of approach. From the point of view of approach direction, all other factors being equal, the worst case for the Tampa Bay region as a whole is that of shore parallel from the northwest for reasons given above. Storm approach angles shifting from shore parallel from the southeast to shore parallel from the northwest result in increasing overall storm surge (albeit specific locations in the bay may have larger surge for other cases depending on the individual compartment orientations, e.g.,

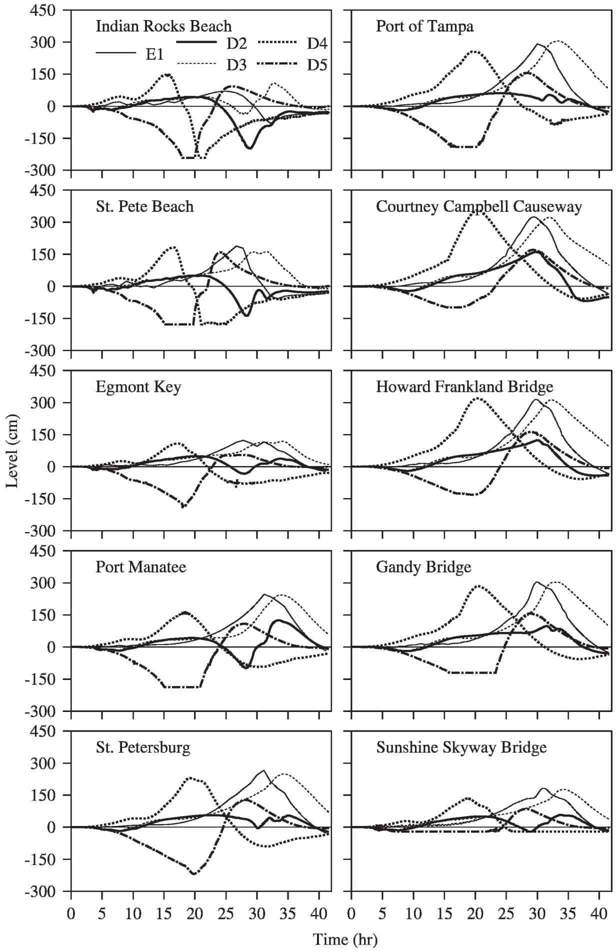

Fig. 8. Same as Fig. 6, except for the D_2 (bold solid), D_3 (dashed), D_4 (bold dashed), and D_5 (dot dashed), respectively.

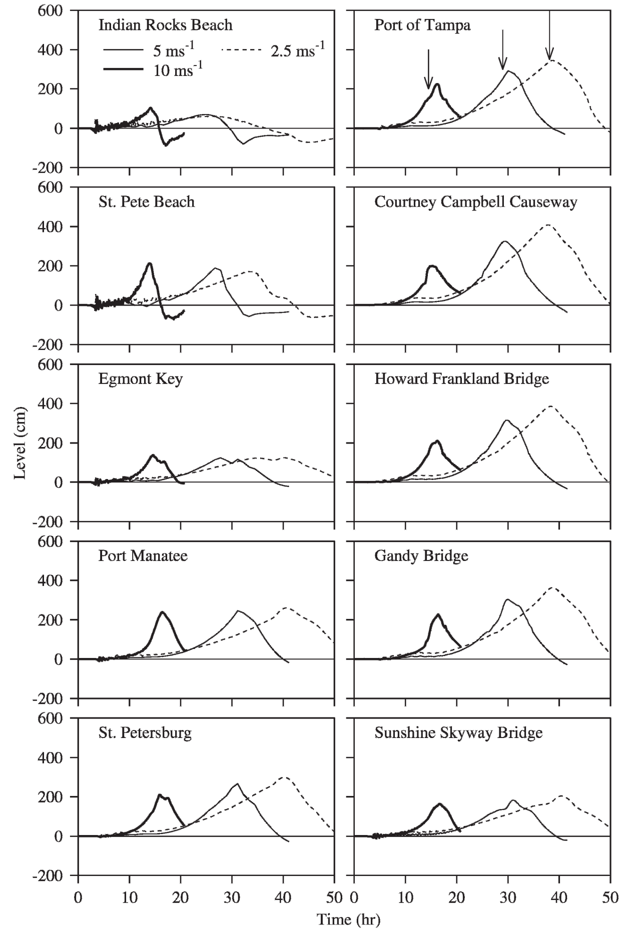

Fig. 9. Same as Fig. 6, except for a category 2 hurricane, making landfall at Indian Rocks Beach and approaching from the west at 5 m s^{-1} (solid), 10 m s^{-1} (bold solid), and 2.5 m s^{-1} (dashed), respectively. Arrows denote the landfall time.

Hillsborough Bay for D_3). This finding would be just the opposite for the east coast of Florida. There, southerly approaching storms would yield worse surges than northerly approaching storms for the same reason given here, namely that the initial conditions would be one of sea level increase versus decrease.

Sensitivity to Approach Speed

So far we considered an approach speed of 5 m s^{-1}. What happens if we either double or halve this value? Consider S_2 and S_3, which are identical to E_1 with the exception of the approach speed being 10 m s^{-1} for S_2 and 2.5 m s^{-1} for S_3. Because of different approach speeds the landfall times are different, as marked on Fig. 9 for the selected locations and bridge causeways as in Fig. 6.

Since storm surge entails a redistribution of mass (in order to generate a sea surface slope) the time for which a given wind acts on a given coastal ocean or estuary geometry is relevant. For the Pinellas County beaches, even though the approach speed may vary, the surge height responses are similar because the winds are acting over a sufficient time to raise sea level there. Once we begin to consider height variations within Tampa Bay we see a dramatic effect of storm translation speed. While somewhat oversimplified, the leading edge of the storm raises sea level in the bay. The trailing edge then lowers sea level. If the trailing edge arrives before the leading edge can fully effect the mass redistribution then the surge height will be suppressed. The slower the translation speed the larger the surge within the bay as seen at the various bridge causeways (Fig. 9). At CCC, the surge height for the slower moving storm (4.2 m) exceeds twice that of the faster moving storm (2.0 m).

The mass redistributions by winds depend on both the along and across shore components of wind stress. Surge due to the along shore component sets up within a fraction of a pendulum day through the Coriolis acceleration. Friction limits the magnitude of the resulting along shore current and the across shore sea surface slope in geostrophic balance with it. In shallow enough water the across shore component of wind stress effectively transports water downwind resulting in larger surface slope and larger surge. The time scale for this is on the order of hours. Mass redistributions within the shallow, geometrically complex estuary are somewhat longer than along the coast. When acted on by a steady, axially directed wind stress the time required to effect the mass redistribution to steady state within a rectangular bay can be estimated from mass and momentum conservation arguments as: $T = L^2\beta/\pi gh$, where L is length of the bay, β is turbulent resistance coefficient, g is the acceleration of gravity, and h is the mean depth (Feng 1982). For Tampa Bay with $L = 50$ km, $\beta = 1.5 \times 10^{-3}$ s^{-1}, and $h = 5$ m, T is approximately 6 h, implying that the surge in Tampa Bay can fully develop if the leading edge of the storm takes longer than 6 h to transit the bay. For the storm translation speeds of 2.5, 5, and 10 m s^{-1} used here, it takes roughly 5, 2.5, and 1.25 h, respectively, for the storm to transit the bay. Consequently the faster storms do not have sufficient time to fully affect the storm surge. In contrast with this inside the bay finding, outside the bay and along the coastline the set up time is more rapid (since the water is deeper) and the surge is not as sensitive to storm translation speed (Fig. 9).

Sensitivity to Hurricane Intensity

Our last sensitivity analysis compares the effects of prototypical category 2 and 4 hurricanes, approaching from the west at 5 m s^{-1} and making landfall at IRB. The simulation for the category 4, I_2 storm is compared with the simulation for E_1. Planar view elevation snapshots for I_2, similar to those of Fig. 5 for E_1, are shown in Fig. 10. The evolutions are similar except that the surge heights and the areas flooded are larger for I_2. At hour 28 the Pinellas County beaches to the south of IRB have surge heights of up to 3.5 m above mean water. From hours 29 through 32 we see a merging of water between the intracoastal waterway and Tampa Bay. As evidenced by the sea level gradients, this occurs first from the intracoastal waterway side when the beaches are flooded and then from the bay side when the west side of Old Tampa Bay is flooded. For this brief period of time SP is an island, and the northeast portions of SP are flooded with surge heights of about 5 m above mean water. Also, for I_2 we see that large portions of Oldsmar at the head of Old Tampa Bay, South Tampa between Old Tampa Bay and Hillsborough Bay, and downtown Tampa at the head of Hillsborough Bay are flooded with surge heights up to 6 m above mean water. After hour 32, when the storm has crossed over the bay, surge heights begin to abate over the northern portions of the bay while building on the eastern side of the bay. Flooding occurs along the Manatee County regions of the bay and in particular within the Manatee River, where surge heights are again approaching 6 m above mean water.

Time series comparisons sampled at specific points are given in Fig. 11. Once the surge begins, it advances and declines quickly with the storm translation across the Tampa Bay region. By the time of IRB landfall, the surge in the bay is already near its peak value, with water beginning to rise some 10–15 h prior to IRB landfall. Depending on position the peak surge lasts for some 3–6 h (for this translation speed; slower moving storms have longer lasting surges, and conversely for faster moving storms). The main difference between the E_1 and I_2 results is the surge magnitude and consequently the areas flooded. The surge heights, in response to wind stress, scale approximately with the square of the wind speed.

Conclusions and Recommendations

Our use of the finite volume coastal ocean model of Chen et al. (2003) to study the hurricane storm surge potential for the Tampa Bay region has allowed us to investigate the sensitivity of hurricane storm surge to point of landfall, direction and speed of approach, and intensity. For landfall (all other factors being equal) the worst case is when the storm center is positioned a radius to maximum winds north of the bay mouth such that the maximum winds are at the bay mouth. Storms making landfall farther north result in lesser surges. Storms making landfall to the south of the bay generally depress sea level along the Pinellas County beaches, although localized surge can still occur in the bay by a combination of onshore Ekman transport in advance of landfall and localized onshore winds as the storm translates past the bay. Surge is also sensitive to the approach direction with storms approaching from the south have lesser surge than those approaching from the north. The worst approach direction depends on the specific bay location. Speed of approach is also important. If a storm moves quickly enough, such that the translational time scale is shorter than the surge set up time scale, the full storm surge potential is not realized. Since surge is in response to wind stress, surge height tends to scale with the square of the wind speed (equations 9 and 10). Storms with stronger winds result in quadratically larger surge heights; a category 2 storm experiment suggested limited flooding, while the flooding potential for a category 4 storm may be catastrophic. Hurricane

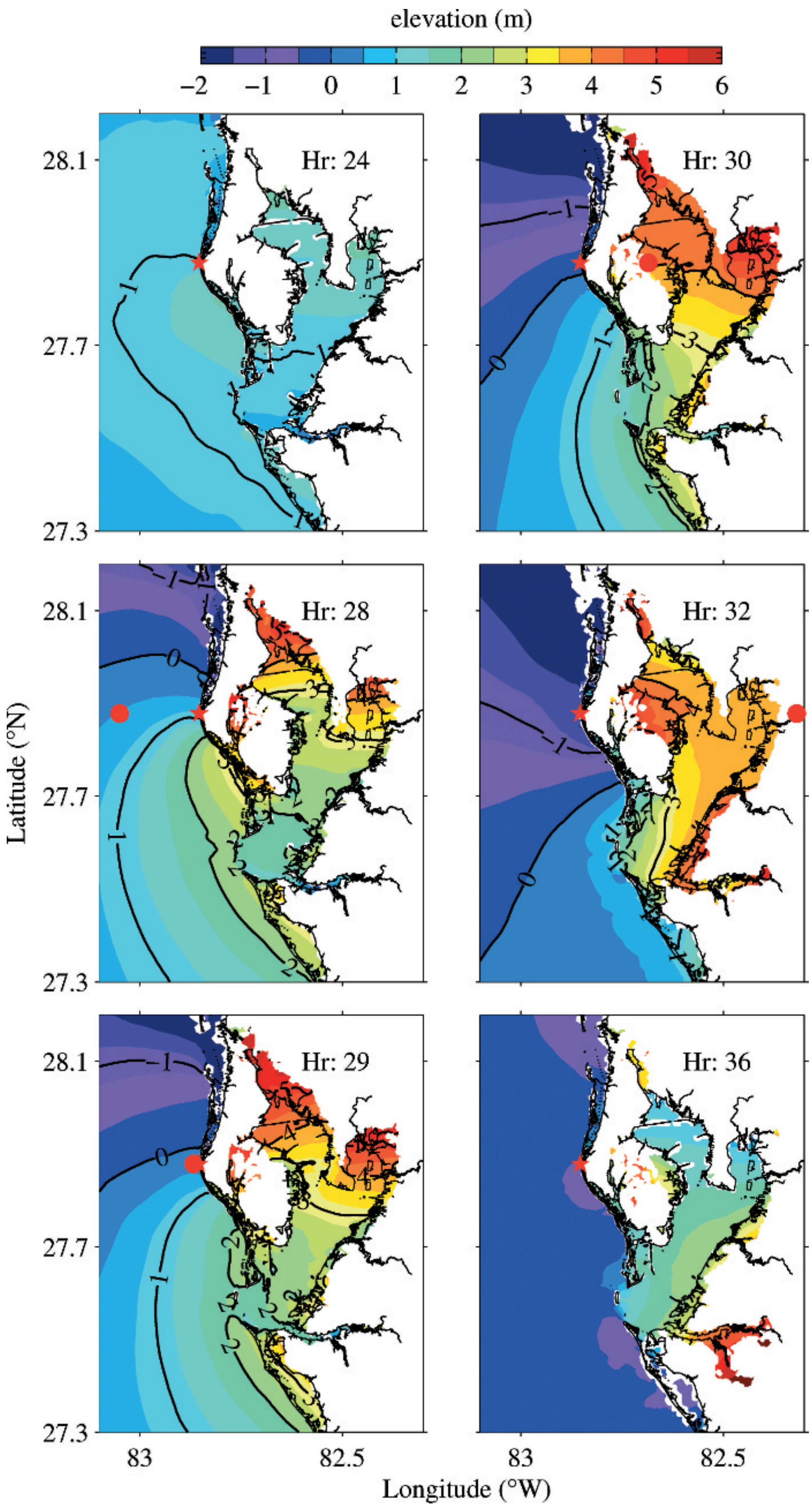

Fig. 10. Same as Fig. 5, except for a category 4 hurricane.

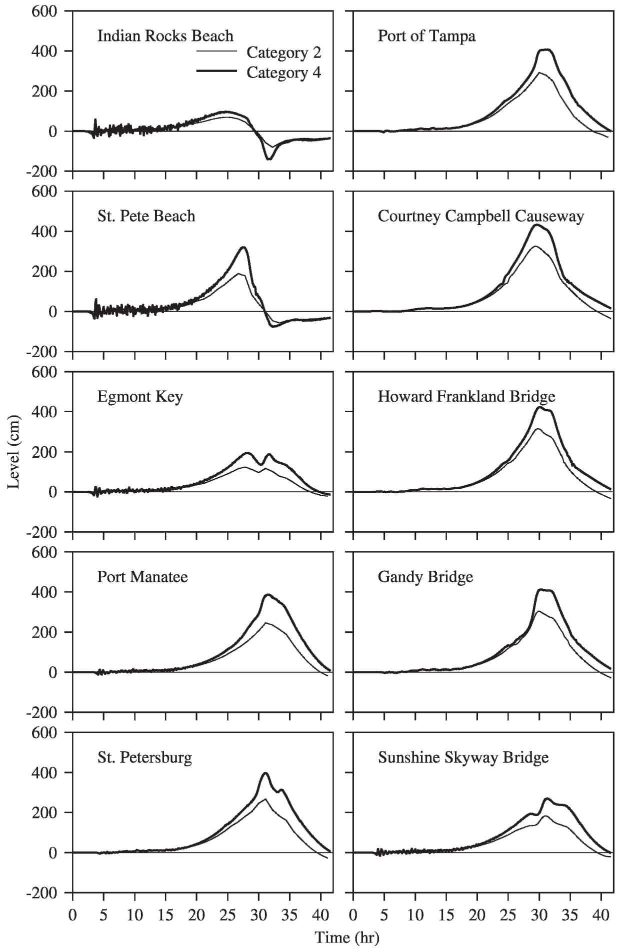

Fig. 11. Same as Fig. 6, except for category 2 (solid) and category 4 (bold solid) hurricanes approaching from the west at 5 m s^{-1} and making landfall at Indian Rocks Beach.

storm surge is also sensitive to the storm size (i.e., radius to maximum winds).

Hurricane Charley provides an example for which all of these factors apply. Hurricane Charley approached the Charlotte Harbor estuary rapidly from the south, made landfall just south of Boca Grande Pass, and then translated up the estuary axis, with a relatively small radius to maximum winds. Despite its category 4 status and its resultant wind damage, the storm surge was small (Weisberg and Zheng 2006a).

Two strategies may be considered for future hurricane storm surge estimation. The first entails real time predictions in advance of an actual storm. The second entails scenario developments as provided here. Recognizing that storm properties cannot be predicted accurately enough in advance of the time required to evacuate, hurricane storm surge scenario developments are necessary for emergency preparedness. Improving the accuracy of coastal ocean weather forecasts is necessary step toward improving hurricane property specifications. This requires data for assimilation, and hence coastal ocean observing systems (cf. Bortone 2006).

Additive to wind stress and pressure induced surges are the effects of tides, rivers, and waves. Tide ranges for Tampa Bay of about 0.5 m to 1 m are small relative to the surge potential by winds and pressure. Flooding by fresh water may be important locally, and additional flooding and damage by waves can be severe. Wave models need to be coupled with storm surge models to analyze the combined effects, as was demonstrated clearly by hurricanes Ivan in 2004 and Katrina in 2005. With surge heights at bridge causeway levels, pounding by waves destroyed sections of bridges. From this example, we can speculate that the Tampa Bay bridges would be in jeopardy under severe hurricane conditions.

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