A SIMULATION OF THE HURRICANE CHARLEY STORM SURGE AND ITS BREACH OF NORTH CAPTIVA ISLAND

R. H. WEISBERG(1) AND L. ZHENG(1)

(1) College of Marine Science, University of South Florida
St. Petersburg, FL 33701

ABSTRACT: A high resolution, three-dimensional numerical circulation model with flooding and drying capabilities is used to simulate the Hurricane Charley storm surge in the Charlotte Harbor vicinity. The model-simulated surge is in sufficiently good agreement with observations at four stations for which data exist to allow us to use the model to explain the surge evolution and to account for the inlet breach that occurred at North Captiva Island. Despite Charley being a Saffir-Simpson category 4 hurricane the surge was only of nominal magnitude and hence the damage, while severe, was primarily wind-induced. We explain the relatively small surge on the basis of the direction and speed of approach, point of landfall to the south of Boca Grande Pass and subsequent translation up the estuary axis, and the collapse of the eye radius as the storm came ashore. These inferences are based on lessons learned from hypothetical hurricane storm surge simulations for Tampa Bay. Under other approach scenarios the potential for hurricane storm surge in the Charlotte Harbor may be catastrophic.

Key Words: Hurricane Charley, storm surge, numerical simulation, inlet breach.

ON August 13, 2004 Hurricane Charley made landfall near North Captiva Island, traveled up the Charlotte Harbor estuary, and made landfall again at Punta Gorda, as the first of four devastating hurricanes to sweep across the State of Florida that year. Wind damage was severe for both the coastal and the inland communities that came under Charley's path. However, despite its Saffir-Simpson scale rating of category 4 the damage by storm surge was modest. Here we provide a simulation of the Hurricane Charley storm surge and explain, in view of the storm's strength, why the surge was relatively small. We also account for the breach at North Captiva Island that resulted in a new inlet being cut there (Figure 1).

Storm surge refers to the rise in sea level that may accompany a severe storm. Surges, or conversely sea level depressions, may result from both tropical and extra-tropical storms. Storm surges are generally associated with tropical storms since these tend to have the strongest winds causing the largest surges. Yet, observations show either higher or lower than normal sea levels, especially in fall through spring months, when extra-tropical systems (synoptic scale weather fronts) regularly transit the Florida peninsula. These weather-induced sea level variations come about by a number of processes that require explanation in order that the more severe instances of hurricane storm surge may be understood.

Sea level varies due to tides, seasonal steric effects, atmospheric pressure, and winds. Other deep-ocean influences may also be felt locally through the propagation of planetary waves (e.g., Sturges and Hong, 2001), or by long gravity waves in the case of a Tsunami. Here we concern ourselves with astronomical tides, seasonal steric effects, atmospheric pressure, and winds. Tides are well represented for the west coast of Florida by existing tidal models, e.g., for the full Gulf of Mexico in the $\frac{1}{4}{}^{0}$ resolution global model of Tierney et al. (2000) and for the west Florida shelf in the higher resolution regional model of He and Weisberg (2002). Steric effects are due to seasonal heating and cooling that alters seawater density and hence the water volume. This amounts to about plus or minus 20 cm for the Gulf of Mexico, with the highest (lowest) elevations occurring in late summer (winter).

Atmospheric pressure affects sea level through the "inverted barometer effect" by amount equal to 1 cm per mbar of pressure variation. Thus if pressure decreases locally sea level will rise, and this adjustment occurs rapidly through long gravity wave propagation at speed $(gH)^{1/2}$, where g is the acceleration of gravity and H is the water depth. Typical pressure fluctuations are a few mbar, and even under the most extreme hurricanes the inverted barometer effect is only about 100 cm so this alone cannot account for observed surges.

Wind effects arise by both the along shore and across shore components of wind stress, with their relative importance depending on the water depth and the duration over which the wind blows. In deep water, and due to the Earth's rotation, the net transport of water by the wind occurs at a 90^0 angle to the right (in the northern hemisphere) of the wind. If this transport impinges on a coast, water will pile up along the coast. Thus an along shore component of wind stress will cause a storm surge (depression) if the coast is to the right (left) of the wind. For instance, in advance of cold fronts, when the winds are from the south, we see higher than normal tides on the west coast of Florida, and, conversely, on the trailing side of cold fronts, when the winds are from the north, we see lower than normal tides. Since these wind-normal transports are a consequence of the Earth's rotation (via the Coriolis force) it takes about a pendulum day ($2\pi/f = 12\text{hr}/\sin\phi$), or about 1 day along the west coast of Florida (since the latitude ϕ is about 30^0) to set up the response. The amount by which sea level may rise depends on the magnitude of the along shore current produced by the along shore winds. The relevant force balance is between the pressure force due to the across shore slope of the sea surface, η_x, and the Coriolis force due to the along shore current, v. Thus $fv = \rho g\eta_x$, where ρ is the water density and f is the Coriolis parameter. Even under very strong winds it is rare for v to exceed about 100 cms^{-1} because of bottom friction, and, consequently, if the slope begins about 100-200 km offshore the surge by the along shore wind stress component may be about 60-120 cm. Moreover, the winds must blow for about a day for this to be fully realized. So while the along shore component of wind stress accounts for the sea level surges of a few feet, as synoptic weather fronts go by, it can only account for a portion of the surge by tropical storms. Here the onshore component of wind stress is the main culprit.

The across shore component of wind stress increases in importance as the water depth decreases since this bottom stress diminishes the Coriolis tendency for transport to be to the right of the wind. Hence winds blowing onshore over shallow water will pile water up along the coast, and conversely. The force balance is between the pressure force due to the across shore slope of the sea surface and the vertical stress gradient. Thus $\rho g\eta_x = \tau_z$, where τ_z is the vertical stress gradient. Integrating over depth results in $\rho gH\eta_x = \tau^w$ -

τ^b, where the superscripts, w and b, denote wind and bottom stresses, respectively. This shows that the across shore sea surface slope is directly proportional to the wind stress and inversely proportional to the water depth. The shallower the water, the larger the sea surface slope, and the farther upslope the larger the surge. Hence broad, shallow continental shelves, and especially long estuaries, are more prone to large surge than narrow, deep continental shelves. It also takes a certain amount of time to drive water from one point to another, thereby establishing the surface slope, so winds must blow over a given region for several hours to develop the slope and hence the storm surge.

In summary, a storm surge comes about by atmospheric pressure, along shore wind stress, and across shore wind stress. For extra-tropical systems the first two are generally the most important, whereas for tropical systems it is the last of these that accounts for the bulk of the storm surge. Not mentioned yet, nor quantitatively treated herein, are the wind induced surface gravity waves whose effects add to the storm surge.

With storm surge entailing several contributors that are each geometry and time scale dependent, its simulation cannot be generalized. Required are three elements: 1) a physics-based model, 2) a supporting data set on water depths and land elevations, and 3) wind and surface pressure fields to drive the model. Elevations and water depths alone are insufficient since sea level does not rise and fall uniformly. Surge is the highly localized impact of surface slopes by the factors discussed above, and since surge is mostly in response to wind, the winds must be sufficiently accurate to drive the model. All three of these elements are available for the Hurricane Charley simulation. We use the finite volume coastal ocean model (FVCOM) with flooding and drying capabilities developed by Chen et al. (2003). The model grid is overlaid on a South Florida Water Management District (SFWMD), merged bathymetric/topographic data set provided by T. Liebermann (personal communication, 2004). For winds and pressure we combine available data with an analytical expression for the structure of a hurricane (Holland, 1980) since there are never enough data to fully specify the wind field for any given storm.

Section 2 describes the model and its implementation for Hurricane Charley. The evolution of the modeled surge is given in Section 3 along with comparisons to the existing data. It is here that we also provide the mechanism by which an approximate 450 m wide breach occurred on North Captiva Island. Section 4 discusses these findings in the light of what we learned from previous Tampa Bay region simulations and offers a set of conclusions.

MODEL DESCRIPTION AND CONFIGURATION ─ There are basically three types of numerical model constructs that may be used for simulating storm surges: finite difference, finite element, and finite volume, all differing in how they organize their grids and how they solve the governing equations of motion. The FVCOM, a finite volume model, combines the attributes of both finite difference and finite element models. As in finite element models it uses a non-overlapping unstructured triangular mesh for high horizontal resolution where needed, but it solves the hydrodynamic equations by finite-differences, using a flux calculation integrated over each grid control volume. This assures the conservation of mass, energy, salt, and heat in both the individual grid cells and over the entire computational domain, even for long integrations. An application of the FVCOM to the baroclinic, three-dimensional and time dependent circulation of the

Tampa Bay estuary is given by Weisberg and Zheng (2005), and Weisberg and Zheng (in preparation) used the FVCOM for hypothetical hurricane storm surge simulations of Tampa Bay, results of which will be discussed in section 4.

The FVCOM domain used here (Figure 2) extends from the Mississippi River delta in the north to the Florida Keys in the south, with an open boundary arching in between. Model resolution increases from the deep-ocean toward the Charlotte Harbor region. The highest resolution of about 80 m (a zoomed-in view is also provided in Figure 2) is centered on the barrier islands, where Hurricane Charley initially made landfall. Within the estuary the resolution is less than 300 m, and the lowest resolution is about 20 km along the open boundary. The reason for a large model domain is to allow for running different hurricane scenarios for storms approaching from different directions. For the transition from ocean to land the model domain extends landward to the 10 m elevation contour. A total of 63077 triangular cells with 31821 nodes comprise the horizontal, and 31 uniformly distributed sigma coordinate layers comprise the vertical. The model grid is superimposed on the 30 m resolution SFWMD, merged bathymetric/topographic data set (Figure 3). We use mean sea level as a datum, and we set the sea wall height at 1.2 m elevation. Therefore a minimum 1.2 m surge is required to cause flooding in this model. While the model is capable of baroclinic simulations we ran it with constant density for the hurricane storm surge simulations since observations show that high winds and heat flux rapidly lead to vertically well-mixed density. Three-dimensionality nevertheless remains important since this determines the bottom stress.

Given the model, supported by high-resolution bathymetry and topography, hurricane storm surge simulation requires sufficiently accurate atmosphere forcing fields (winds and pressure). We used the analytical expression for the structure of a prototypical hurricane developed by Holland (1980) since actual measurements over the evolution of any storm are sparse and error prone. This prototypical hurricane construct requires information on the eye radius, the central pressure, and the maximum wind speed, and these information, along with the storm track, were obtained at three-hour intervals from the National Oceanic and Atmospheric Administration (NOAA), National Hurricane Center (NHC) website. We further modified the storm track for consistency with local Doppler radar images. Figure 4 shows the track, eye radii, central pressures and maximum wind speeds employed, and Figure 5 gives an example of the prototypical hurricane wind and pressure distributions corresponding to the time when the eye passed over Punta Gorda. Such distributions were calculated for every model time step (at 20 sec intervals) by linearly interpolating between the three-hourly NOAA NHC data. In this way we were able to model the Hurricane Charley surge using winds and pressure that systematically varied as the storm approached and transited across the Charlotte Harbor region. Drawbacks to this approach are that the Holland (1980) prototypical storm is symmetric, whereas asymmetries occur in nature, and the actual winds contain a background field on which the storm is superimposed. These are of particular note after the storm passes since in the wake of a storm there tends to be a continuation of winds feeding it as it progresses away.

HURRICANE CHARLEY STORM SURGE SIMULATION ─ The start time for the model run is 0300 UTC on August 13, 2004, when Hurricane Charley was positioned south of Cuba, and the end time is 2400 UTC on August 13, 2004, when the hurricane was positioned 140 km northeast of the study region. All future times will be referenced to UTC (local daylight savings time is minus four hours). The model sea level and currents were initialized as zero since the hurricane started far way from the model domain. Hurricane Charley entered the Gulf of Mexico at 1200 with an eye radius, central pressure, and maximum wind speed of 27.5 km, 967 mbar, and 48.8 ms^{-1}, respectively. At 1500 the hurricane veered right toward Charlotte Harbor and started to intensify to category 4. From 1800 to 2100 the winds remained about the same while the eye radius decreased and the central pressure dropped to 10 km and 941 mbar, respectively. During this interval it made landfall near North Captiva Island, proceeded up the axis of the estuary, and passed over Punta Gorda.

Hurricane Charley moved very rapidly across the study region, taking about three hours to transit 100 km. Figure 6 shows the model simulated sea level evolution from 1900 to 2130 in half-hourly snapshots. Areas of sea level set up (storm surge) and set down are evident, but nowhere is the storm surge very large. The largest surge of about 250 cm occurred near Ft. Myers Beach at 2030. Beginning at 1900 when the hurricane eye is some 35 km southwest of North Captiva Island sea level is first set down on by about 100 cm in advance of the storm since the winds are directed offshore, and some draining is found around the shallow Pine Island Sound region. It is only within the hurricane eye where sea level is elevated by about 60 cm due to the inverted barometer effect. By 1930 the hurricane eye is within 15 km of landfall, additional draining occurs on both sides of the Captiva Islands and on the sound side of Sanibel Island. It is at this time when the maximum sea level depression of about 200 cm occurs on the gulf side of North Captiva Island, whereas sea level is increased on the sound side by approximately 50 cm, generating a seaward directed sea level gradient across the barrier island. Farther south from the hurricane eye we see sea level beginning to rise as winds blow onshore there. For example, the sea level at San Carlos Pass increases to about 50 cm.

Landfall occurred at 2000, at which time Figure 6 shows sea level to be elevated everywhere along the coast to the south of the eye, particularly at Sanibel (150 cm) and Ft. Myers Beach. To the north of the eye and within most of the Charlotte Harbor estuary sea level is set down, particularly on the east side with draining there, in Pine Island Sound, and on the gulf side of Cayo Costa Island. Some surge is beginning on the west side of the estuary, however.

By 2030 we see a significant change when the hurricane eye moves about half way up the axis of the estuary. The entire Captiva/Sanibel barrier island complex now has about a 100 to 150 cm surge, with the local maximum at North Captiva Island (the maximum recall is near Ft Myers Beach). More draining occurs on the east side of the estuary, and surge, although small, increases on the west side. Landfall at Punta Gorda occurs at 2100, but with a very small eye radius. With winds acting over a smaller region the surge offshore diminishes, and by 2130 sea level in this simulation is returning toward normal.

Explanations for why the Hurricane Charley storm surge was relatively small and also why an inlet was cut at North Captiva Island are both straight forward. Before providing these, however, it is important to lend some credibility to the analyses by comparing simulated with observed sea level elevations. Recorded data with sea level measures that are resolved by our model are limited to four stations: Ft Myers, Big Carlos Pass, Peace River, and Boca Grande Pass. The locations are shown in Figure 3. Data from the Ft. Myers gauge, located in the Caloosahatchee River, were provided by NOAA. The Big

Carlos Pass data are from a University of South Florida, Coastal Ocean Monitoring and Prediction System station that was coincidentally deployed a few weeks prior to the event. The Peace River and Boca Grande Pass data are from US Geological Survey gauges. Because we simulated storm surge relative to mean sea level, adjustments must be made to correct for tide gauge datum, astronomical tides, and seasonal steric elevations. Datum corrections are based on tide gauge site surveys relative to the North American Vertical Datum of 1983, or NAVD83. Records of long enough duration were available at the Ft. Myers and Big Carlos Pass stations to perform a tidal harmonic analysis in order to subtract the astronomical tides from the record. Shorter records from the Peace River and Boca Grande Pass stations were not amendable to detiding so we adjusted our model datum to conform with the tidal phase at the time of maximum surge. Tides are not a major factor for two reasons. First the tidal range in the Charlotte Harbor vicinity is generally small and August 13, 2004 corresponded to neap tide. For all gauges we also made adjustment for the seasonal steric sea level obtained from an analysis of ten years of detided data. For the Hurricane Charley time period this amounted to 10 cm.

Figure 7 shows the resulting comparisons. Three time series are shown for the Ft. Myers and Big Carlos Pass stations: observed, datum adjusted sea level; detided sea level, or surge; and the simulated surge adjusted for the seasonal steric effect. Two time series are shown for the Peace River and Boca Grande Pass stations: observed, datum adjusted sea level, and the simulated surge adjusted for both the seasonal steric effect and the astronomical tidal elevation at the time of maximum surge. At each of these stations the maximum surge and the time of occurrence agree fairly well. Quantitatively, the differences between observed and simulated surges are –4 cm at Ft. Myers, 23 cm at Big Carlos Pass, 10 cm at the Peace River, and 5 cm at Boca Grande Pass, where positive (negative) denotes a model overestimate (underestimate). The time differences between observed and simulated surges are less than one hour except at the Ft. Myers station, where the difference is about two hours. At Ft. Myers and Big Carlos Pass sea level remains elevated after the simulated surge abates. This may be a consequence of two factors. First, as mentioned earlier, hurricane winds tend to be asymmetric, with strong winds remaining in the wake of the storm that are not included in the simulation. Second, the simulation makes no provision for fresh water drainage. Despite these drawbacks the agreements in the maximum surge magnitudes and times (the two most important factors in storm surge prediction) between observed and simulated surges suggests that our Hurricane Charley storm surge simulation is sufficiently accurate. These results find additional support in the Florida State Emergency Operations Center website (http://floridadisaster.org/eoc/Charley04.asp), which states that the highest surge plus tide (and plus the steric sea level adjustment) was about 10-13 ft from Vanderbilt Beach (north of Naples) to the Lee County line. This agrees with our simulated estimate there of about 250 cm, or about 8.5 ft. The difference may easily be accounted for by wind wave run up not included in the model.

Given the veracity of the simulation we can now use it to explain the breach of North Captiva Island. Figure 8 shows model simulated sea level time series sampled on the gulf and sound sides of the location that was breached. As the hurricane approached and passed over this region we see an initially small depression of sea level on both sides followed by a large (200 cm) depression on the gulf side. Within an hour the sea level gradient across the island reversed such that the surge on the gulf side was 125 cm and the depression on the sound side was 90 cm. In total there was a sea level difference of more than 200 cm across a very narrow low-lying strip of island. This allowed for flow across the barrier island driven by a very large horizontal pressure gradient force. Once the breach began, sand transport then very rapidly eroded the barrier island, resulting in the new, 450 m wide inlet (Figure 1).

DISCUSSION AND CONCLUSIONS ─ Having simulated the evolution of the Hurricane Charley storm surge and establishing some degree of credibility by comparing the simulation with observations it remains to explain why the surge was relatively small given the category 4 nature of the hurricane. There are five reasons for this developed based on simulations of hypothetical hurricanes making landfall in the Tampa Bay vicinity (Weisberg and Zheng, in preparation, and available at http://ocgweb.marine.usf.edu). Using the same model strategy we considered the storm surges due to category 2 and 4 hurricanes, approaching Tampa Bay from different directions, at different speeds of approach, and making landfall at different locations. All of these factors are of importance to the evolution and magnitude of the surge. The point of landfall is important since, with winds blowing counterclockwise around the hurricane eye, the surge by onshore-directed winds occurs to the south of the eye for the west coast of Florida. North of the eye the winds are directed offshore and sea level is depressed. The speed of approach is important since it takes a finite amount of time to transport water from one point to another. Fast moving storms may yield lesser surge than slow moving storms since there may not be sufficient time to fully set up the sea surface slope that comprises the surge. The direction of approach enters in two ways. First, if the storm approaches from the south the affect of offshore-directed winds in advance of the eye initially sets sea level down. Hence when surge occurs it begins from a condition of depressed sea level. To the contrary, if the storm approaches from the north, sea level is set up directly. Hence surge magnitude increases for the west coast of Florida as the angle of approach rotates from southeast to northwest. Second, should the storm move up the axis of the estuary the tendency is to lower sea level on one side and raise sea level on the other side, effecting a redistribution of water mass in the estuary, versus a net increase in water mass. Finally, the physical dimension of the storm is also highly relevant. Large eye radii storms have large winds extending over larger areas than small eye radii storms.

All of these factors tended to mitigate storm surge for Hurricane Charley. The eye radius collapsed to a very small value (less than 10 km) as it made landfall, the storm approached from the southerly quadrant and proceeded directly up the axis of the Charlotte Harbor estuary, it moved very swiftly (about 18 kts), and it made landfall to the south of the largest pass, namely Boca Grande Pass. Thus despite its category 4 status, the size, approach speed, approach direction and movement up the estuary axis, and point of landfall all led to the relatively small surge.

In summary we applied a three-dimensional, high-resolution, finite-volume coastal ocean model with flooding and drying capabilities (the FVCOM of Chen et al., 2003) to simulate the Hurricane Charley storm surge in the Charlotte Harbor vicinity and to account for the new inlet breach at North Captiva Island. The model was supported by high-resolution, SFWMD bathymetry and topography data, and it was driven with prototypical hurricane wind and pressure distributions (Holland, 1980) using a NOAA

NHC supplied storm track along with the eye radii, maximum wind speeds, and central pressures observed along the track. Comparisons with observed data, after appropriate adjustments for astronomical tides referenced to NAVD83 datum and seasonal steric effects, demonstrated the veracity of the simulation.

A 450 m wide new inlet that was cut across the narrowest portion of North Captiva Island was attributed to a sufficiently large gulf to sound directed sea level gradient that set up as the eye transited the island to the north of the breach. The region of largest storm surge (about 250 cm in our simulation and slightly larger than this in anecdotal emergency management narratives) occurred to the south of the Charlotte Harbor region near Ft. Myers Beach. The surge within the Charlotte Harbor estuary was relatively small in view of Hurricane Charley's category 4 status, and we attributed this finding to the direction and speed of approach, the point of landfall to the south of Boca Grande Pass, the translation of the hurricane up the estuary axis, and the compact eye radius. Despite this relatively small hurricane storm surge event (Hurricane Charley damage was primarily wind generated), we caution that the Charlotte Harbor region is highly susceptible to severe storm surge under other conditions. Had Hurricane Charley approached more slowly, from a more westerly to northwesterly direction and made landfall to the north of Boca Grande Pass with a larger eye radius, the storm surge would also have been catastrophic. These findings are based on simulations performed for prototypical category 2 and 4 storms conducted for the Tampa Bay region (Weisberg and Zheng, in preparation). Finally, while not included in these simulations wind waves also add to the storm surge and to the destructive power thereof.

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Fig. 1: Coastline of the North Captiva Island on September 21, 2001 (left panel) and on August 16, 2004 (right panel) after Hurricane Charley made landfall (A. Sallenger, personal communication).

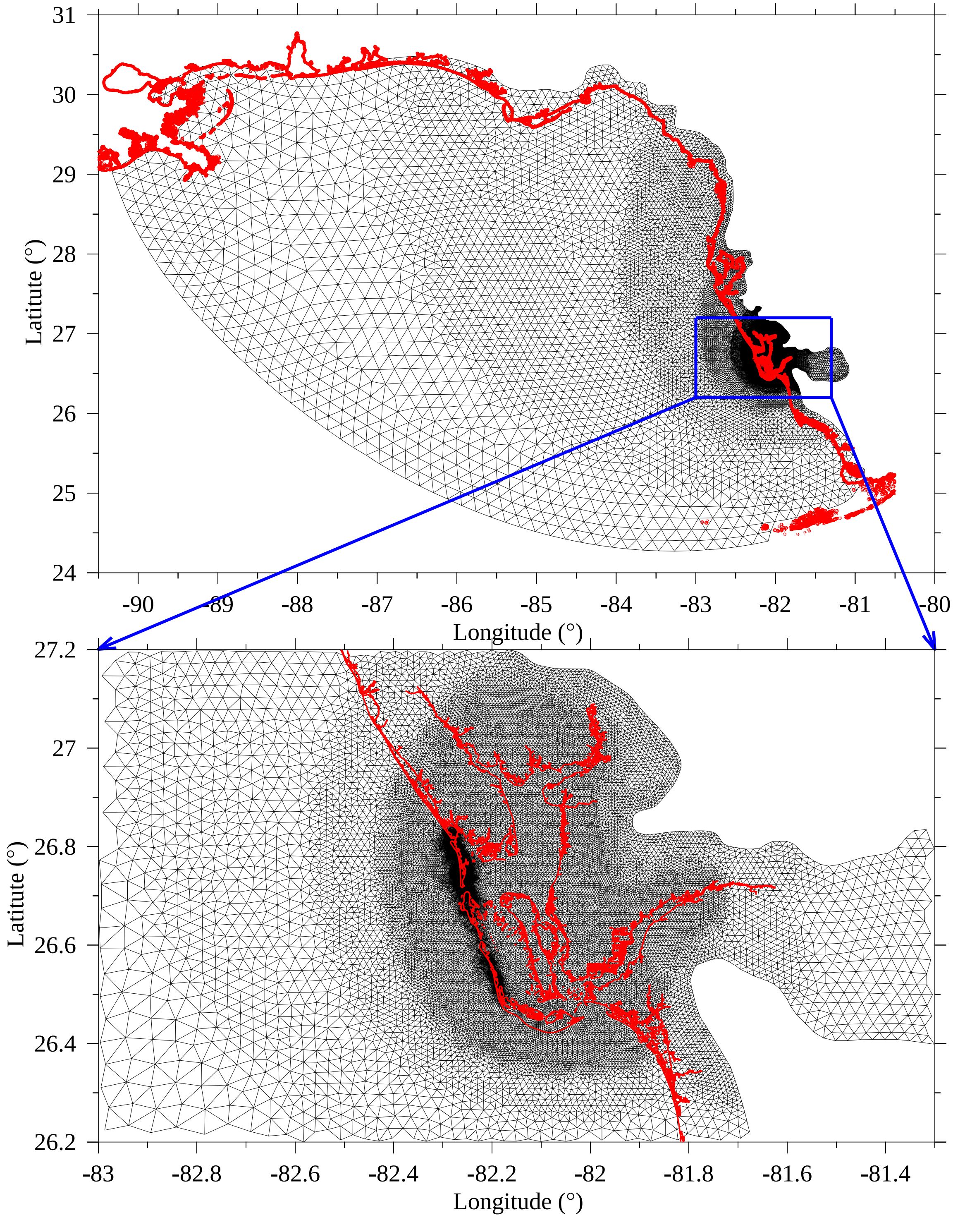

Fig. 2: The non-overlapping, unstructured triangular grid used in this simulation (upper panel) and its zoomed view focusing on Charlotte Harbor vicinity (lower panel).

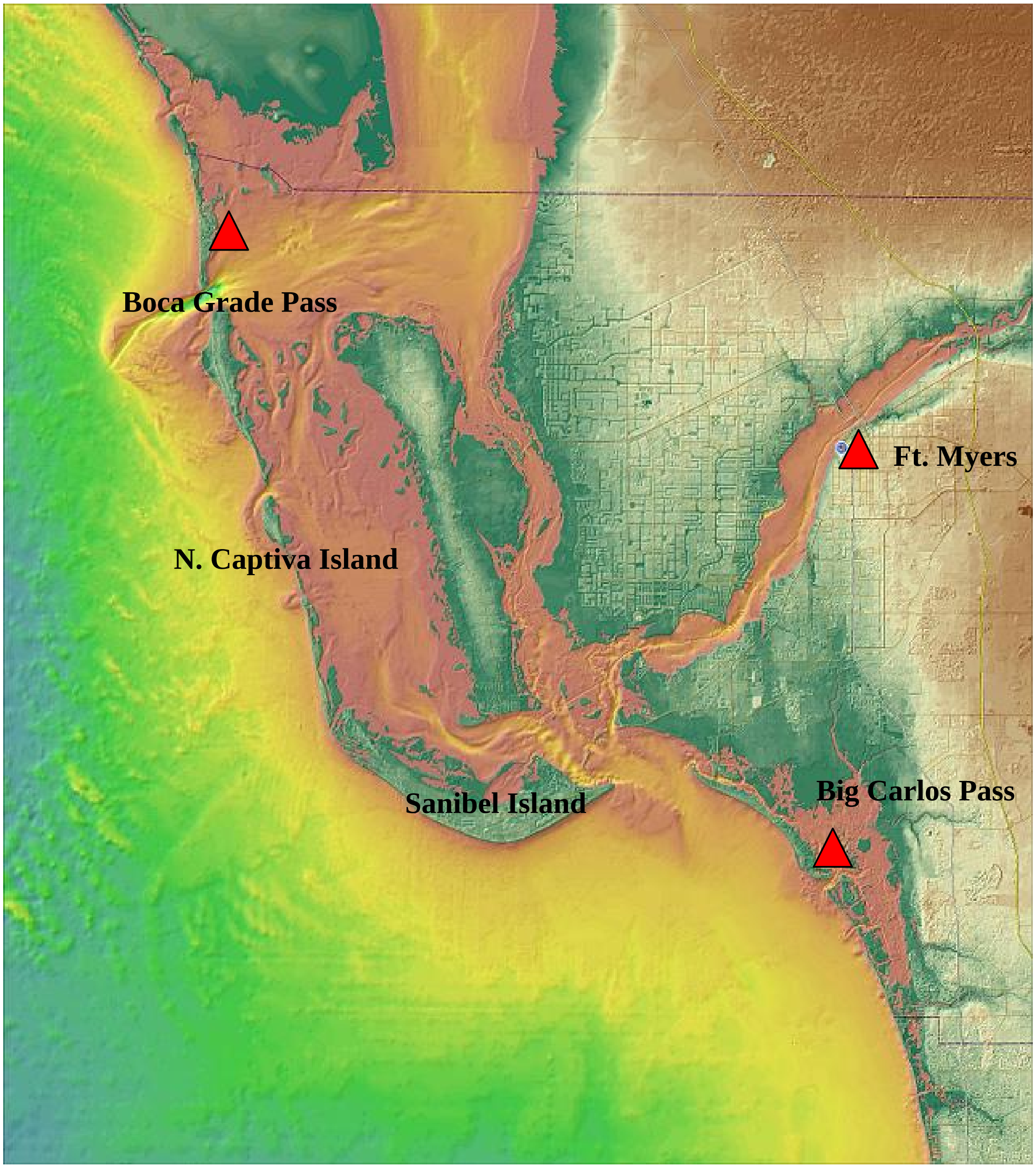

Fig. 3: The 30-m resolution bathymetric and topographic image. Filled red triangles denote observed sea level stations used (Peace River station beyond image range).

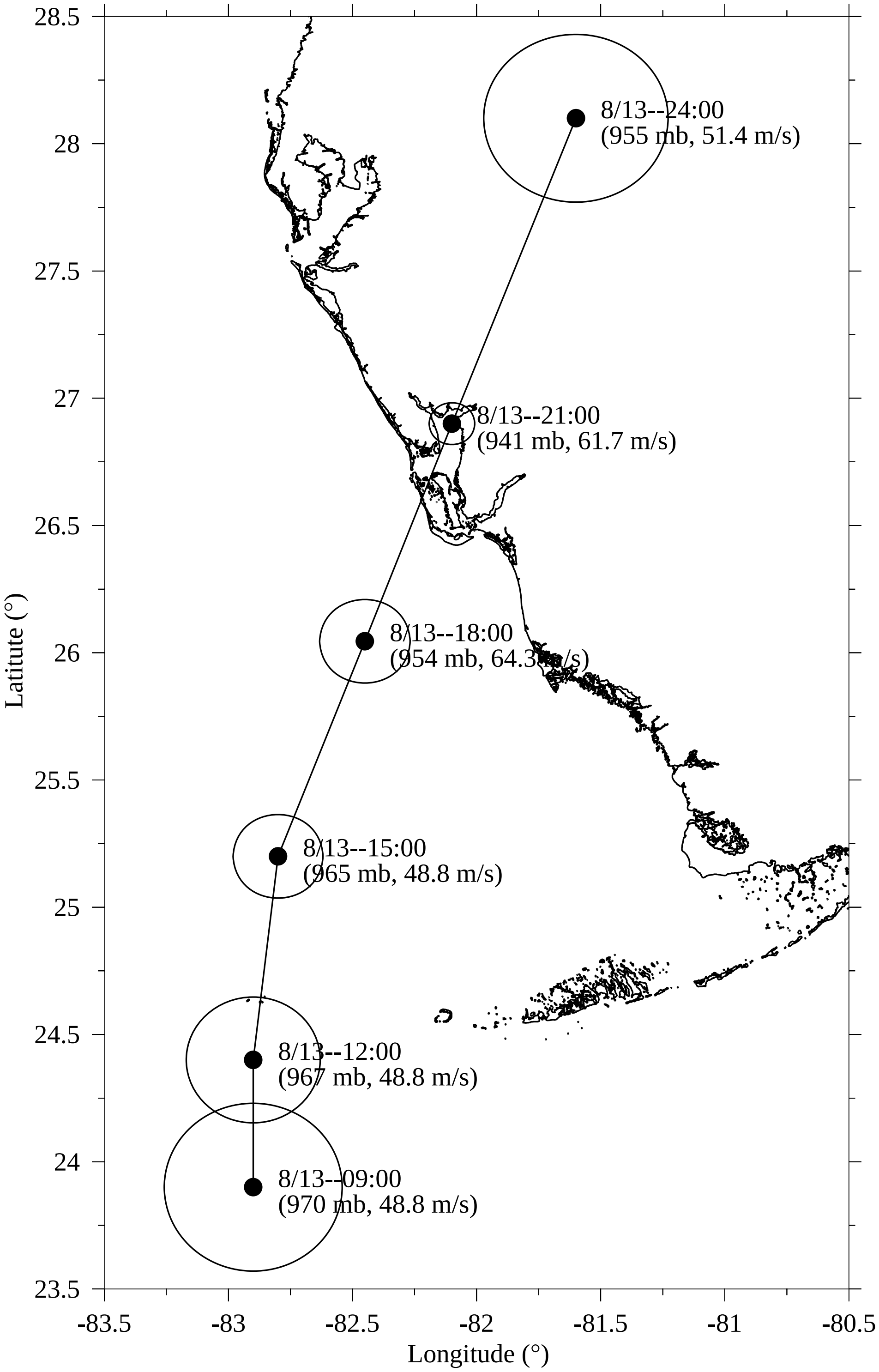

Fig. 4: The Hurricane Charley track along with eye radii, central pressures, and maximum wind speeds provided from NOAA NHC website.

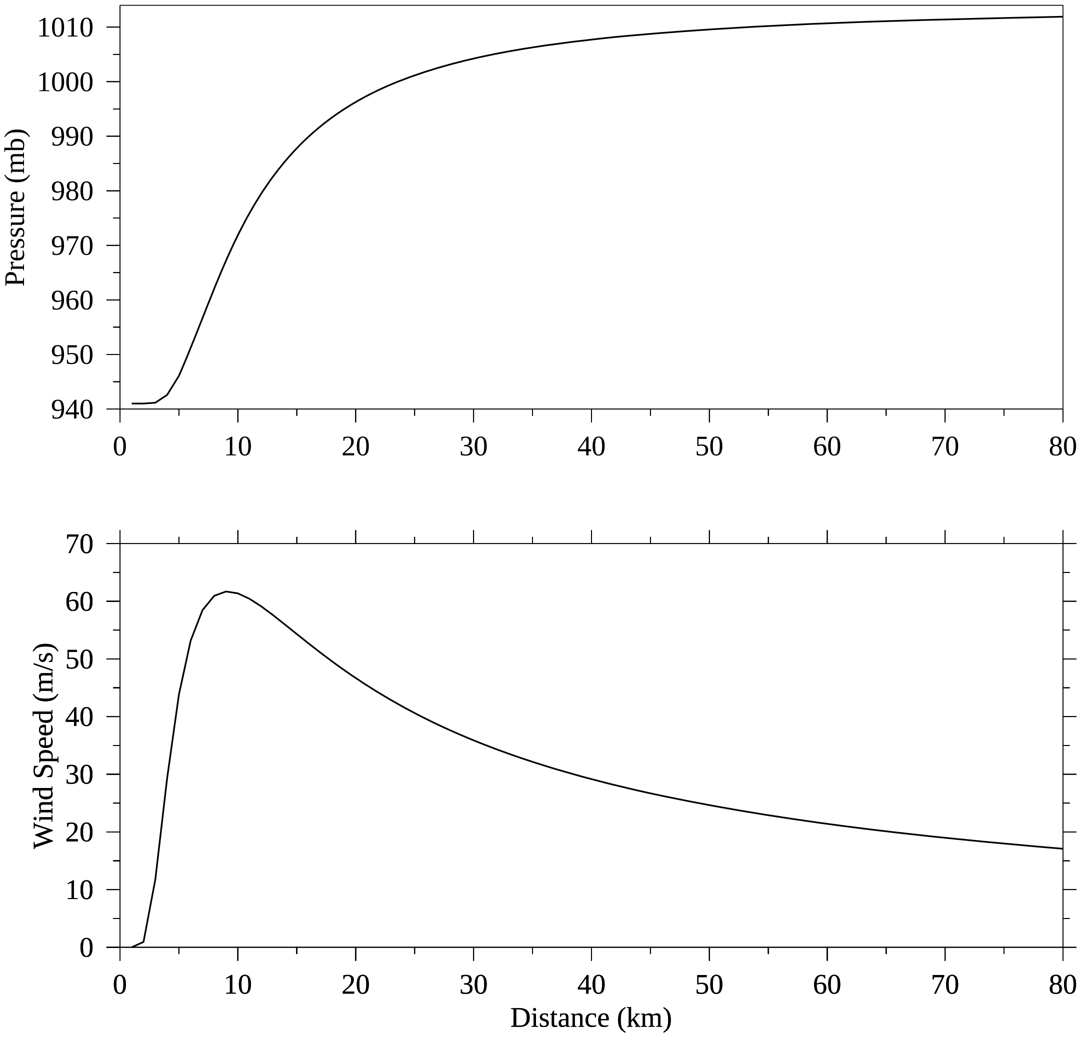

Fig. 5: Distributions of pressure (upper panel) and wind speed (lower panel) as a function of radial distance from the hurricane eye. These distributions are corresponding to the time when hurricane eye passes over Punta Gorda.

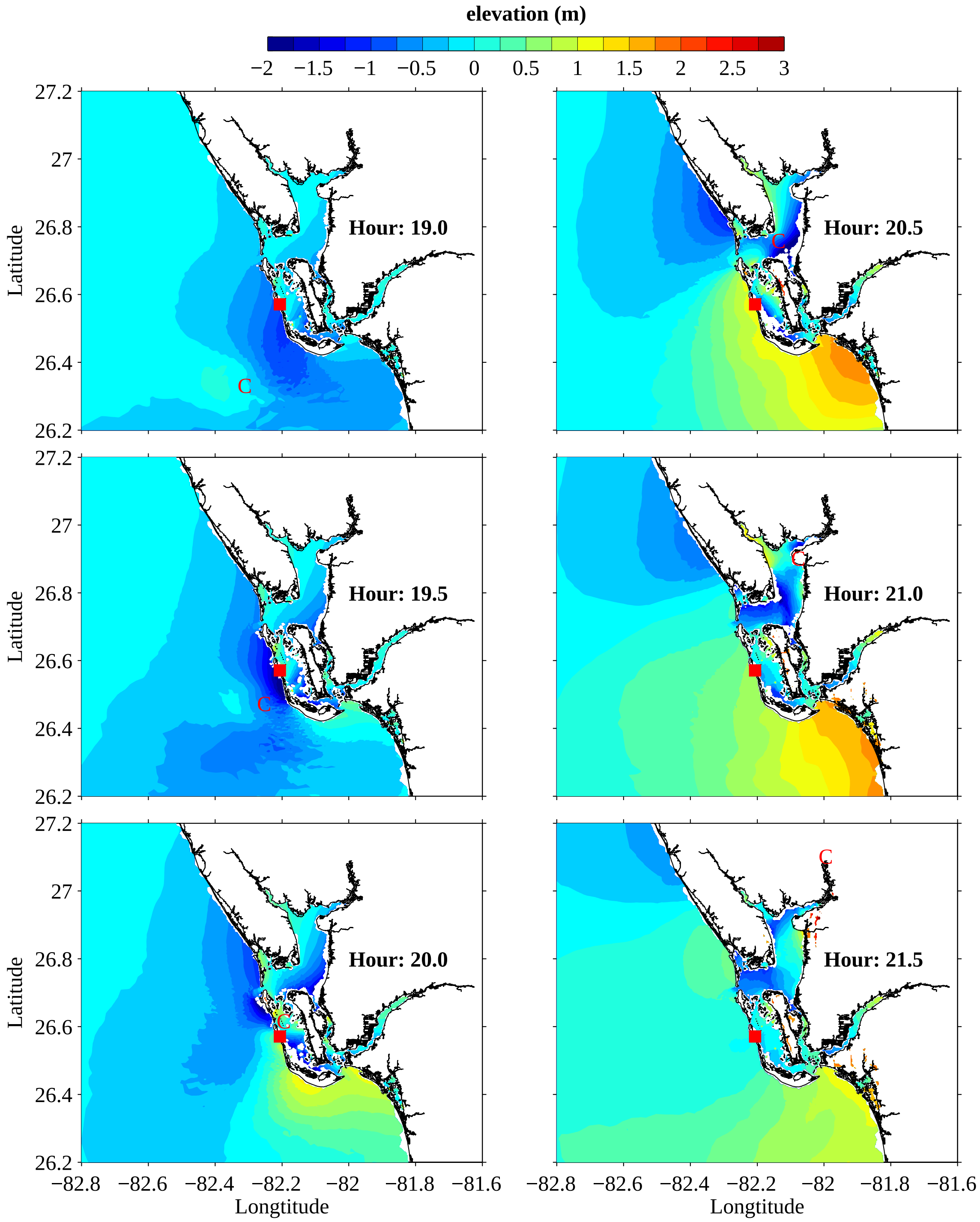

Fig. 6: Model simulated sea level evolution from 1900 to 2130 in half-hourly snapshots. The C denotes the hurricane eye location, and the filled square denotes the breach location on North Captiva Island.

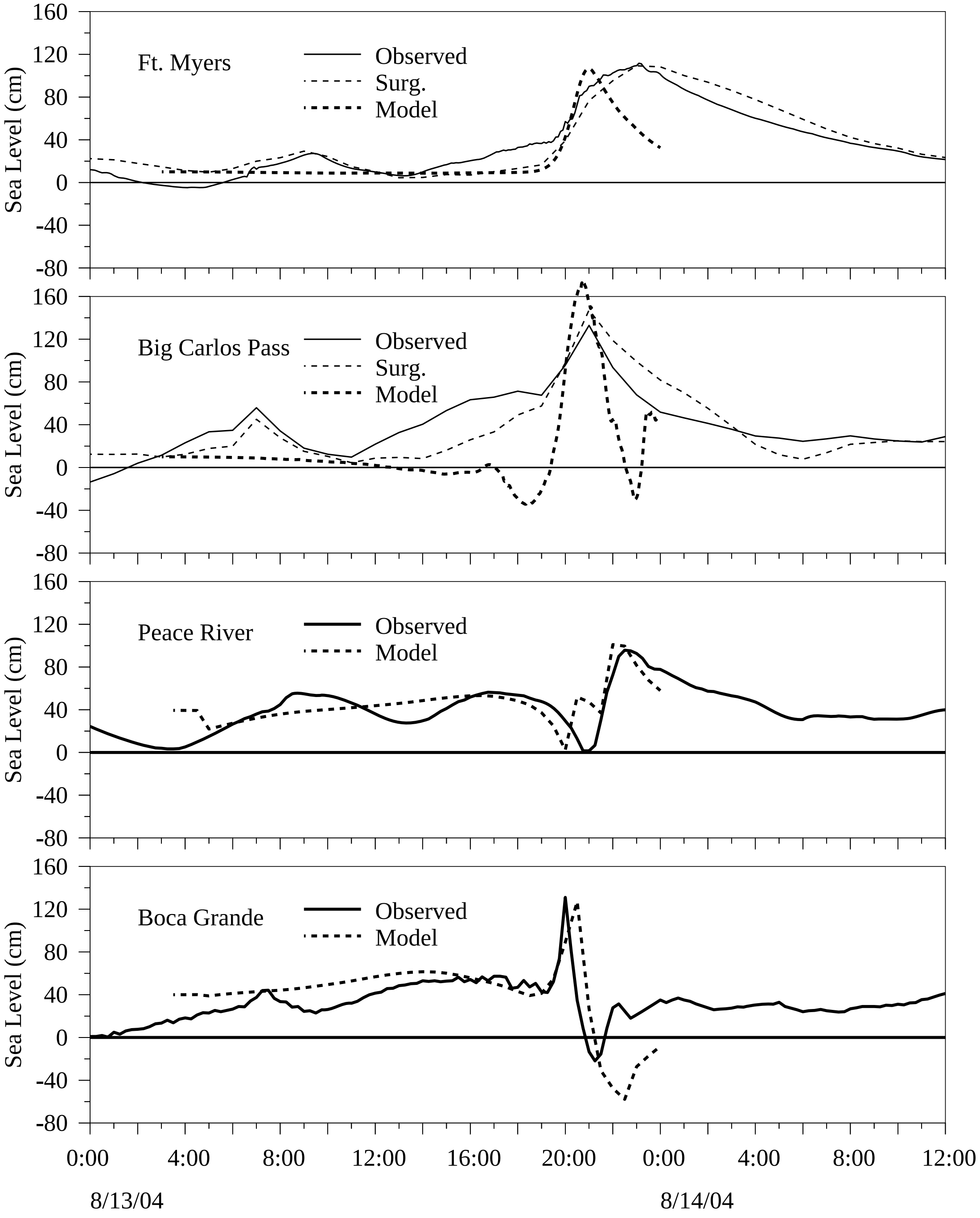

Fig. 7: Time series comparisons for observed and simulated sea levels at Ft. Myers, Big Carlos Pass, Peace River, and Boca Grande Pass. The thin-dashed lines are observed, detided sea levels; the solid lines are observed sea levels; and the thick-dashed lines are the simulated sea levels.

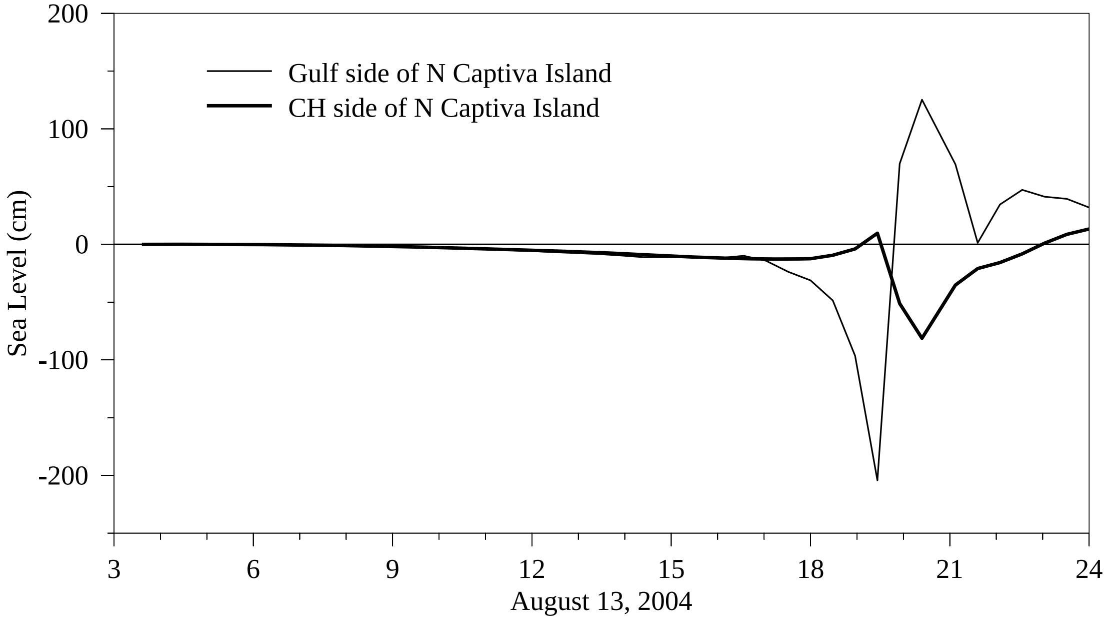

Fig. 8: Model simulated sea level time series sampled on the gulf (grey line) and sound sides (dark line) of the location in North Captiva Island where an inlet breach occurred.