HURRICANE STORM SURGE FORECASTING

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ABSTRACT

The National Weather Service (NWS) has developed a hurricane storm surge model called SLOSH (Sea, Lake, and Overland Surges from Hurricanes) to compute hurricane storm surges, given storm data as input. The numerical model incorporates a dynamic coastline, overland flooding, and sub-grid features such as barriers, cuts between barriers, and one-dimensional flow along channels of varying width. The SLOSH model has been applied to most of the United States' Gulf of Mexico and Atlantic coastlines vulnerable to hurricanes. A description of the model's use and limitations for hurricane storm surge forecasting is presented. Some specific examples of the use of SLOSH are drawn from Hurricane Elena, 1985.

In addition to SLOSH's use for real-time surge forecasting, SLOSH is used extensively in hurricane evacuation planning. The model is run with several hundred hypothetical hurricanes, selected according to an area's climatology. The model generates the flooding expected for each storm. Combining these flooding patterns helps to determine an area's vulnerability to hurricanes. Also, model-generated winds assist planners in determining when evacuation routes may be shut down due to high wind. State and local agencies integrate this information with population studies and road capacity estimates to develop a comprehensive evacuation plan. One outcome of such a plan is the "evacuation time"--the lead time needed for a safe evacuation of a coastal area from an impending hurricane.

1. INTRODUCTION

Storm surge--the significant increase in water level caused directly by a storm--poses the most serious threat to life along the coast from a hurricane. Looking back over past events, the hurricane of 1900 that hit Galveston, Texas resulted in between 5000 and 6000 deaths. This storm ranks as the most devastating weather-related disaster for the United States. Galveston Island was completely overtopped by the surge generated by this great hurricane. Most of the deaths resulted from drowning; virtually every building on the island was destroyed.

More recently, hurricane Camille in 1969 devastated the Gulf Coast in the Gulfport, Miss. area with a peak surge measuring 24 feet! This section of coastline was threatened again in 1985 by hurricane Elena. However, the region was spared from high surges because of a fortuitous track. Had Elena travelled further south and out to sea, then surges could have reached 13 to 15 feet over most of the coast from Bay St. Louis to Biloxi, Miss. Damage from Elena, however, was confined to wind-related problems, with only minor storm surge damage.

The NWS has long recognized the threat of storm surges along our coasts, especially in light of today's extensive coastal development. Two numerical models have been developed in the NWS's attempts to forecast surge heights for an impending hurricane. First came the SPLASH model, which stands for Special Program to List the Amplitude of Surges from Hurricanes. This model computes surges up to and including coastlines, unbroken by bays or estuaries. A more sophisticated model, SLOSH--for Sea, Lake, and Overland Surges from Hurricanes--extended the treatment of surges to include flooding over inland water bodies, as well as overland flooding. In addition, the model treats, in a simple fashion, adverse flow up rivers. For most areas of the Gulf of Mexico and Atlantic coasts, the SLOSH model has replaced SPLASH for all estimates of hurricane storm surge.

2. THE SLOSH MODEL

The SLOSH model is two-dimensional in space, covering the continental shelf, inland water bodies, and terrain. The equations of fluid motion are solved numerically, incorporating finite amplitude effects but dropping the advective terms from the equations of motion. SLOSH uses a time-history bottom stress (Platzman, 1963; Jelesnianski, 1967) corrected for finite amplitude effects. At any given point, the computed surge is designed to reproduce the time-history of a long-period gravity wave--the observed still water surge as shown in a tide gage hydrograph or stage record. Short period phenomena, such as wind waves and their associated run-up, are ignored.

All of the SLOSH basins use a polar grid with the exception of the Lake Okeechobee basin which uses a cartesian grid (Fig. 1). The main advantage of the polar gird is that resolution is enhanced in the area of interest and the boundary conditions are pushed far from the area of concern.

The SLOSH model must be tailored to a geographical area before it can be run. Values of terrain height or water depth must be supplied for each of the model's grid squares. Barriers which impede the flow of water must be represented. Such barriers include coastal sand dunes, natural ridges, reefs, levees, and other man made structures. Cuts between barriers must also be entered to properly allow for water flow. In addition, deep, narrow channels and rivers with varying widths are incorporated. These geographical data are extracted from literally hundreds of maps and charts. U.S. Geodetic Survey quadrangle maps and National Ocean Survey bathymetric charts are the most useful maps for our purposes. Imbedded within the SLOSH model is a hurricane wind model--perhaps the most important feature of SLOSH. Winds for the model are formed by specifying the hurricane's central pressure and its radius of maximum wind. A wind speed profile with respect to radius from the storm's center is assumed. The wind model balances forces so that wind, pressure, and inflow angle across isobars are in balance. Corrections to the wind speeds are made for forward storm motion, giving the storm an asymmetric characteristic. However, note that wind speed itself is <u>not</u> used as input to the model. Instead, wind is a computed variable within the model. One reason for this choice of variables is that winds are poorly defined within a hurricane. Much confusion exists between surface wind, aircraft wind, fastest-mile wind, one-minute average wind, etc. Experience by users is that the winds produced by SLOSH correspond most closely to observed 10-minute average winds for an overwater trajectory.

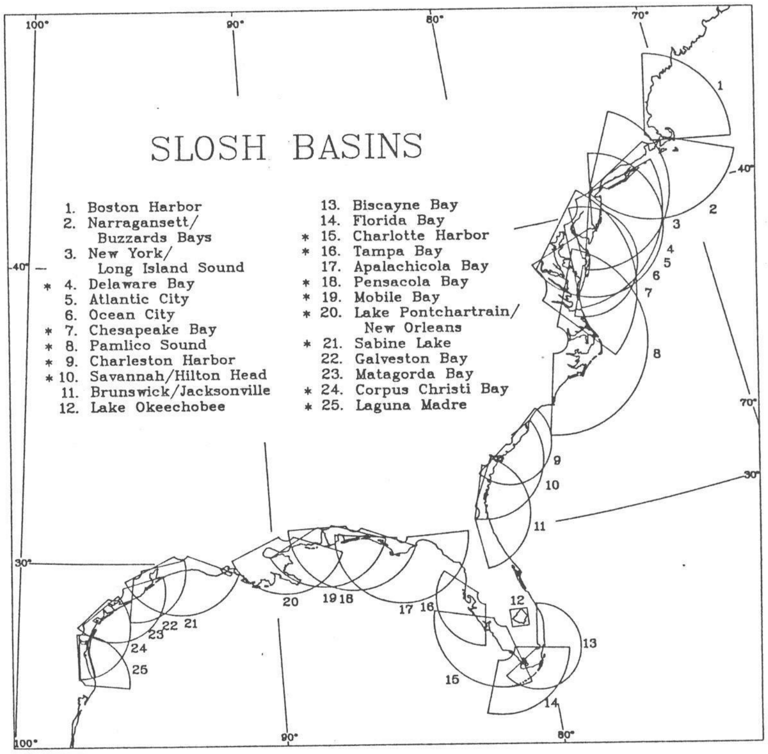

Figure 1. The 25 currently "operational" SLOSH basins used by the National Weather Service. Asterisks before the basin name denote basins where comprehensive evacuation studies are underway or have been completed.

Input to the SLOSH model is limited to parameters that can (in theory, at least) be forecast by an experienced hurricane forecaster. The first and most obvious input to SLOSH is the hurricane's track. Six-hourly, latitude and longitude track positions must be given 48 hours before landfall and 24 hours after landfall. (In the event of a hurricane not making landfall, the time of the storm's nearest approach to a given point in a basin is substituted for the landfall time.) Another time variant input is the storm's central pressure, which is used to indicate the intensity of the hurricane. The final time variant input is the storm's radius of maximum wind. This distinguishes large hurricanes (such as hurricane Carla, 1960) from small storms (hurricane Camille, 1969). Both the central pressure and the radius of maximum wind are entered at the 6-hourly storm positions. Positions and storm parameters between 6-h positions are interpolated values from a spline curve fit.

3. "REAL-TIME" FORECASTS AND SIMULATION STUDY RUNS

SLOSH was designed to forecast surges produced by <u>any</u> hurricane in a given basin, regardless of the region's past experience with hurricanes. Even if no hurricane was ever experienced in a basin, SLOSH can produce a reasonable surge forecast. The reason for this is that SLOSH was not "tuned" for any given storm in a basin. Instead, generalized formulations applicable to all basins are used for such variables as the surface drag coefficient. SLOSH, and its wind model, has been applied to many different hurricanes along the Gulf and Atlantic coasts. Although the model winds don't match published or so-called observed winds, the salient characteristics are retained.

In each SLOSH basin, model simulation runs are made with historical hurricanes when sufficient meteorological and surge data can be obtained. The "best fit" track, intensity and radius of maximum wind are determined by a careful analysis of the meteorological data and then input into SLOSH. Generally, only one or two historical hurricanes with sufficient data exist in this type of model verification. To get an overall estimate of the SLOSH model's accuracy, computed values of surge and measured surges are compared for many historical storms and many basins. When this is done, SLOSH's computed surges have an error of roughly ±20% (Jarvinen and Lawrence, 1985). Keep in mind that this error is for known, after the event, hurricanes when meteorological data are "quasi-accurate".

The most critical input to the SLOSH model is the hurricane's track. If, as in the case of hurricane Elena, the landfall is forecast to occur at Cedar Key, Fla. but actually occurs at Biloxi, Miss., SLOSH surge forecasts will be totally incorrect.

Current NWS forecasts of hurricane position have an average error of ±100 miles for a 24-h forecast. With such inaccuracy in hurricane landfall, forecasters should not base their forecasts of surges from a single SLOSH run. Instead, several runs should be examined to get an overview of the potential surge flooding from a threatening hurricane.

An overview of the possible flooding from a given hurricane can be estimated long before a hurricane threatens. The NWS has developed a methodology for making these estimates. SLOSH is run for a great number of hypothetical hurricanes--approximately 300 in some studies--which vary in intensity, size, forward speed and track. Climatology is first studied to determine the most likely conditions. An example is the New Orleans area, where a family of parallel tracks was chosen from hurricane climatology for directions of N, NE, NW, E, and W. Two forward speeds were used--5 mph for slow-moving storms, 15 mph for fast storms. For each track and speed combination, hurricanes for each of the five Saffir-Simpson categories (1 to 5) were run. In other basins, different sets of hurricane characteristics are used.

The amount of data produced by such runs is overwhelming. To condense the data into a more useful form for NWS forecasters, selective composites of various runs are made. The most useful combination of storms lumps together a family of parallel track storms, all of the same category and speed along the tracks. At each SLOSH grid square, the highest value of surge from the family of storms is displayed, giving a composite called the <u>M</u>aximum <u>E</u>nvelope <u>o</u>f <u>W</u>aters, or MEOW. Since a forecaster can't be certain of a hurricane's landfall, we suggest that he examine the appropriate MEOW to estimate the <u>potential</u> surge. This eliminates the possibility that a critical path will be missed in which extreme values of surge could be generated, such as critical paths for long, narrow waterways. Hurricanes traveling over or to the right of a waterway's axis (observer at sea, facing land) will produce little surge. However, for a hurricane which is to the left of this area roughly at a distance of the radius of maximum wind, extreme values of surge can be generated.

The SLOSH user must keep in mind that only a small portion of the coastline will experience the high flooding associated with a MEOW. For a hurricane landfall normal to a coastline which is not broken by bays or estuaries, the highest flooding will be experienced to the right of the hurricane's track at the distance of the radius of maximum wind as shown in Fig. 2. A more detailed view of flooding along broken coastlines and inland bodies of water may be obtained by examining one or more specific hurricanes used to form the MEOW.

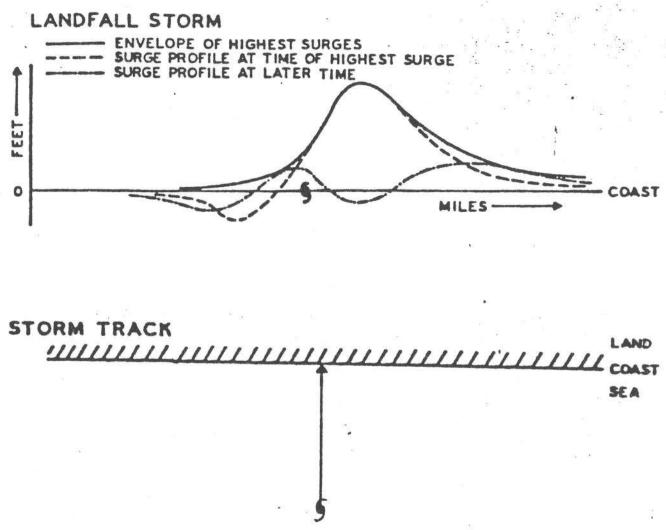

Figure 2. Storm surge location relative to a hurricane's track for the special case of a hurricane making landfall normal to the coast. The maximum surge height is experienced at roughly the radius of maximum wind to the right of the landfall point.

Generally, the timing of the highest coastal surge corresponds roughly to the time of landfall. For a bay or estuary, the time of the maximum surge may vary considerably from the time of landfall on the open coast.

When a hurricane threatens the East Coast, tides can significantly change the flooding. In some coastal areas, a tidal range of six feet or more is common. For such areas, it would be ideal to forecast the time of hurricane landfall and use superposition of the surge and tide (or compute the tide and its interaction with the surge) for an estimate of the flooding. However, just as the error in landfall location presents problems, so does the timing of landfall. The average landfall error for a 24-h forecast is approximately 100 miles. This error can be interpreted as an average landfall time error of about 6 hours, which is roughly the time between high and low tide for most locations! Thus, we can't realistically forecast whether or not a hurricane will make landfall at high or low tide. Most forecasters will wish to examine the worst possible scenario--landfall at high tide levels.

4. EVACUATION STUDIES

The Federal Emergency Management Agency (FEMA) and the U. S. Army Corps of Engineers have joined with the NWS in conducting hurricane simulation studies along U. S. coasts. Several hundred hypothetical hurricanes for each basin representing a local area are simulated with SLOSH, and the surge flooding is noted. MEOWs are formed from a logical combination of this output. FEMA and the Corps then use this information as the basis for a comprehensive local hurricane evacuation plan. The final evacuation plan includes not only SLOSH results, but also population and transportation studies for the impacted area.

The basins which have asterisks before them in Fig. 1 denotes hurricane evacuation studies underway. For each of these basins, the SLOSH simulation runs have been completed.

One result of vital concern to the NWS is the evacuation time. This time gives NWS forecasters an idea of the forecast lead time needed to clear people to safety from barrier islands and flood-prone areas.

5. SLOSH COMPUTATIONS DURING HURRICANE ELENA, 1985

Let us illustrate some of SLOSH's utility and some problems surrounding its use by examining forecasts made for hurricane Elena. This intense hurricane threatened much of the Gulf coast during its lifetime of August 29 to September 3, 1985. During Hurricane Elena's earliest phase, the storm was intensifying and heading on a northerly track toward New Orleans. The SLOSH model was not run at the National Weather Service's National Hurricane Center located in Miami, Fla., because the storm was well out in the Gulf. Rather, an experimental graphics display of the appropriate MEOW was used to estimate the potential surges along the coast. Surges of 8 to 12 feet appeared likely for a category 2 hurriane moving rapidly in a northerly direction. The MEOW data for a family of northerly moving storms showed the most vulnerable locations in the area between Slidell, La. and Gulfport, Miss.

When the storm later turned eastward with a projected landfall in the Cedar Key, Fla. area, surge forecasts of 8 to 12 feet were issued based on real-time SLOSH forecasts (as opposed to MEOW data). Elena decelerated and circled offshore near Cedar Key, then headed westward. The surge estimates for the westward track remained at 8-12 ft based on real-time forecasts.

As Hurricane Elena then moved to a projected landfall in the Biloxi-Gulfport area of Miss., two real-time SLOSH runs were made. One had a projected track about five miles south of Slidell, La. (Fig. 3). The other had a track which crossed over New Orleans. The Slidell track was considered by forecasters the more likely of the two. The second track would be more critical for the New Orleans area.

Figure 3 also shows the SLOSH-generated surges for the forecast track passing five miles south of Slidell. This track, it turns out, produces some of the highest possible flooding along the coast for this category of westerly-moving hurricane. Notice that in the Bay St. Louis area, computed surge values are 16 feet! Computed surge values along the outer coast ranged from approximately 12 feet at the Rigolets to 15 feet just south of Bay St. Louis, and back down to 10 feet and lower further east. The highest water to impact the city of New Orleans computed by this SLOSH run was 6 to 8 feet.

No surges of the magnitude predicted by this SLOSH run were observed. Why? The answer lies in a SLOSH run produced with the "best-fit", after the event, track and storm parameters. These parameters, of course, were not available until Elena made landfall. Values of "best-fit" are from presently available data. As more data are analyzed, a better fit of the storm's track, intensity, and size can be expected.

When SLOSH was run on this best-fit track computed surges ranged to 8 feet, with most of the Gulfport-Biloxi area experiencing about 7 feet on the outer coast (Fig. 4). Bay St. Louis surges were calculated to be only about three feet--much below the values computed with the original forecast track. The highest surge noted in this run occurred in the area of Pascagoula Bay. Had Elena passed on its predicted path surges of approximately 15 feet would have been experienced (Fig. 3). However, since Elena's actual track, (Fig. 4) passed just 15-20 miles offshore, the winds were mostly offshore. With offshore winds, water was blown away from the coastline, generating negative surge values. Local observations indicated that was the case. The tide gage for Gulfport illustrates this quite emphatically, as shown in Fig. 5. Only after the hurricane's center passed a given location did the wind shift to onshore, giving the potential for generating positive surges. The water level at the time the winds shifted was depressed; water had to be brought back in to replace this depressed state before positive surges could be generated. This, coupled with the weakening of the hurricane and the weaker winds behind the storm, led to the modest computed and observed values for the storm surge (Figs. 4 and 6).

6. SOME PROBLEMS RELATING TO MEOW'S AND SLOSH

One of the main concerns expressed during and after Hurricane Elena was that SLOSH overforecasted the surge values. Several users examined SLOSH MEOW data and expected the extensive flooding shown in the MEOW's to be experienced. Properly used, the MEOW's indicate the extent of possible flooding, not the flooding from one individual storm. The SLOSH computed surges (Fig. 4) agree reasonably well with observed values (Fig. 6) for the "best-fit" track. Unfortunately, such precision in track forecasting is not viable with today's forecast methodology.

Another problem with SLOSH is keeping the model's data base current. Levees surrounding parts of east New Orleans were recently raised. Since these changes were not incorporated into the latest version of the model's data base, overtopping of these levees may have been overestimated. As a result of questions concerning the model's data base, the NWS will revise the levee heights in the New Orleans SLOSH basin yearly. In other areas, periodic updates are planned for land subsidence, new construction of levees, dykes, etc.

7. REFERENCES

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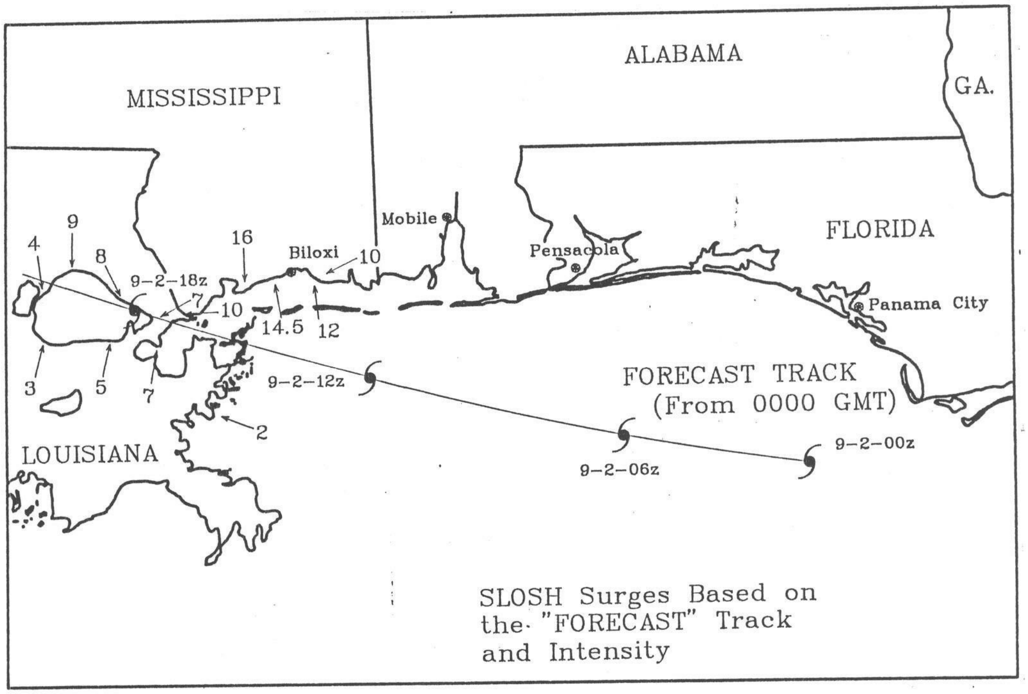

Figure 3. Storm surges computed by SLOSH using the "forecast" hurricane track and intensity. The surge values shown here are in feet above National Geodetic Vertical Datum (NGVD).

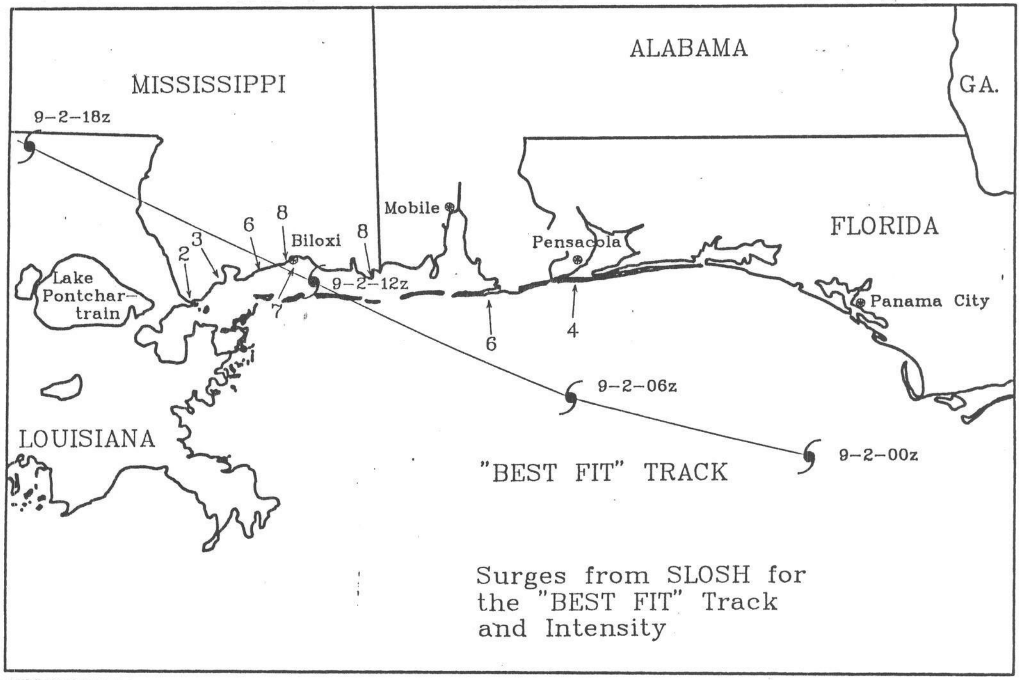

Figure 4. Same as Fig. 3, but for the "best fit" after the event track of hurricane Elena.

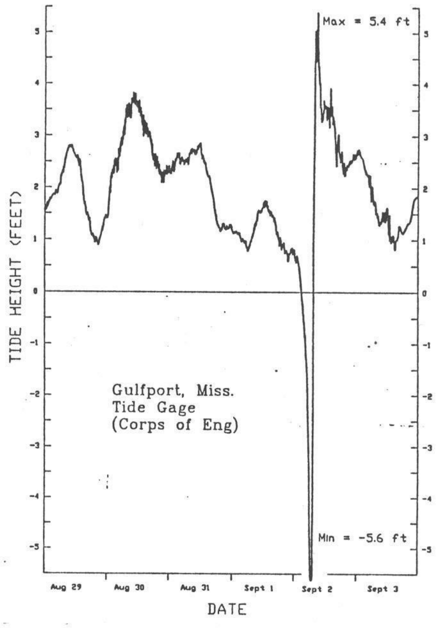

Figure 5. Tide gage trace for Gulfport, Miss. during hurricane Elena. The gage went from a low of -5.6 ft. to +5.4 feet very rapidly as the winds shifted at Gulfport.

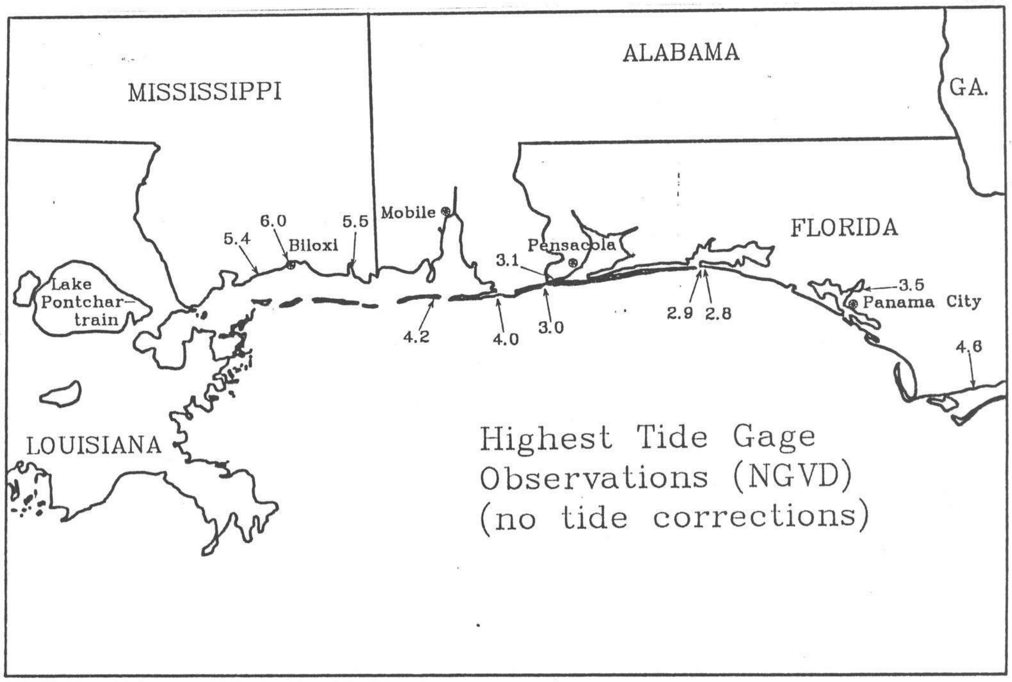

Figure 6. Highest observed tide gage readings along the Gulf Coast due to hurricane Elena, with no correction for astronomical tide. Gage values are given in feet above National Geodetic Vertical Datum (NGVD).