Comparison of Observed and SLOSH model computed storm surge for hurricane Ivan (2004) along the north central Gulf of Mexico coastline.
March 2005

The Storm Surge Team of the Tropical Prediction Center/National Hurricane Center, NOAA, has received a copy of the U.S. Army Corps of Engineers (USACE) report on Tide Gauge Data for Hurricane Ivan. The Mobile District Engineering Division, Hydrology and Hydraulics Branch prepared the report in September 2004. The report contains the time history of the storm surge associated with the passage of Hurricane Ivan observed at 23 tide gauges. High-water elevations are included for an additional nine points. Non-verbatim quoting from the report:

The USACE maintains a network of tide gauges along the Gulf Coast from Gulfport, MS eastward to Carrabelle, FL. Three USCACE gauges were removed prior to storm landfall in anticipation of equipment and data loss. Of the remainder five USACE gauges were destroyed and three malfunctioned. For the report data from 4 USGS gauges in the affected area were used to fill in gaps in the USACE record. Non-gauge high water marks were obtained at or near the sites where the USACE gauges were removed, destroyed or malfunctioned.

The high water marks include "inside high water marks" inside of structures, which generally reflect the storm tide elevation without the effect of waves, and "outside high water marks" which generally reflect the combined effect of storm tide and wave set up and run up. Outside high water mark elevations are generally higher than inside high water marks because of the added wave effects. In this particular location on the outer coastline of the Gulf of Mexico the additional "breaking wave effects" that are being produced on top of the storm surge can increase the observed water elevations in shoreline structures by a factor of 100 to 200 percent. For example, if the storm tide was observed to be 10 feet above NGVD at a tide gage just offshore then values ranging from 10 to 30 feet above NGVD could be measured in structures along the shoreline. Out of the 9 surveyed coastal high water marks the surveyors labeled 6 as inside high water marks and 3 as outside high water marks. In addition to the 9 high water marks 23 tide gage maxima were also available and were added to give a total of 32 values. The purpose of this report is to compare these observed high water marks with the SLOSH storm surge model calculated values at the same location.

The reference datum used for the high water marks in this study is the National Geodetic Vertical Datum of 1929 or NGVD. This is where sea level was in 1929 and this was the Azero@ elevation. Since 1929 the tide gages along the northern Gulf of Mexico coast show a rise in sea-level ranging from 1.1 ft. at Waveland, MS to 0.4 ft. at Panama City, FL. The average rise is about 0.6 feet. To take the rise in sea level into account for the high water marks the Ivan SLOSH model simulation will include 0.6 feet in the initial water elevation. Also, during landfall the peak storm surge occurred approximately near the time when the coastal astronomical tide elevation was at 0.3 feet MSL. Thus the initial water elevation was increased to 0.9 feet to take the tide into account. Finally, before the arrival of Ivan, the tide gages showed a rise of water along the northern Gulf of Mexico of approximately 0.6 feet. This initial rise of water is termed the pre-storm tide anomaly. Therefore, the final initial water height for the SLOSH model run will be 1.5 feet above NGVD.

The Pensacola Bay, Apalachicola Bay, and New Orleans SLOSH Basins

The SLOSH model is a numerical storm surge model that computes water elevations generated by the wind and pressure forces in a tropical cyclone. Part of the model is a grid, covering the area of interest, which contains land elevations, water depths and vertical barriers, which can impede storm tide flooding. All of these are referenced to NGVD. The grid is termed a basin and given a name. The basins covering the north central Gulf of Mexico, where Ivan made landfall, are called Pensacola Bay, Apalachicola Bay and updated New Orleans. Figure 1 shows the three basins and their associated grids. Another part of the SLOSH model allows a tropical cyclone track and intensity as input and creates a wind and pressure field, which is passed through the grid. This in turn, moves the water in the grid numerically and creates a storm surge-flooding pattern. This is termed a SLOSH model run. The history of the water elevation is saved in each grid cell and the maximum for each grid cell is displayed in what is termed the Envelope Of High Water (EOHW). The EOHW is commonly compared against high water mark observations.

Comparison of Observed High Water Marks to SLOSH Values

A SLOSH model run was made in each of the three basins using Ivan track and intensity data as input. The EOHW for the SLOSH model runs are shown in Figures 2a, 2b and 2c. Shown in Figure 3 are Ivan’s track and a circle representing the location of the maximum winds near Ivan's landfall in the Pensacola Bay SLOSH basin. The radial distance of this circle is called the Radius of Maximum Winds (RMW) and is usually given in statute miles. The RMW for Ivan near landfall and during its progression inland was approximately 40 miles. This RMW value is a little large climatology speaking and a more typical value would be 20 to 25 miles. The EOHW shows the storm surge that was largely generated by the strong wind field ahead of and to the right of the hurricane. These strong winds created currents in the Gulf of Mexico that moved toward the shorelines and piled water up on the islands, the mainland and inside the bays. In several locations the barrier islands were over-topped and eroded and Gulf of Mexico water spilled into the bays and sounds behind. This caused higher storm surge flooding than would normally be expected if the barrier islands had remained intact. The height of the water is given by a color code and all heights are referenced to NGVD. On the outer coast, a large area experienced storm surge elevations of 8 feet or greater with the SLOSH model runs. The maximum storm surge values of approximately 10 feet occurred in an area from Pensacola Beach, Florida westward to Gulf Shores Alabama. The Pensacola SLOSH EOHW also shows a higher maximum of 11 to 12 feet within Escambia Bay. Figures 4a, 4b, 4c are snap-shots of the SLOSH model wind field for the 3 basins when the hurricane's center is located near landfall just to the west of Gulf Shores. The wind arrows are blowing parallel to the wind. The barbs on the end of the arrow represent the wind speed in knots. A full barb is 10 knots, a half barb is 5 knots and a flag is 50 knots. The wind speed on any wind arrow is obtained by adding up the barbs and flags. For example, the wind speed over Gulf Shores is approximately 75 knots and the wind speed at the RMW near Pensacola about 95 knots. Figure 5a shows the locations of high water marks and their values as reported by USACE. The high water marks in Figure 5a were compared to the SLOSH generated EOHW values shown in Figures 2a, 2b and 2c. The results are listed in Table 1.

A histogram of the differences (SLOSH minus observed) is shown in Figure 6. The error characteristics are indicated in the legend: Sixty-six (66) percent of the differences fall between plus 1.0 to minus 1.0 feet (plus or minus one standard deviation) while 97 percent are in the range plus 2.0 to minus 2.0 feet. Also to be noted is the negative average bias of the SLOSH results. This is due, in large part, to the fact that the SLOSH model does not compute breaking wave effects. Also adding to this negative bias may be the erosion of barriers, such as sand dunes and roadways, due to the rising storm tide and breaking waves. Subsequent over-topping of these lowered barriers may lead to additional water in bays and sounds with resulting higher measured water marks. Although the SLOSH model computes over-topping of barriers, it maintains invariant barrier elevations during a simulation. Figure 6 is otherwise similar to case studies on other individual hurricanes where the SLOSH model results were compared to observed high water marks.

Some preliminary experiments were conducted with SLOSH to emulate the portions of the Pensacola Bay basin in which the 10+ ft. barrier island dune elevations were reduced to near grade level. The results showed increased storm surge along the north side of Santa Rosa Sound, similar to values measured by survey contractor, URS Inc.

Comparison of Tide Gage and SLOSH Storm Surge Hydrographs

Observed storm surge hydrographs from a number of the gauges were compared to the SLOSH model-generated storm surge hydrographs for the same location based upon hurricane Ivan input parameters. As an example Figure 7 shows the National Ocean Service's tide gage record at Pensacola, Florida. At this location the gage malfunctioned before the maximum was reached. A high water mark was measured nearby at 10.2 feet above NGVD. This is very likely close to the maximum that the gage would have observed if it had continued to function. The SLOSH model does an excellent job in capturing the rate of rise of the storm surge and calculates a maximum of 10.4 feet. Comparisons are also shown for GIWW at West Bay, Florida and USACE gauges at Biloxi Bay, MS (Pt. Cadet).

Conclusions

For hurricane Ivan (2004), comparison of 32 observed tide gauge high water marks along the north central Gulf of Mexico coastline yielded typical storm surge model error characteristics, with differences between the observed high water marks and the SLOSH generated values showing that 66% of the values fall between plus 1.6 to minus 1.6 feet and 97% are within plus 3.2 to minus 3.2 feet.

Comparison of the observed storm surge hydrographs to the SLOSH model calculated storm surge hydrographs showed reasonable results.

Recommendations

Based upon the above results it is recommended that the following be done:

1. The SLOSH basins for Pensacola and Apalachicola Bays should be reconfigured with a finer mesh of grid cells and that the latest measured water depths and land elevations be used to do this. Ground controlled LIDAR data should be utilized if available. Especially important will be studies of the barrier islands where overwash and overtopping has reduced the sand dune elevations in locations where those barriers will not quickly be rebuilt.

2. A series of hypothetical hurricanes, based upon hurricane climatology, should be run using these new SLOSH basins to determine the hurricane storm tide flood plain. Also, small compact hurricanes, similar to hurricane Charley that occurred earlier in 2004, as well as Ivan-sized hurricanes, should be included in the hypothetical runs.

Table 1. Observed peak storm tide and SLOSH–calculated peak storm tide at location of the observations*

Tide Gage Designation	OBSERVED (ft. NGVD)	SLOSH (ft. NGVD)
Mississippi Sound at Waveland, MS (USGS)	4.56	4.0
Gulfport Harbor at Gulfport, MS (540)	4.63	4.2
Mississippi Sound at Ship Island	5.15	5.2
Biloxi Bay at Point Cadet	4.23	3.8
West Pascagoula River at Hwy. 90 at Gautier, MS	4.10	3.8
Pascagoula River (NOAA) at Pascagoula, MS	6.72	7.1
Mississippi Sound at Pascagoula PI-Rear Range	5.83	7.0
Mississipp Sound at Petit Bois Island	4.83	4.8
Escatawpa Riverat I -10 nr Orange Grove, MS	3.93	4.1
Middle Gage at Bayou LaBatre	4.66	3.4
Mobile Bay at Cedar Point, AL	6.90	7.1
Dauphin Island Bay at Dauphin Island	7.80	7.3
Mobile Bay at Dauphin Island (USCG)	8.00	7.5
Mobile River at Mobile, AL	4.87	4.4
Mobile Riverat Bucks, AL (Barry Steam Plant)	6.82	6.0
Mobile Bay at Ft. Morgan Front Range	7.85	7.8
Perdido Pass Orange Beach, AL	8.81	5.6
GIWW at Pensacola Gulf Beach, FL	9.68	9.2
Pensacola Bay at Ft. McRee, FL (USCG)	9.70	9.7
Pensacola Bay at Penscola, FL (NOAA)	10.20	9.0
Escambia Bay West Bank at Hwy 90	12.92	10.3
Escambia Bay West Bank at 1.5 miles N. of I-10	12.12	9.9
GIWW at Gulf Breeze, FL	10.30	8.3
Yellow River nr. Milton, FL	9.66	9.2
Fort Walton Brooks Bridge	6.12	4.6
Destin at Choctawachee Bay (SCG)	5.39	5.4
GIWW at Choctawhachee Bay (Hwy 331)	5.51	3.9
GIWW at West Bay, FL	6.60	6.2
St. Andrew Bay at Panama City, FL	4.94	5.5
Apalachicola River at Apalachicola, FL	5.10	4.3
GIWW at St. George Island, FL	3.55	4.0
Carrabelle River at Carrabelle, FL	5.04	4.3

*Observations from USACE report on tide gauge data for Hurricane Ivan

Figure Captions

Figure 1a. Pensacola, FL SLOSH Basin

Figure 1b. Apalachicola Bay, FL SLOSH Basin

Figure 1c. New Orleans, LA SLOSH Basin

Figure 2a. The SLOSH model Envelope of High Water (EOHW) for Pensacola Bay, FL

Figure 2b. The SLOSH model Envelope of High Water (EOHW) for Apalachicola Bay, FL

Figure 2c. The SLOSH model Envelope of High Water (EOHW) for New Orleans, LA

Figure 3. Ivan's track and a circle representing the location of the maximum winds near landfall in the Pensacola Bay SLOSH basin

Figure 4a. Snapshot of the SLOSH model wind field for Pensacola Bay, FL near the time of Ivan's landfall

Figure 4b. Snapshot of the SLOSH model wind field for Apalachicola Bay, FL near the time of Ivan's landfall

Figure 4c. Snapshot of the SLOSH model wind field for New Orleans, LA near the time of Ivan's landfall

Figure 5a. Map of High Water Marks, from USACE report

Figure 5b. Observed and SLOSH-predicted peak storm tide plotted by location of the observations. Also shown is a +/- 20% band surrounding the observations.

Figure 6. SLOSH Storm Tide values minus Observed High Water Marks for Hurricane Ivan

Figure 7a. National Ocean Service tide gage record at Pensacola, Florida compared to the Storm Surge SLOSH Model time history of water elevation in the nearby model cell.

Figure 7b. USACE tide gage record at West Bay, Florida compared to the Storm Surge SLOSH Model time history of water elevation in the model cell containing the gauge location.

Figure 7c. USACE tide gage record at Biloxi Bay, MS compared to the Storm Surge SLOSH Model time history of water elevation in the model cell containing the gauge location.

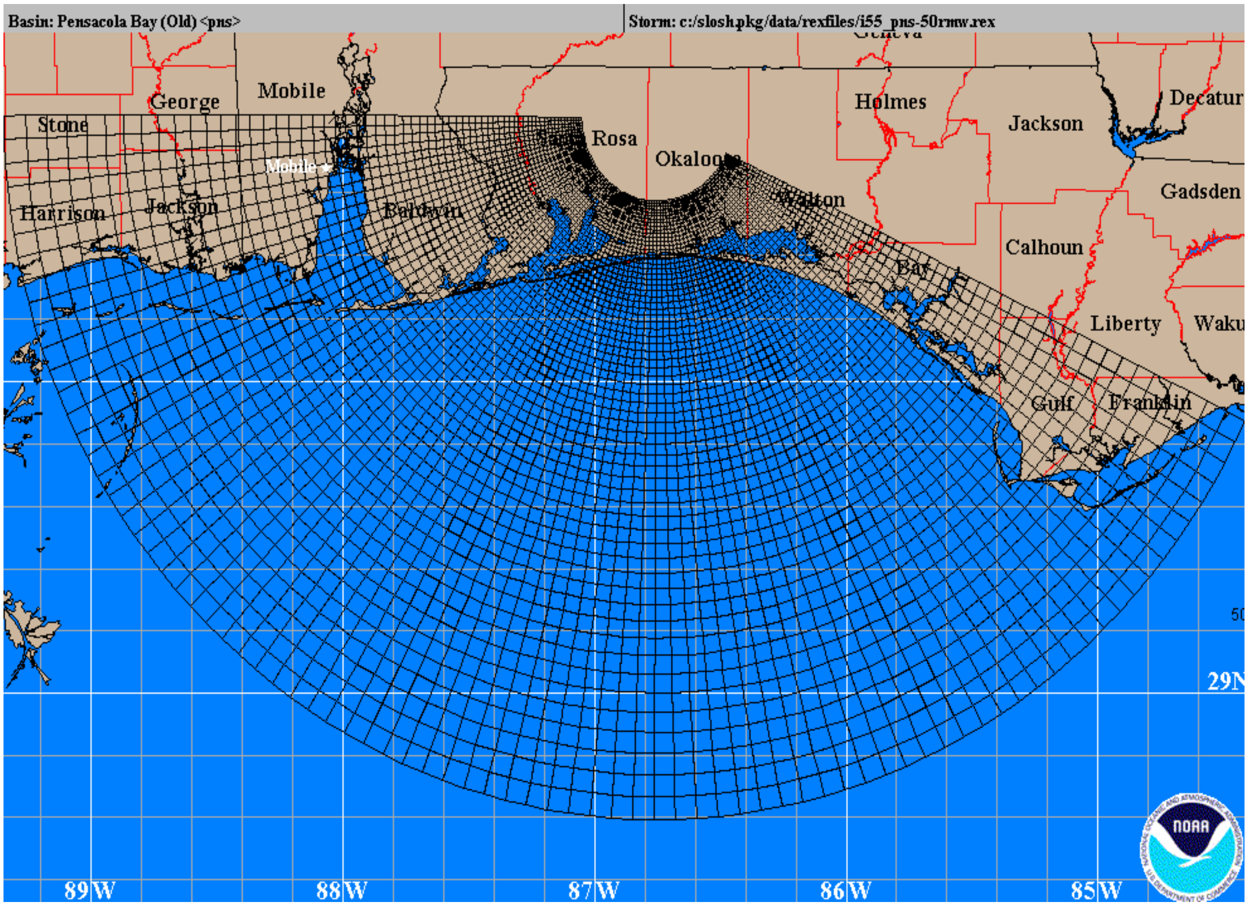


Figure 1a. Pensacola, FL SLOSH Basin

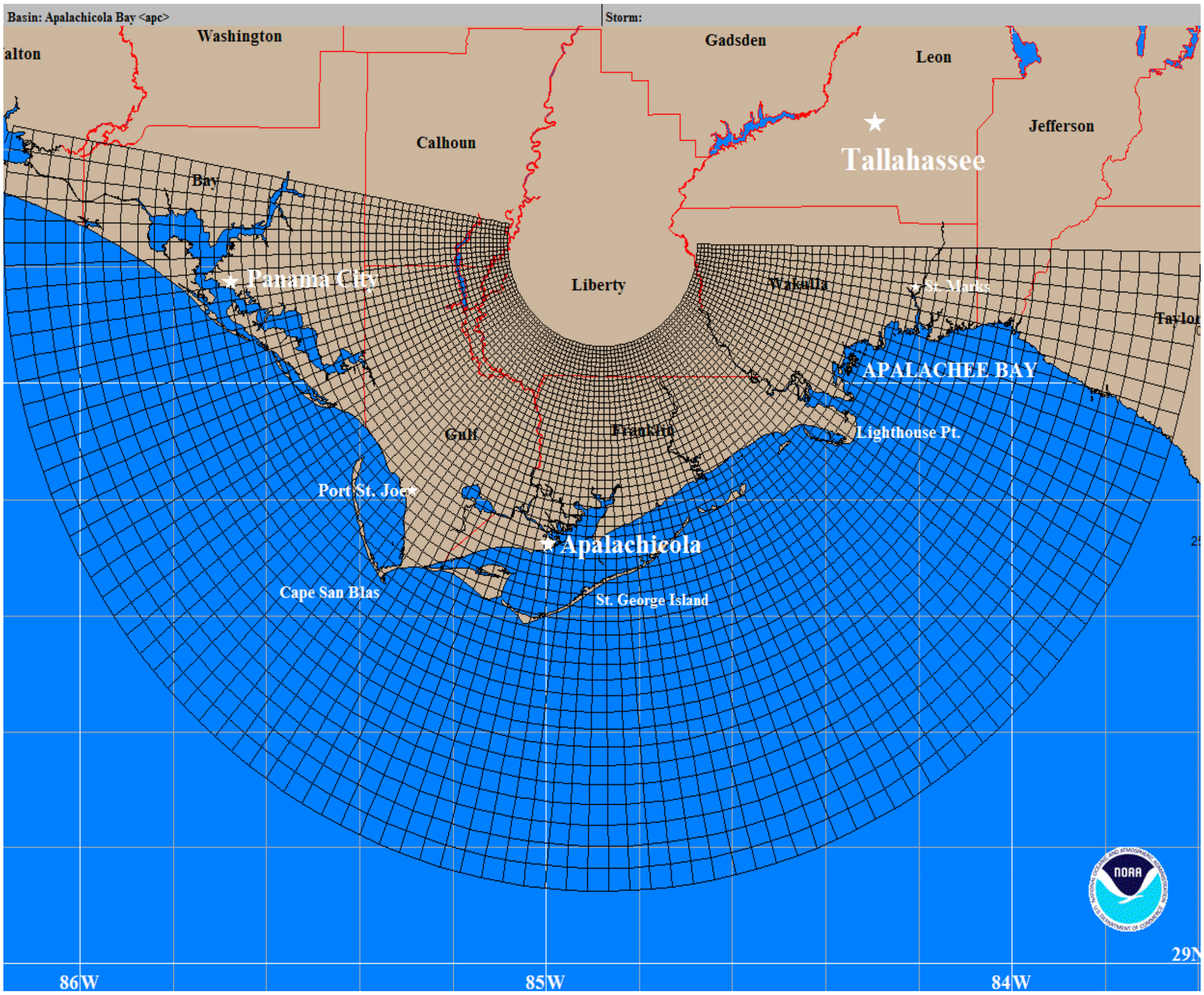


Figure 1b. Apalachicola Bay, FL SLOSH Basin

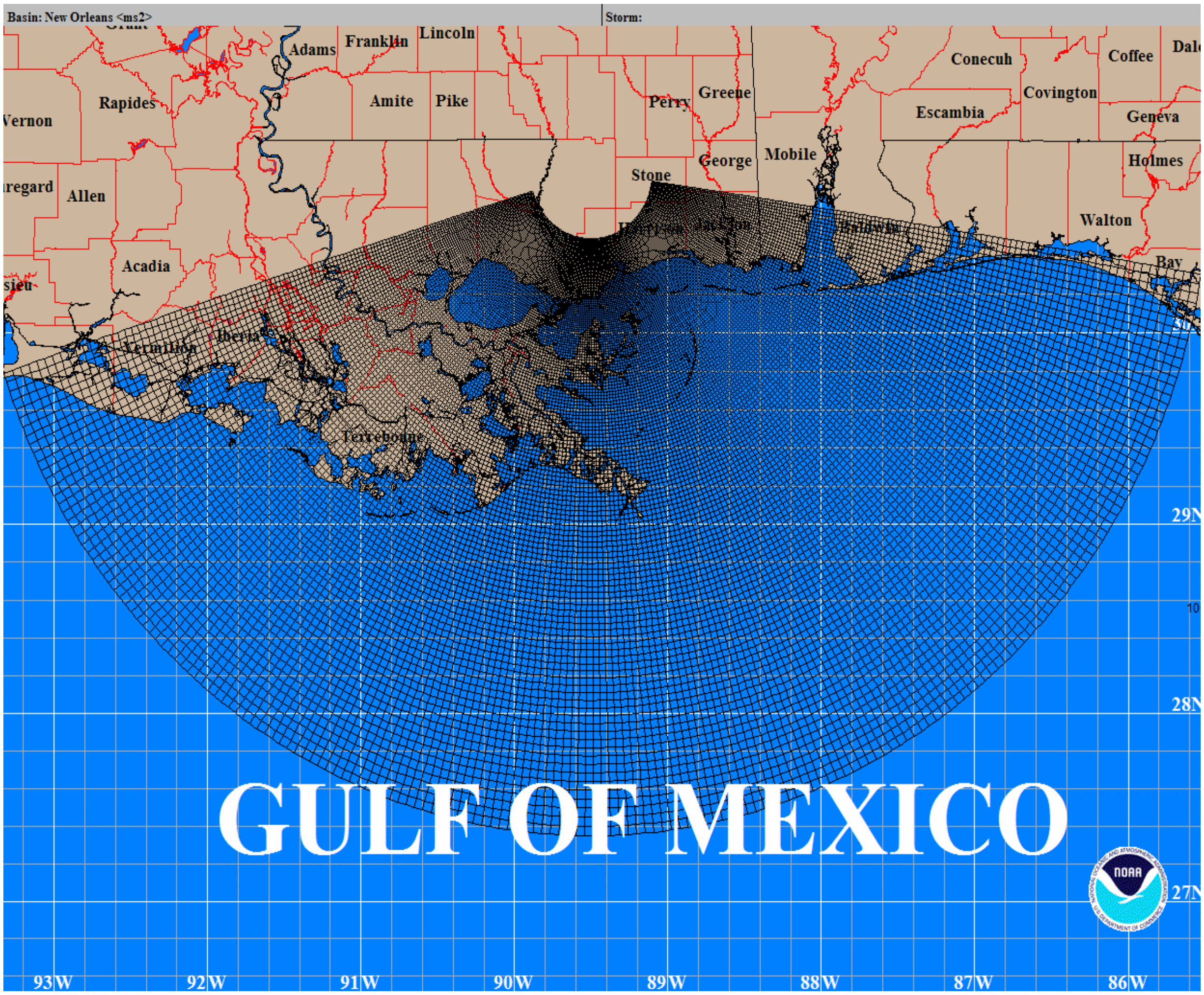


Figure 1c. New Orleans, LA SLOSH Basin

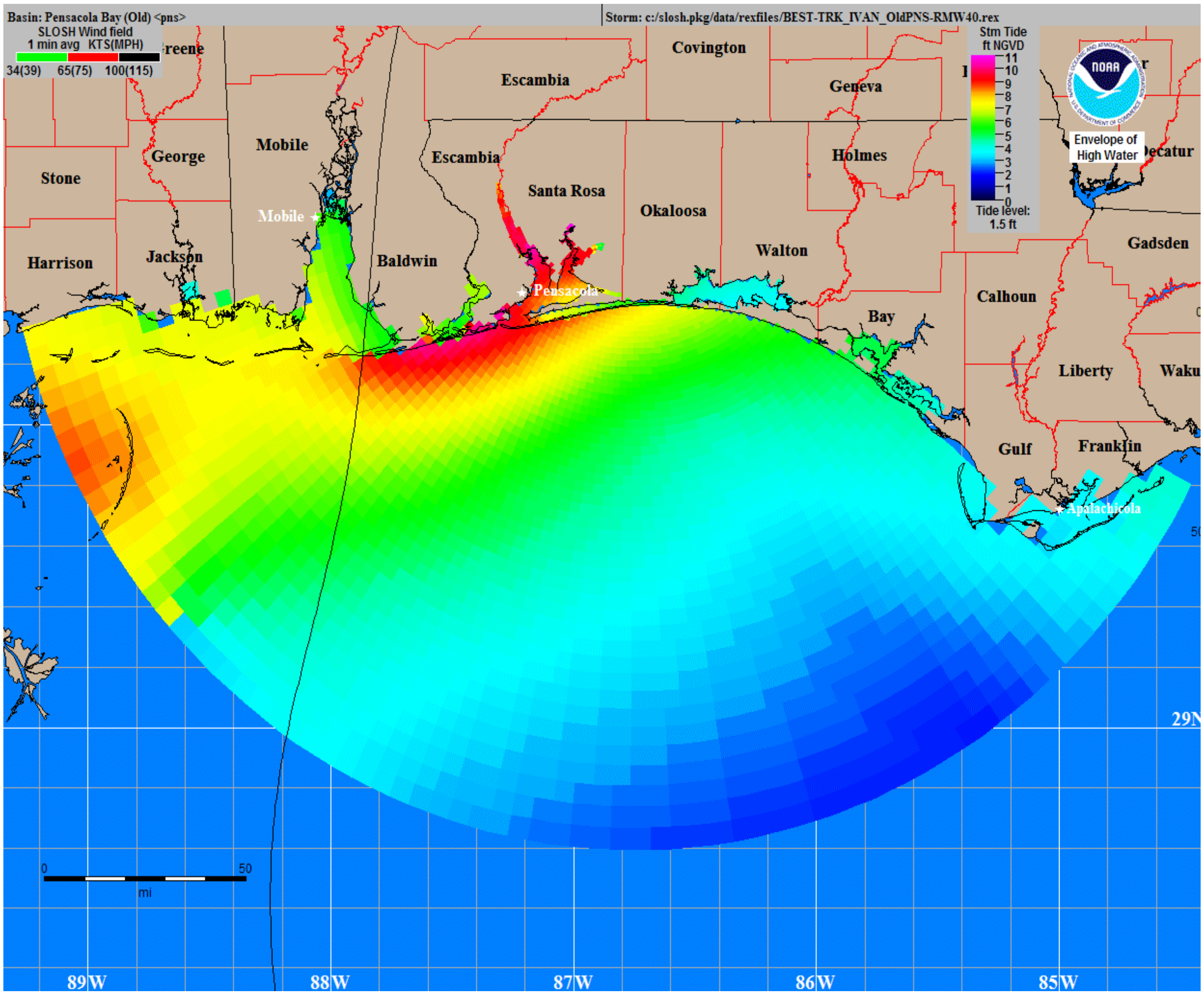


Figure 2a. The SLOSH model Envelope of High Water (EOHW) for Pensacola Bay, FL

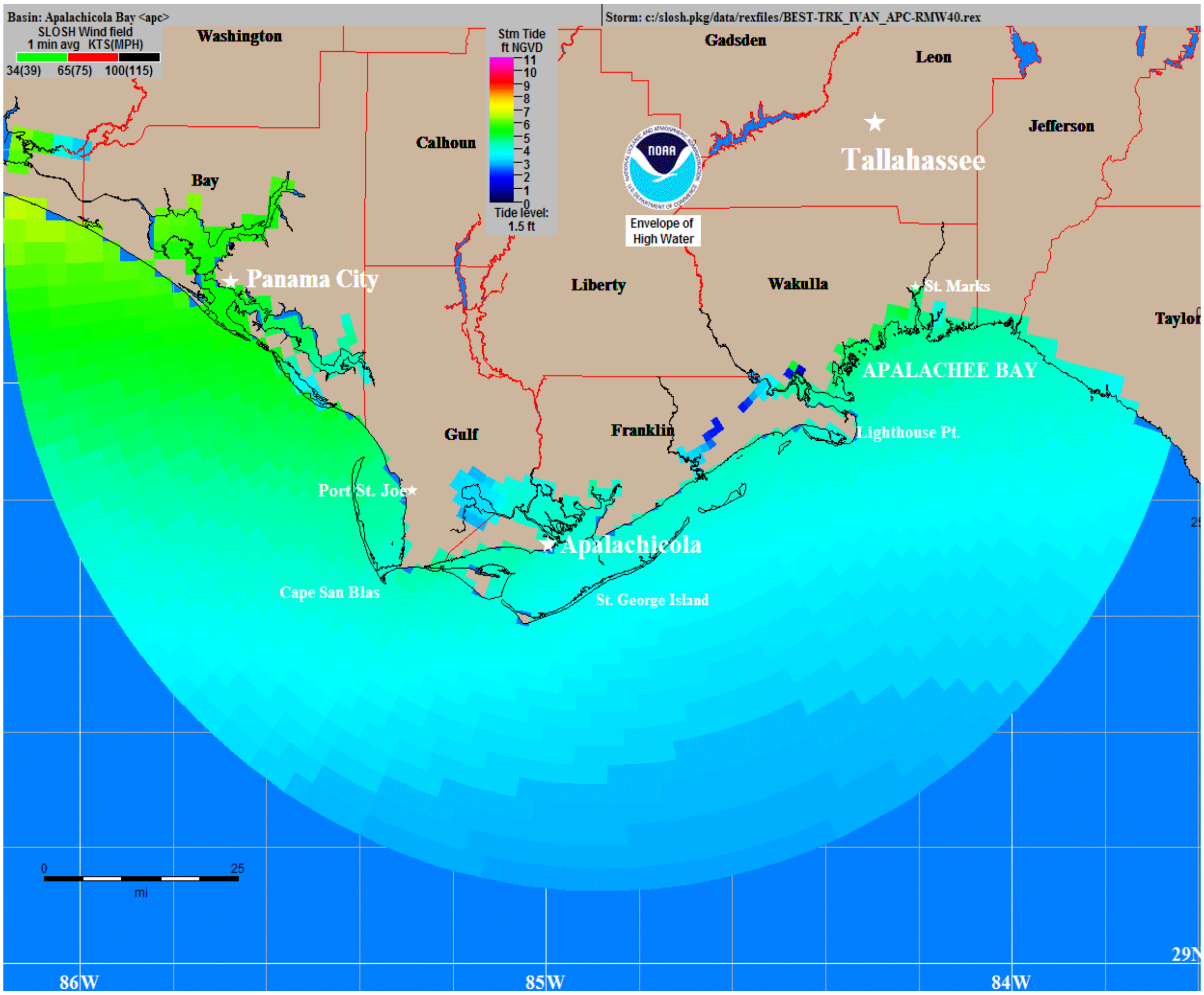


Figure 2b. The SLOSH model Envelope of High Water (EOHW) for Apalachicola Bay, FL

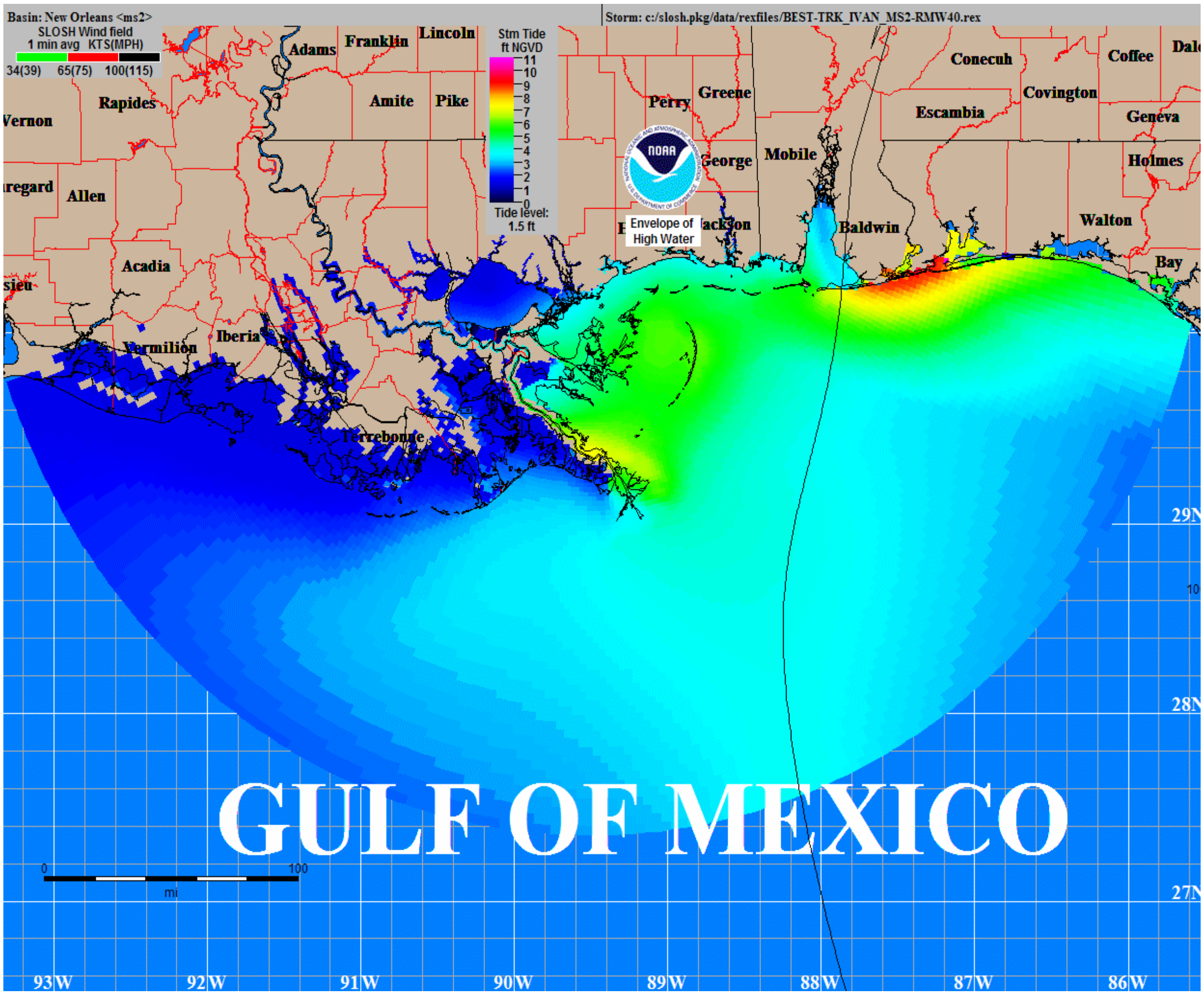


Figure 2c. The SLOSH model Envelope of High Water (EOHW) for New Orleans, LA

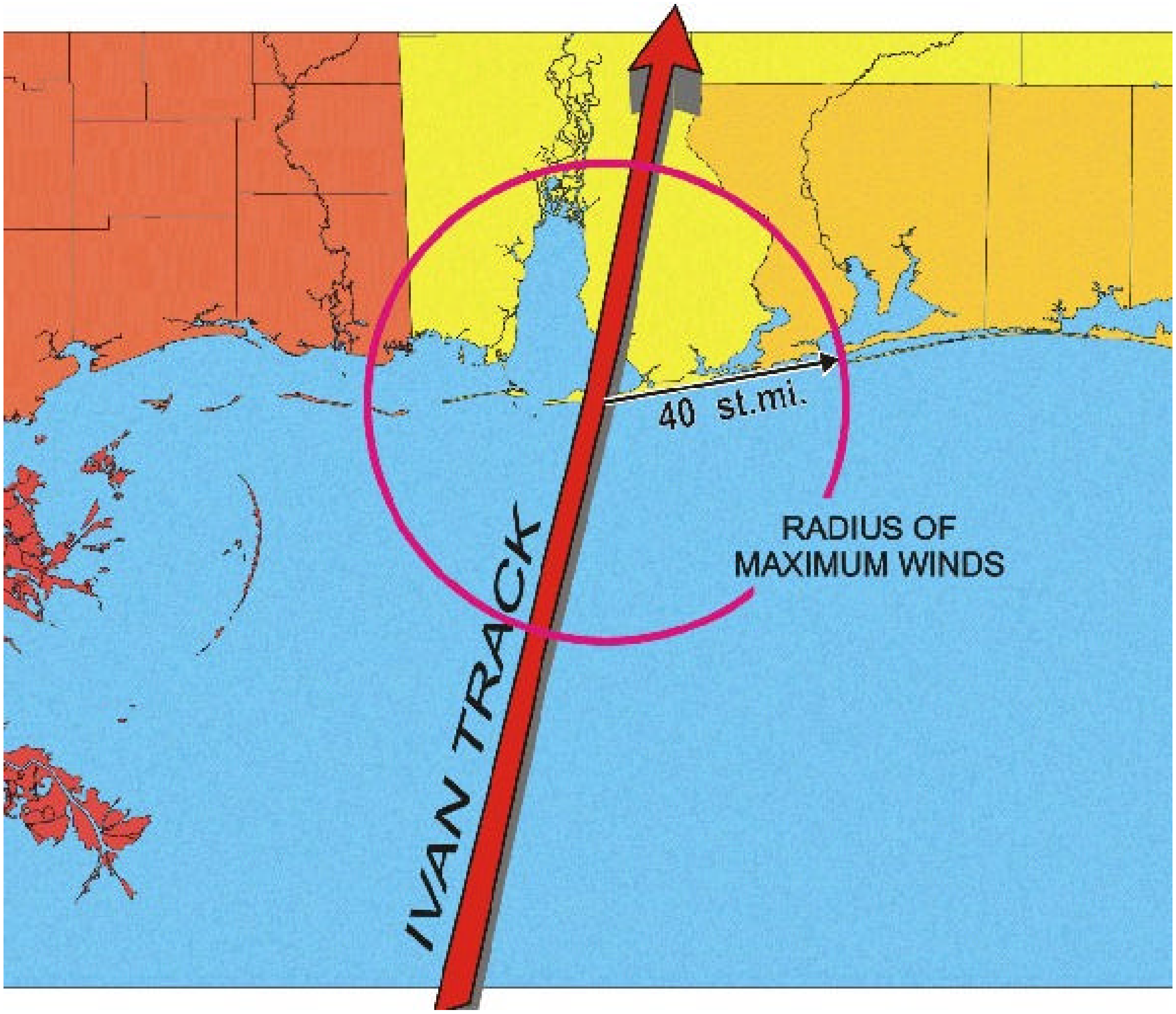


Figure 3. Ivan’s track and a circle representing the location of the maximum winds near landfall in the Pensacola Bay SLOSH basin

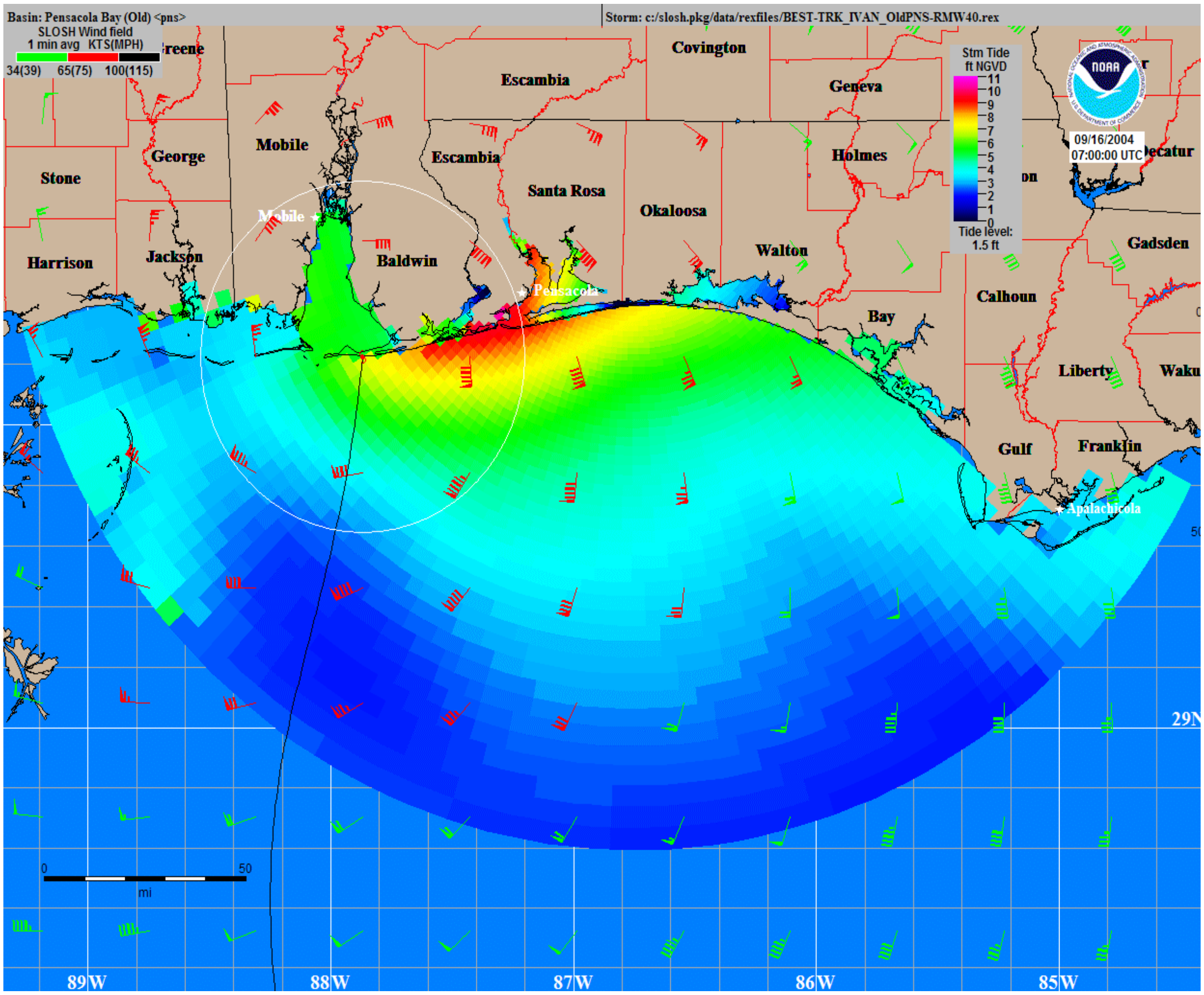


Figure 4a. Snapshot of the SLOSH model wind field for Pensacola Bay, FL near the time of Ivan's landfall

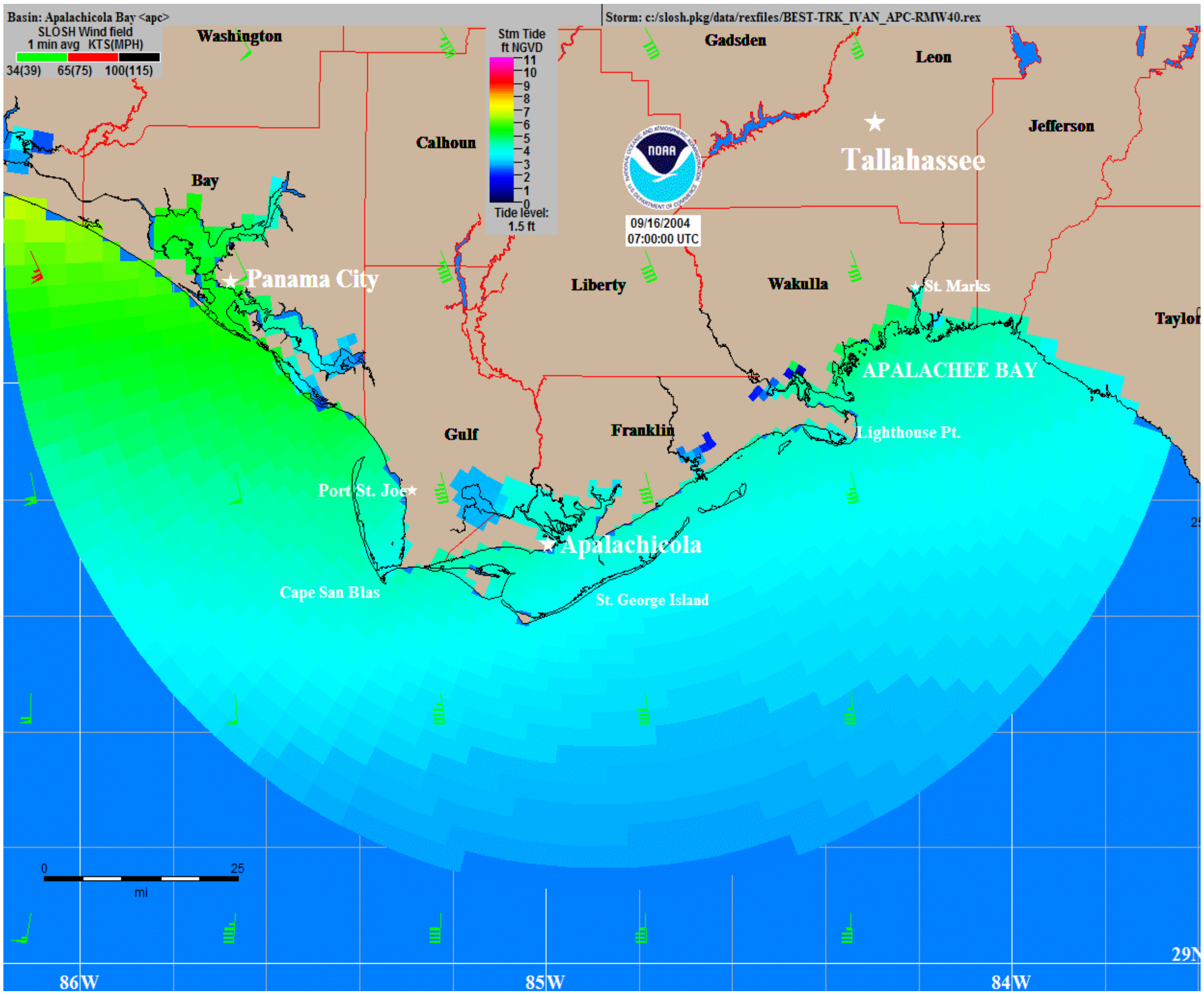


Figure 4b. Snapshot of the SLOSH model wind field for Apalachicola Bay, FL near the time of Ivan's landfall

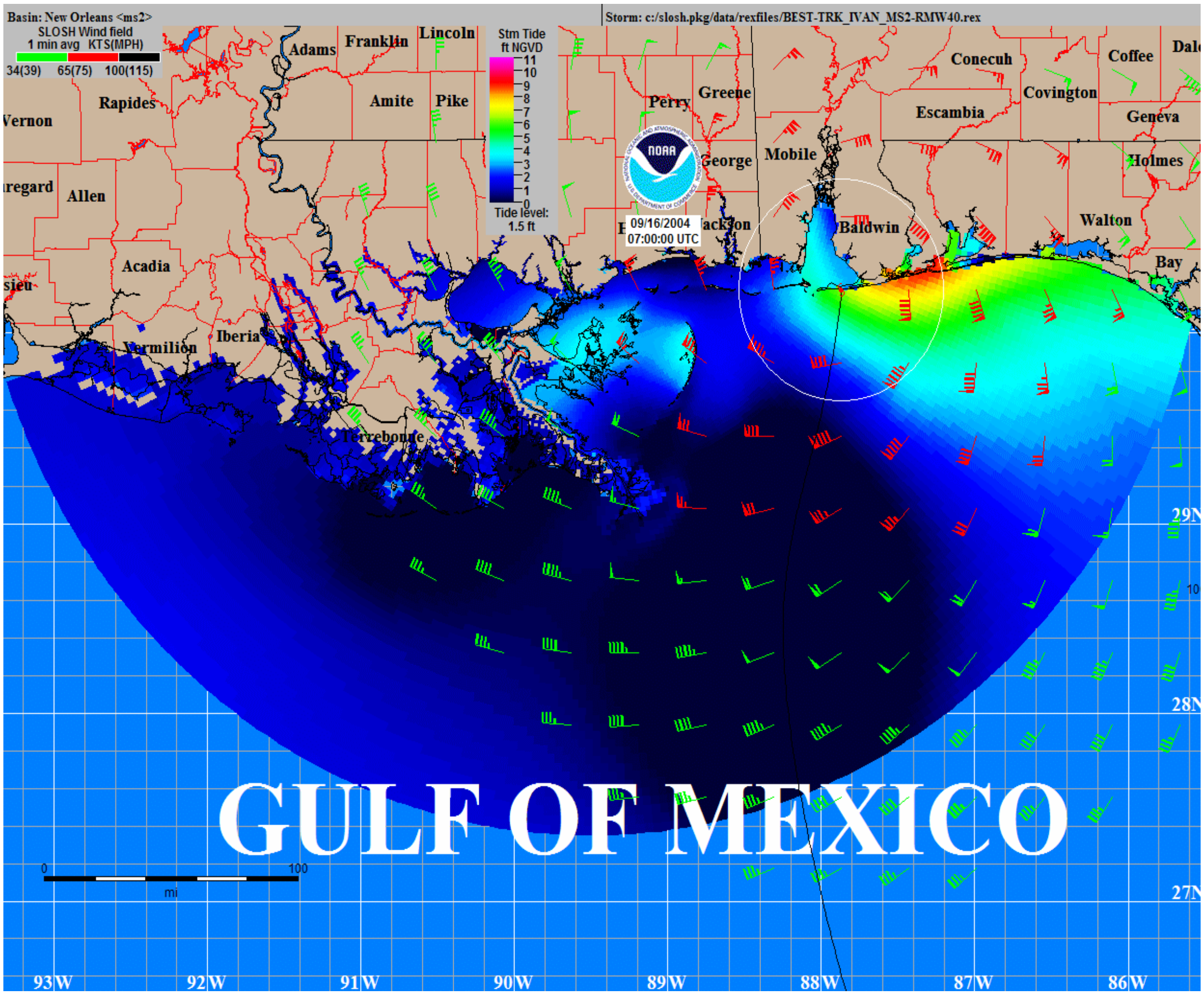


Figure 4c. Snapshot of the SLOSH model wind field for New Orleans, LA near the time of Ivan's landfall

Figure 5. Map of High Water Marks, from USACE report

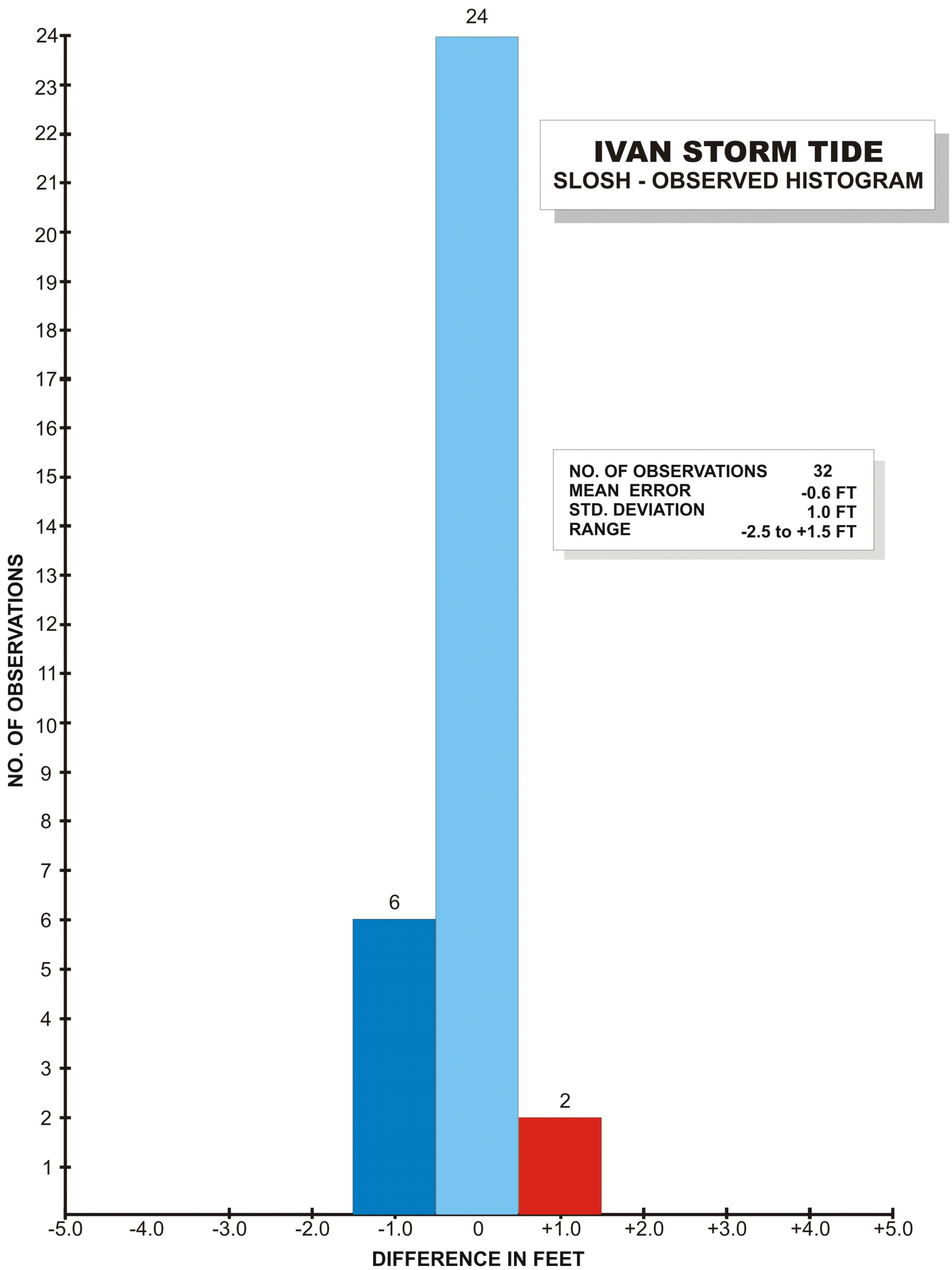
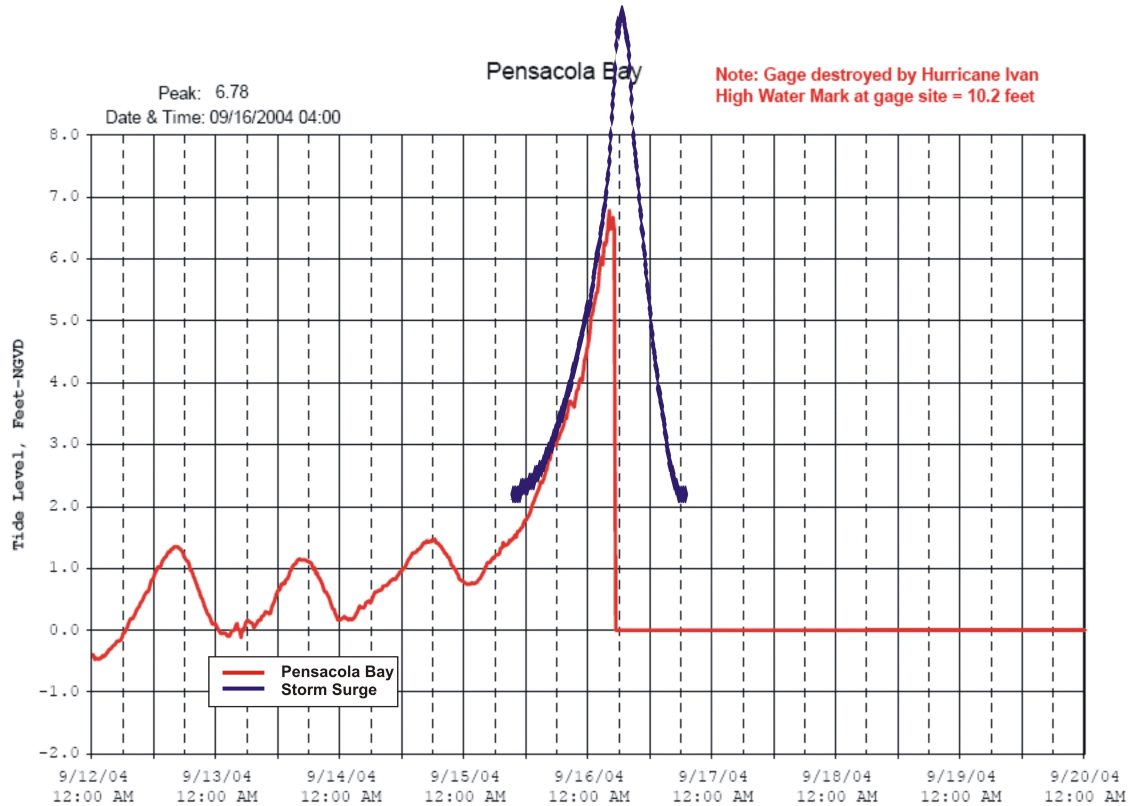


Figure 6. SLOSH Storm Tide values minus Observed High Water Marks for Hurricane Ivan



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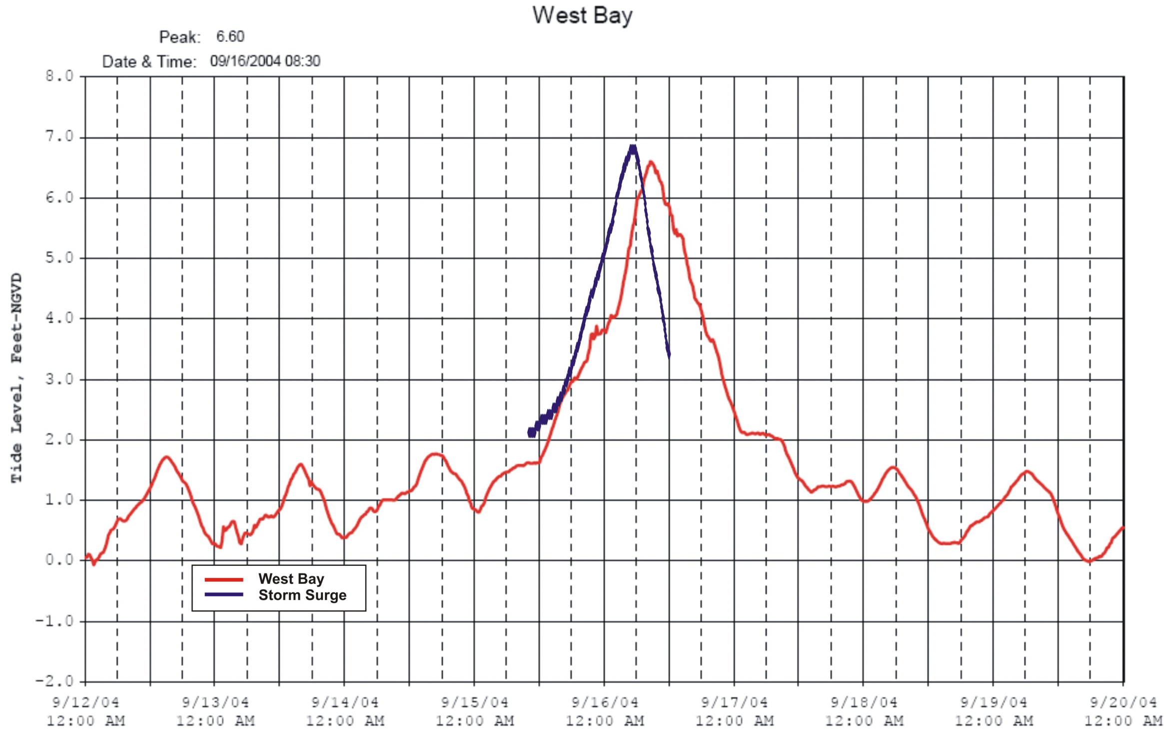

Figure 7b. USACE tide gage record at West Bay, Florida compared to the Storm Surge SLOSH Model time history of water elevation in the model cell containing the gauge location.

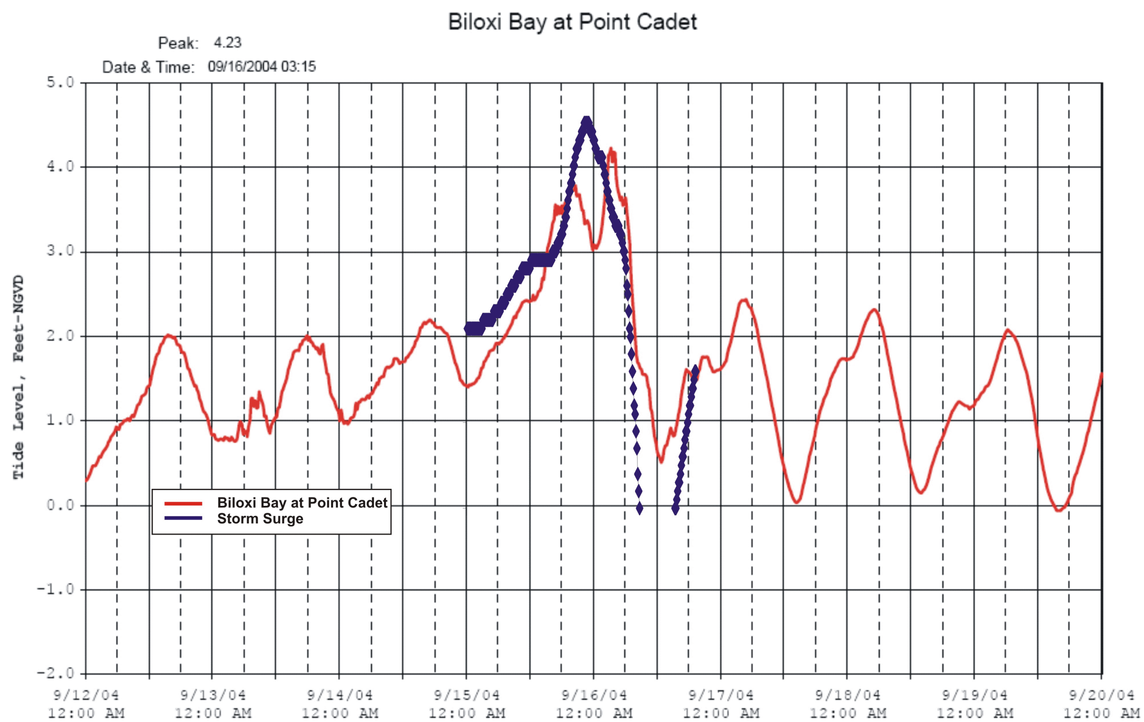

Figure 7c. USACE tide gage record at Biloxi Bay, MS compared to the Storm Surge SLOSH Model time history of water elevation in the model cell containing the gauge location.