NOAA Technical Memorandum NWS NHC 37

OBSERVED VERSUS SLOSH MODEL STORM SURGE FOR NORTH CAROLINA IN HURRICANE GLORIA, SEPTEMBER 1985

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August 1987

UNITED STATES DEPARTMENT OF COMMERCE / National Oceanic and Atmospheric Administration, Anthony J. Calio, Administrator / National Weather Service, Richard E. Hallgren, Assistant Administrator

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ABSTRACT

For hurricane Gloria over North Carolina, the peak storm surge generated by the SLOSH model is within ± 2 ft of the observed surge at all locations. Also, the occurrence of the peak surge generated by SLOSH is within ± 2 h of the observed surge at all locations.

1. INTRODUCTION

The Army Corps of Engineers, Federal Emergency Management Agency and the National Weather Service are extensively involved in determining the areas that are prone to flooding by hurricane storm surge along the U.S. Atlantic and Gulf of Mexico coastlines. Determination of flood prone areas is an essential prerequisite to evacuation planning.

Flood potential could be specified through a study of past events if, for the region of interest, a horizontal network of meteorological (pressure and wind) and hydrographic (tide gage) sensors had continuously recorded data during hundreds of historic hurricanes of varying intensity, direction, and forward speed. In reality, hurricanes are very rare events for any region along the Atlantic and Gulf coastlines. Also, in the historical cases that do exist, many of the meteorological and hydrographic sensors failed during passage of the hurricane. Thus, for most of the U.S. coastline, the climatology of hurricane storm surge flooding is very limited.

To compensate for this lack of historical data, the National Weather Service developed a numerical model termed SLOSH (Sea, Lake, and Overland Surges from Hurricanes). The SLOSH model, given hurricane input parameters, computes storm surge heights over a geographic area that is covered by a network of grid points. This network, or model domain, is called a basin. At present, 27 basins cover approximately 90% of the U.S. Atlantic and Gulf of Mexico flood plains. The basin that covers the flood plain of North Carolina has been designated the "Pamlico Sound basin."

A hurricane evacuation study is nearing completion for North Carolina. A series of hypothetical hurricanes of varying intensity, direction, and forward speed has been simulated using the SLOSH model in the Pamlico Sound basin. The storm surge data generated by the SLOSH model simulations determines the flood-prone regions. With this knowledge, evacuation plans are being formulated for future use. During an evacuation study, historical hurricanes are also simulated with the SLOSH model. The comparison of the SLOSH model storm surge values and the observed storm surge values determine the confidence in the model (Jarvinen and Lawrence, 1985). Unfortunately, in the Pamlico Sound region, simultaneous observations of the storm surge and hurricane meteorological parameters for historical hurricanes have been rare. However, during the 1985 hurricane season, Gloria presented an opportunity for a comparison in the Pamlico Sound basin. The purpose of this paper is a comparison of observed versus SLOSH computed storm surge values in the Pamlico Sound basin for Hurricane Gloria.

2. PAMLICO SOUND BASIN

The Pamlico Sound basin grid is shown in Figure 1. The grid is a telescoping polar coordinate system with 60 arcs and 100 radials. Unlike a true polar coordinate grid, which would have a radial increment that was invariant with radius, this grid uses a radial increment that increases with increasing distance from the grid's pole. The result is that, in each grid of the mesh, the radial increment of the square is approximately equal to its arc length.

The telescoping grid is a compromise. It is desired that a large geographical area with small detailed topography be modeled. In the Cartesian coordinate system, this combination of large area and spatially small grid increments requires a computational mesh with many grid squares. A large grid requires a computer with a large central processing unit as well as time to perform calculations in the numerous grid squares. The telescoping grid, by comparison, resolves these conflicting needs: it has an acceptably small spatial resolution of 1 to 10 square miles per grid segment over land which is the area of the greatest interest. Thus, topographic details, such as highway and railroad embankments and dikes in harbors of cities, are included in the model. However, the range increment contained in each grid square becomes progressively larger with increasing distance from the pole. As a result, a large geographic area is included in the model, and the effects of the model's boundaries on the dynamics of the storm surge are diminished.

The grid is tangent to the earth at Cape Hatteras, North Carolina, at 35°13'22"N and 75°31'50"W. There, the grid increment is 3.6 statute miles. The pole (or origin) of the grid is located at 36°00'00"N and 77°25'00"W

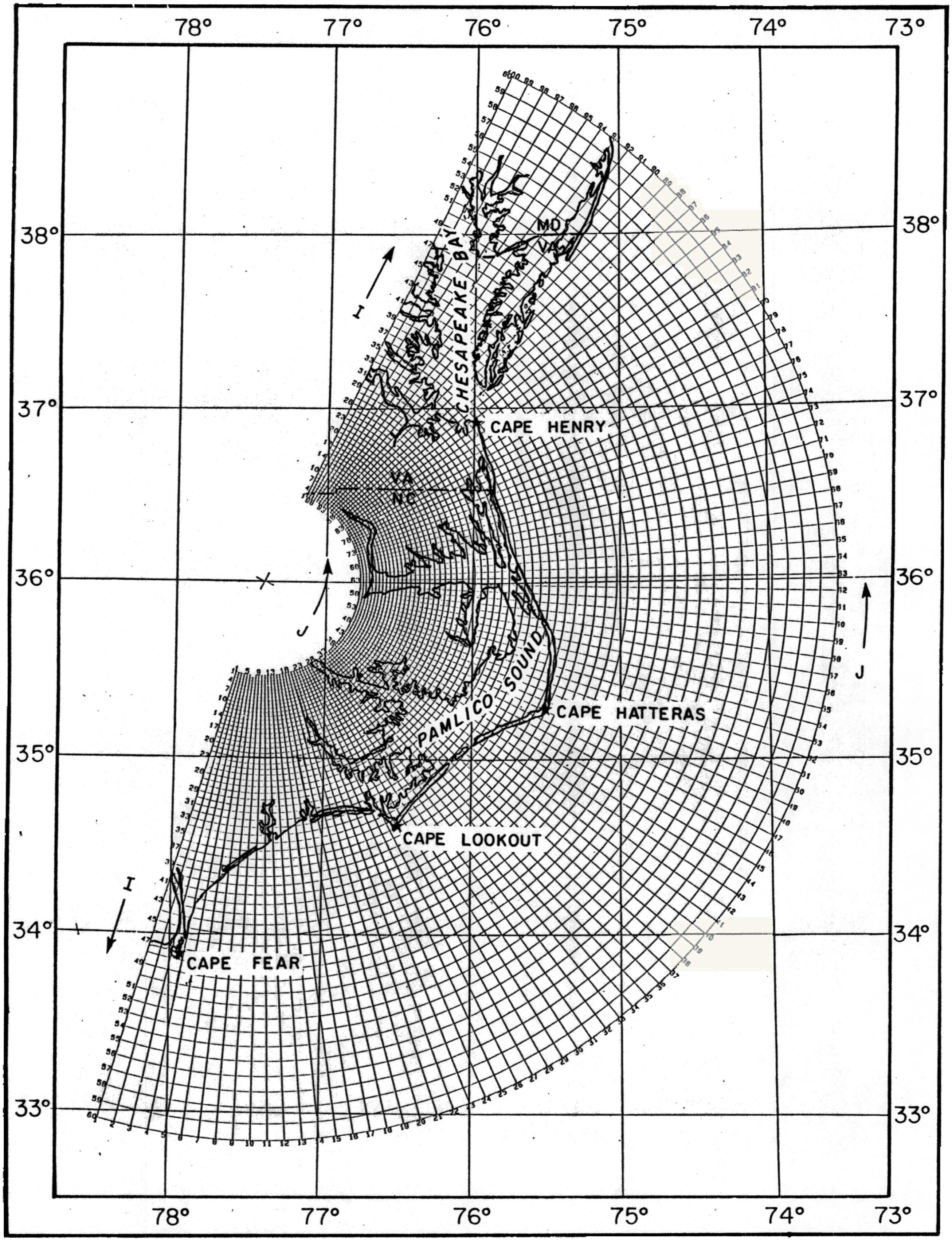

Figure 1. Pamlico Sound SLOSH basin grid

3. SLOSH MODEL AND HURRICANE INPUT PARAMETERS

The SLOSH model's governing equations are those given by Jelesnianski (1967), plus a finite amplitude effect. Coefficients for surface drag, eddy viscosity and bottom slip are given by Jelesnianski (1972). There is no calibration or tuning to force agreement between observed and computed surges; coefficients are fixed and do not vary from one geographical region to another.

Special techniques are incorporated to model two-dimensional inland inundation, routing of surges inland when barriers are overtopped, the effect of trees, the movement of surge up rivers, and flow through channels and cuts and over submerged sills.

The SLOSH model requires hurricane input parameters at specified time intervals. These parameters include the latitude and longitude of the eye, the atmospheric sea-level pressure in the eye, and the radius of the maximum surface wind speed (RMW).

4. METEOROLOGY:

4.1 Track

Gloria represents a classical recurving Cape Verde hurricane. Figure 2 shows Gloria's track with positions marked every 24 h at 0000 UTC[1]. After forming in the Cape Verde region on September 17, Gloria moved generally westward for 5 days before beginning a gradual recurvature to the west-northwest as the center approached the Lesser Antilles. A more northwesterly direction in movement began as the center approached the eastern Bahamas on the 24th. In the next two days, Gloria began to increase its forward motion and gradually turned toward the north. Gloria made its first landfall near Cape Hatteras, NC, on September 27, between 0500 and 0600 UTC. The forward motion at landfall at Cape Hatteras was approximately 30 mph. Influenced by a strong southerly deep-layer tropospheric steering, Gloria continued to accelerate toward the north-northeast. Gloria raced by Delaware and New Jersey on the 27th and made landfall on Long Island moving about 40 mph at approximately 1600 UTC on the same day. The hurricane continued across Long Island into Connecticut and affected several other New England states and the Canadian maritime provinces before reemerging in the Atlantic Ocean, where it dissipated on October 2.

Figure 3 shows hourly eye locations of Gloria during its passage over the Outer Banks of North Carolina. The hourly locations are labeled by three values separated by slashes. The first value is Eastern Daylight Time (EDT). The second value is the central sea-level pressure in millibars. The final value is the RMW in statute miles. For example, 0200/942/12 means 0200 EDT, 942 mb central sea-level pressure, and a radius of maximum wind of 12 statute miles.

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[1] UTC is Universal Time Coordinated. Subtract 4 hours to convert to Eastern Daylight Time.

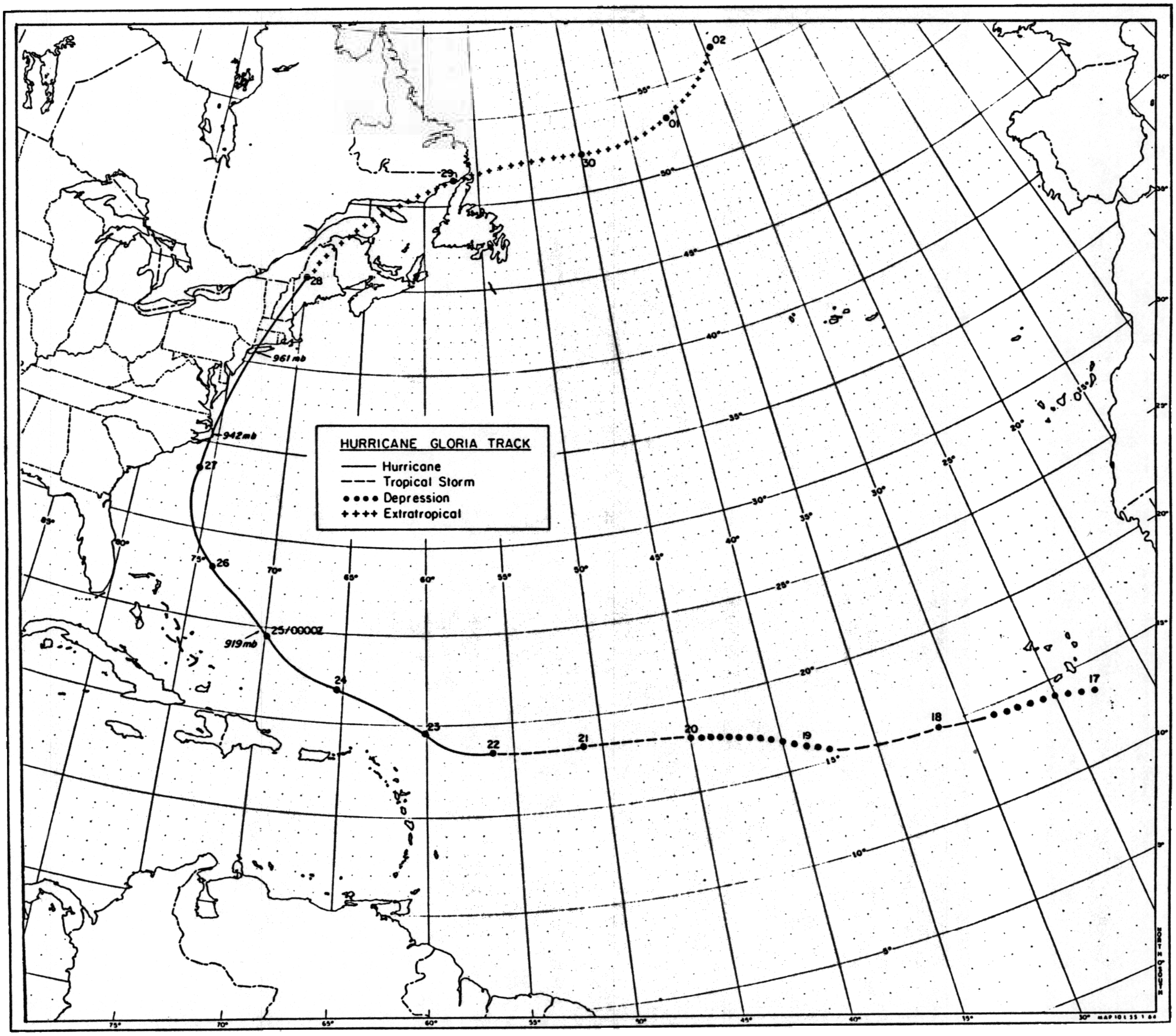


Figure 2. Track of Hurricane Gloria, 17 September to 2 October 1985. Positions are given every 24 h at 0000 UTC.

The hourly positions over the Atlantic Ocean were obtained by analyzing all land-based radar center fixes and locations of minimum central sea-level pressure as observed by reconnaissance aircraft. In determination of the hourly positions, heavy weight was given to the surface pressure locations. For the portion of the track over or near land, a two-dimensional isobaric analysis was made using all available surface pressure observations (i.e., land stations and ships of opportunity) to obtain the center position.

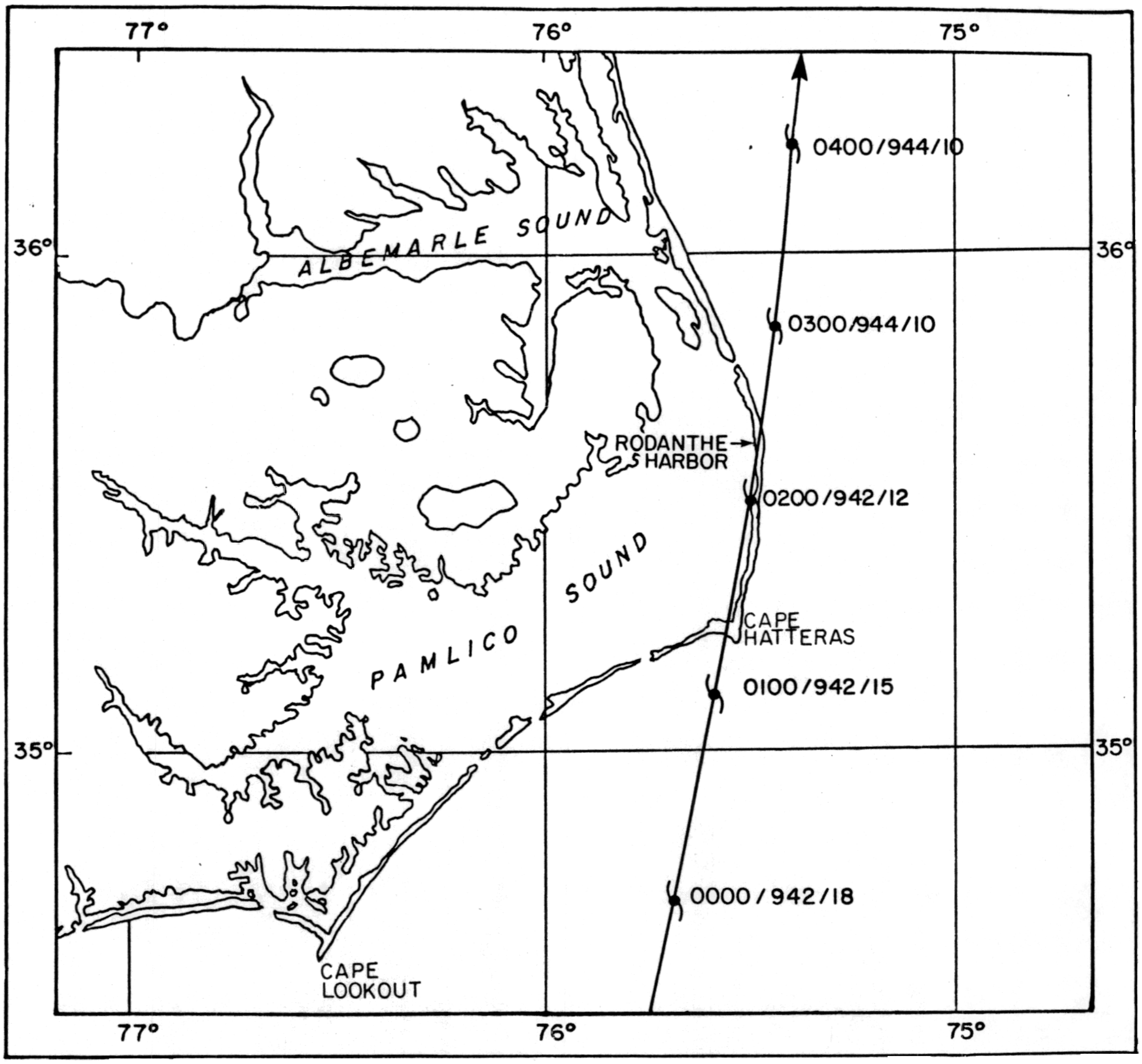


Figure 3. Track of Hurricane Gloria over the Outer Banks of North Carolina. Hourly locations are indicted by a hurricane symbol. Legend example: 0200/942/12--0200 EDT/942 mb central sea-level pressure/12 statute mile radius of maximum winds.

4.2 Intensity and Radius of Maximum Wind (RMW)

The lowest central sea-level pressure values in Hurricane Gloria are shown for selected times in Figure 2. Gloria's lowest pressure of 919 mb occurred on 25 September at 0100 UTC. As Gloria recurved up the east coast, the central pressure rose, reaching 942 mb near Cape Hatteras, NC, and 961 mb at Long Island, NY. Hourly central sea-level pressure values and RMW are shown in Figure 3. Over the Atlantic Ocean, the determination of the minimum surface pressure in the eye and the RMW were determined primarily from aircraft measurements. Over land, the determinations were made from analyses of pressure and wind measurements at surface observing stations. Figure 3 shows that Gloria's central sea-level pressure remained almost constant during its traverse over the Outer Banks of North Carolina. The RMW, on the other hand, was decreasing from 18 statute miles at 0000 EDT to 10 statute miles at 0300 EDT.

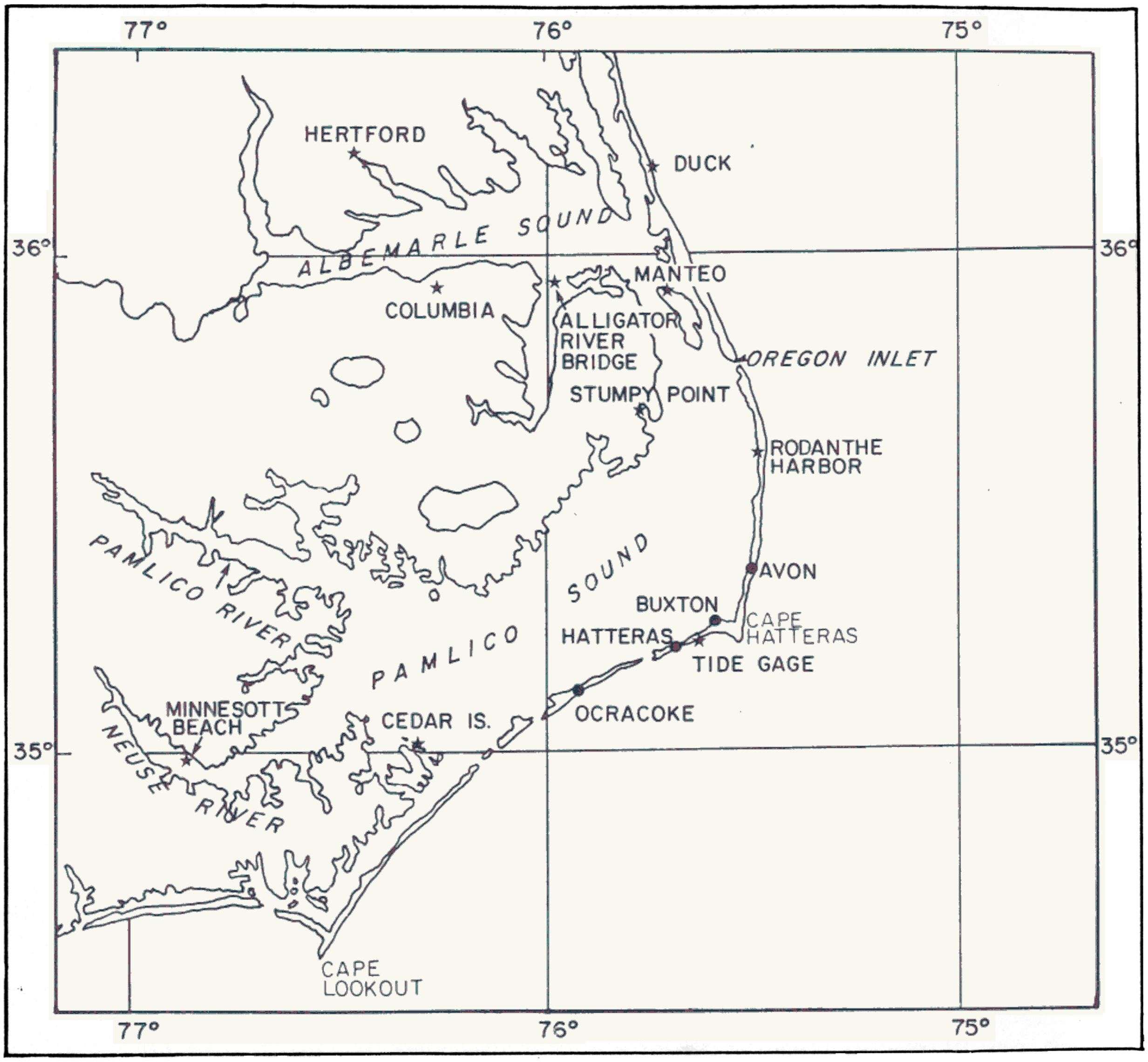
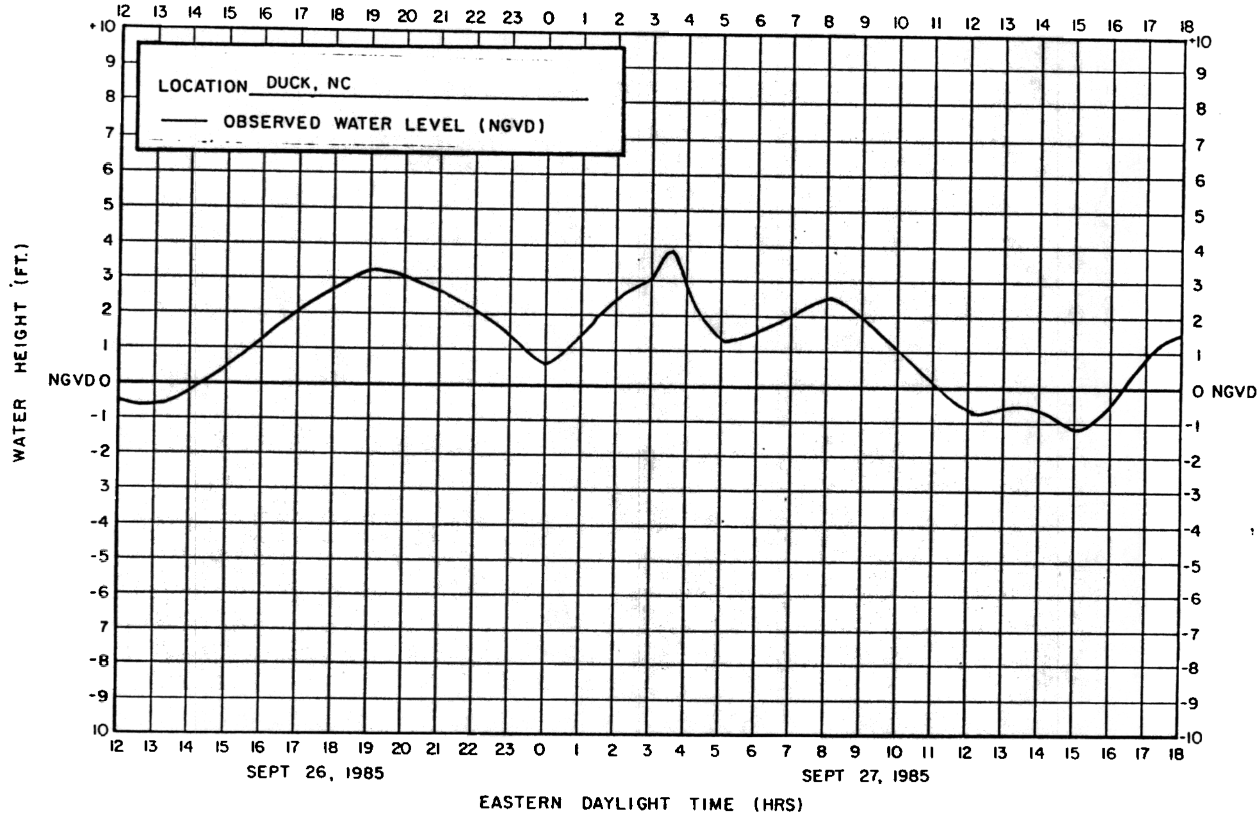


Figure 4. Stars indicate location of tide gages in North Carolina.

5. HYDROLOGY:

5.1 Hydrographs

Hydrographic records from ten tide gages along the North Carolina shoreline were obtained during Gloria's passage. Figure 4 shows the locations and names of the gages. Hydrographs recorded at Cape Hatteras and Duck are shown in Figure 5. The period is from 1200 EDT 26 September to 1800 EDT 27 September. The dominant regular feature is the semi-diurnal tide oscillation. Superimposed on this tide oscillation on the 26 and 27 of September is the storm surge caused by Hurricane Gloria. Storm surge is defined as the observed tide minus the predicted astronomical tide. Thus, to determine the hydrograph of the storm surge, it is necessary to subtract the astronomical tide. This was done by using predicted hourly and maximum and minimum National Ocean Survey (NOS) tide values and subtracting them from the actual hydrograph. Figure 6 shows the same hydrographs as Figure 5, with the NOS-predicted tide curves and the storm surge hydrographs. It is useful to note that the peak storm surge occurred near low astronomical tide at Cape Hatteras and on a rising tide at Duck. Also, at Duck, a negative storm surge occurred because of offshore winds after the center of Gloria had passed.



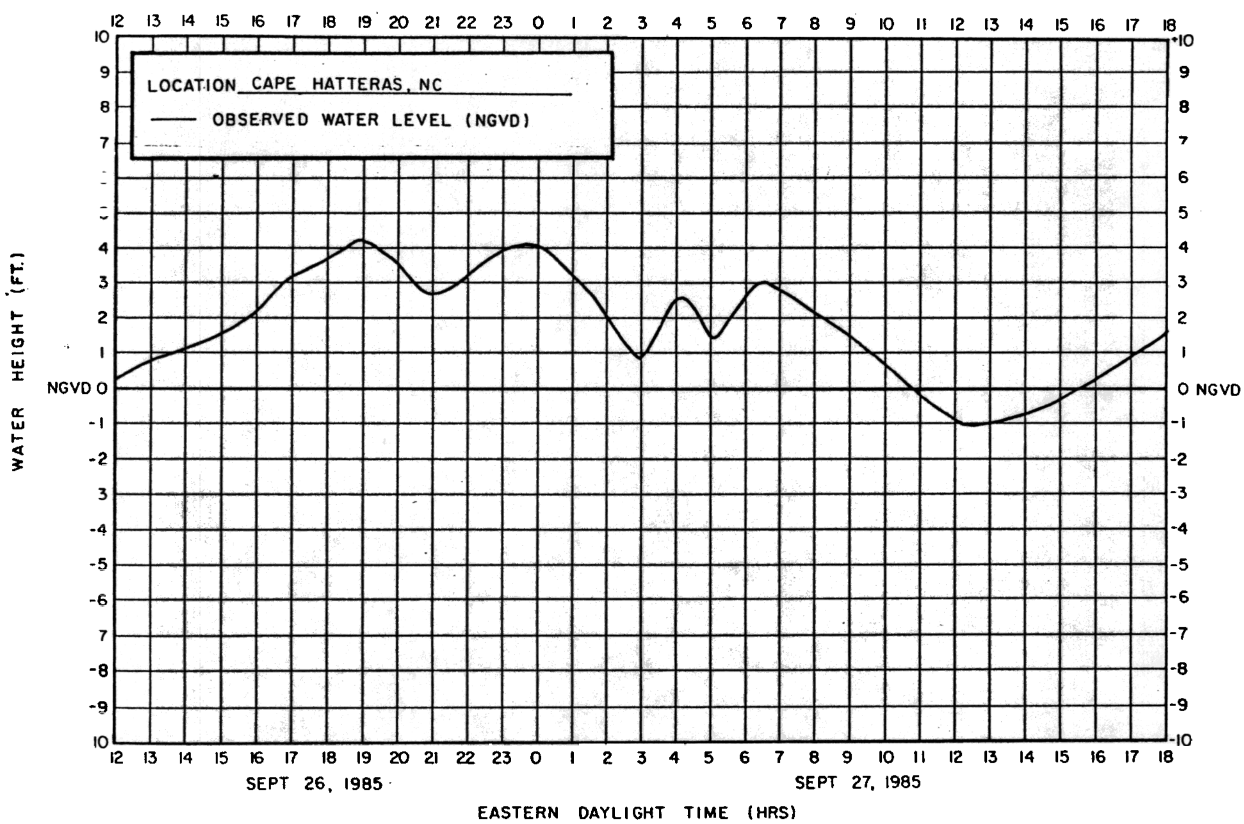
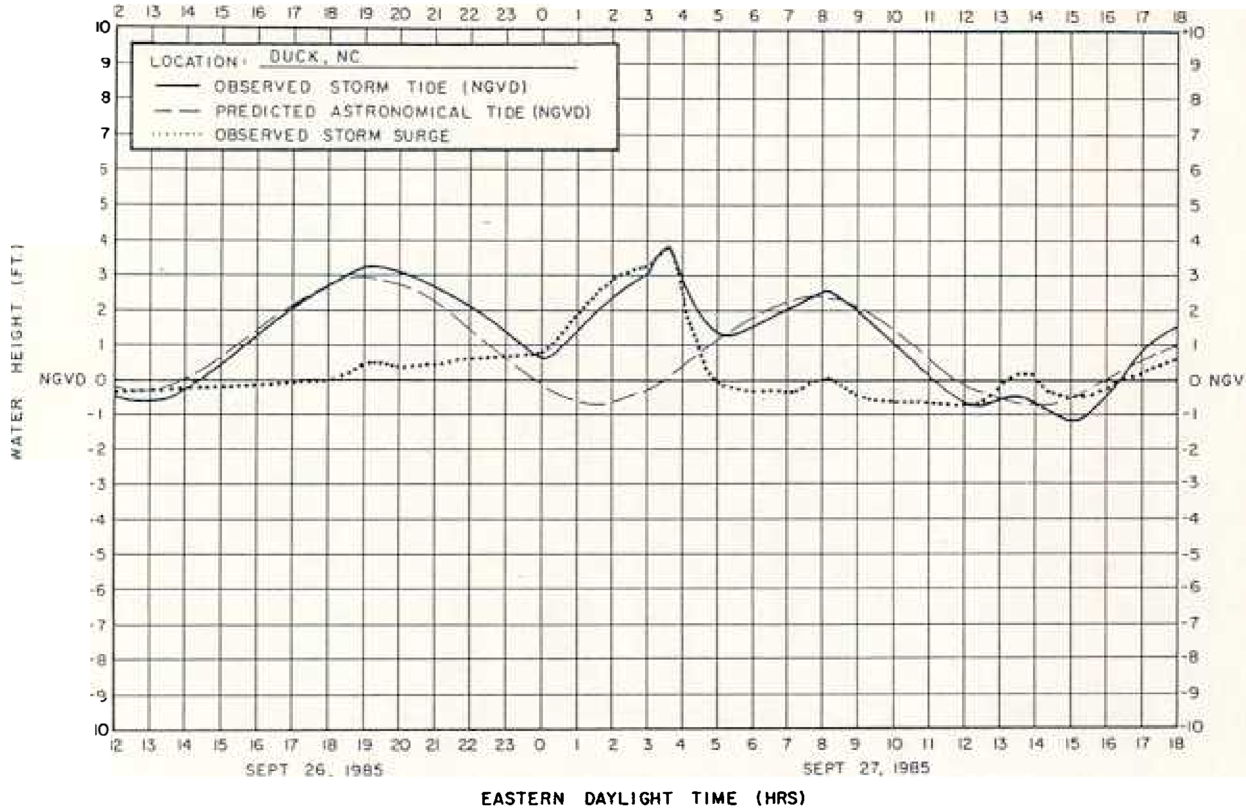


Figure 5. Hydrographs from Cape Hatteras and Duck, North Carolina; tide gages covering the period before, during and after Hurricane Gloria's passage.



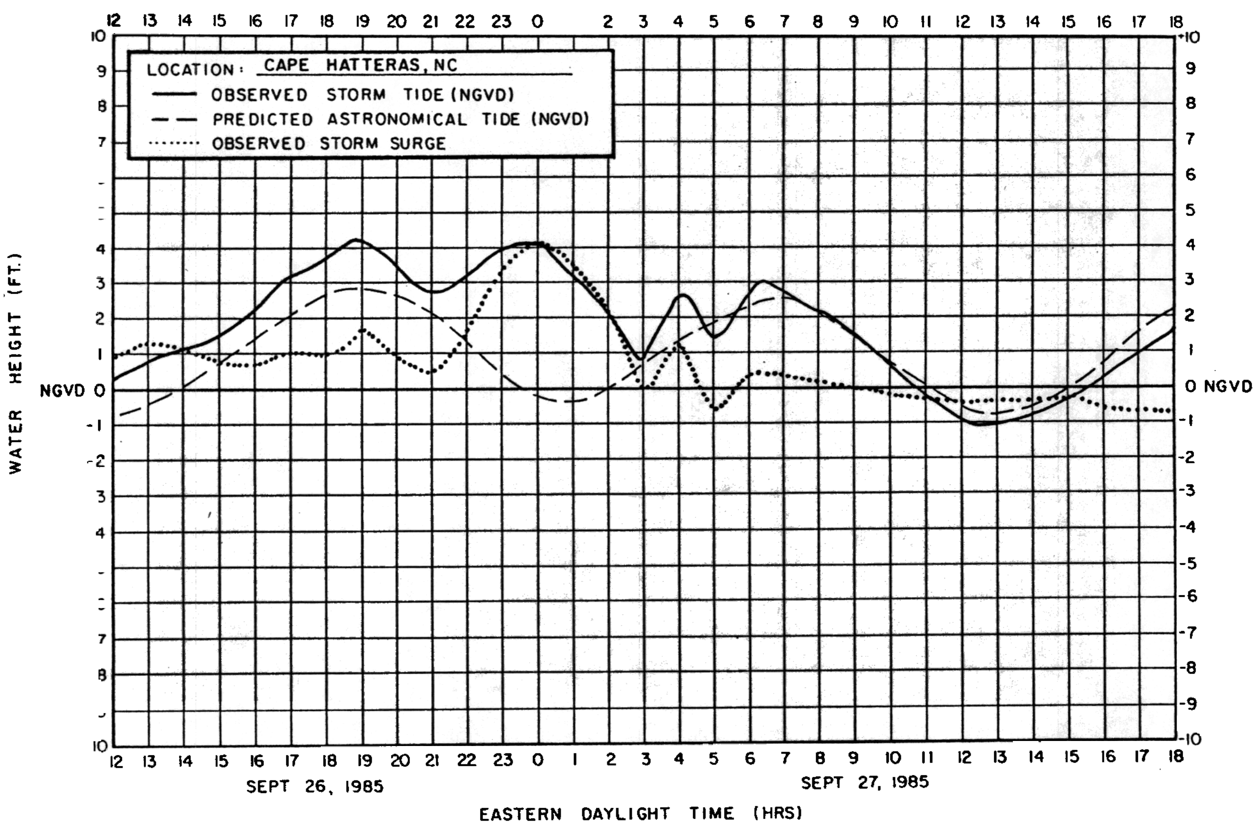


Figure 6. Demonstration of the technique to remove the astronomical tide from the hydrographs shown in Figure 5. Final products are the storm surges generated by Gloria.

We did not apply this technique to the remaining eight tide gages, which are all located in the Sounds and rivers, because the astronomical tide ranges at these locations are only a few inches. The ten measured storm surge hydrographs are shown in Figures 7a through 7e. Also plotted on Figures 7a through 7e are the SLOSH model-generated storm surge hydrographs for the same location based upon Hurricane Gloria input parameters as shown in Figure 3. Using Figures 7a through 7e, we subtracted the observed peak surge from the SLOSH model-computed peak surge to determine the SLOSH model "error." Figure 8 is a bar graph of these ten errors. The class interval is 1 ft centered on zero. The value in the interval -2.5 to -1.5 was -1.8 ft.

Comparison of results in Figures 7a through 7e and Figure 8 shows that:

1. The peak storm surge value generated by SLOSH is within $\pm$ 2 ft of the observed storm surge at all locations.

2. The time of peak surge generated by SLOSH is within $\pm$ 2 h of the observed surge at all locations. Six locations are within $\pm$ 1/2 h of observed while the remaining four are within $\pm$ 1 to 2 h of observed.

3. The SLOSH model nearly replicates the rapid rise in storm surge at Rodanthe Harbor. Figure 7c shows the storm surge hydrograph for the tide gage in Rodanthe Harbor, located on the Pamlico Sound shoreline (Figure 4). As the eye of Gloria approached Rodanthe Harbor from the south, the winds in front of the hurricane had a strong easterly component which drove water away from the Pamlico Sound shoreline. This is indicated by the increasing negative values in both the observed and SLOSH model hydrographs.[2] After Gloria'e eye passed over Rodanthe Harbor, the winds reversed direction and produced a strong westerly component or on-shore wind. The effect of this westerly component is evident in the rapidly rising hydrographs. The observed hydrograph shows that from 0300 EDT to 0430 EDT the water level went from -3.5 ft to +6.5 ft, or a total rise of 10 ft in 1.5 hrs.[3] The SLOSH model slightly under-calculates both the minimum and maximum surge values.

4. The SLOSH model indicates erroneous large negative surges after eye passage at both Cape Hatteras and Duck.

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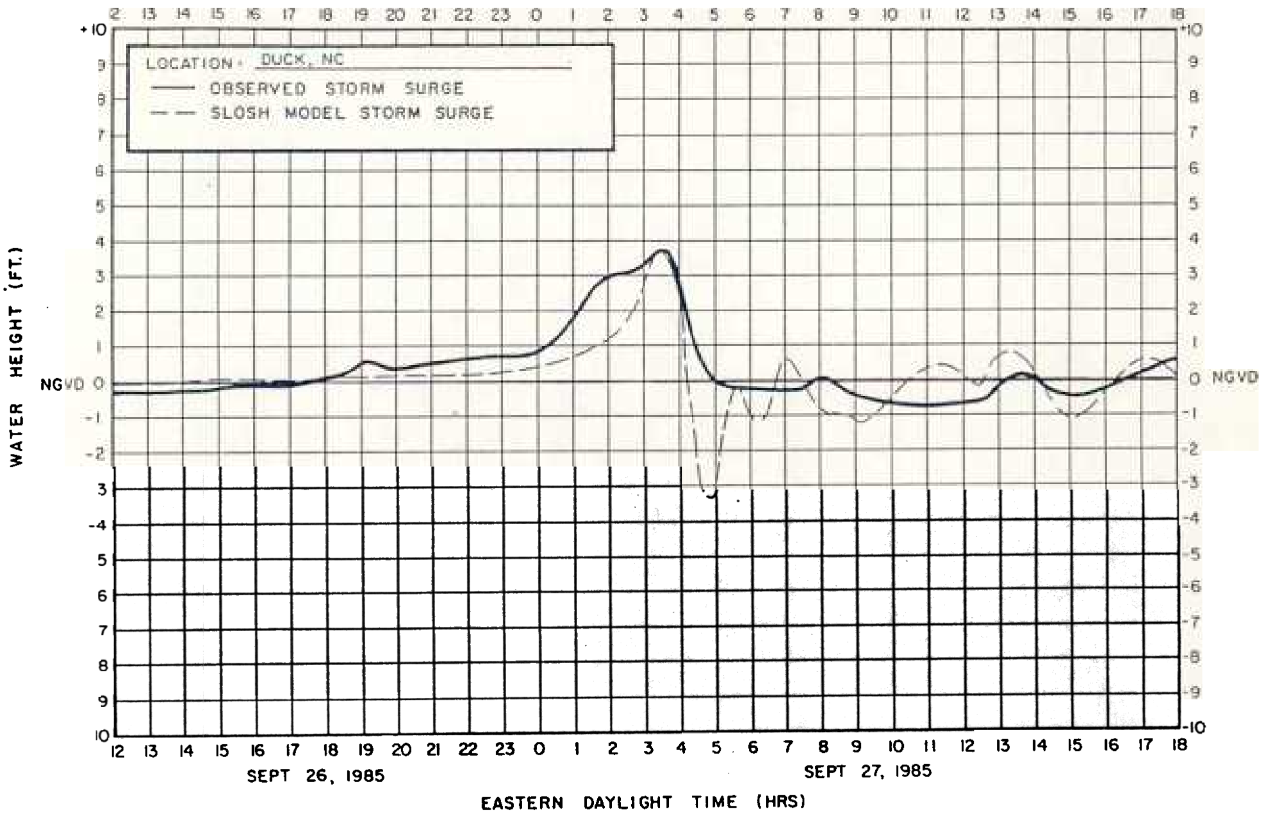
[2]The SLOSH model indicates that the same winds were driving Atlantic Ocean water into the sand dunes on the Atlantic shoreline near Rodanthe Harbor. However, none of this water moved past the dunes.

[3]The SLOSH model indicates that the same winds drove water away from the Atlantic shoreline and produced a negative surge.



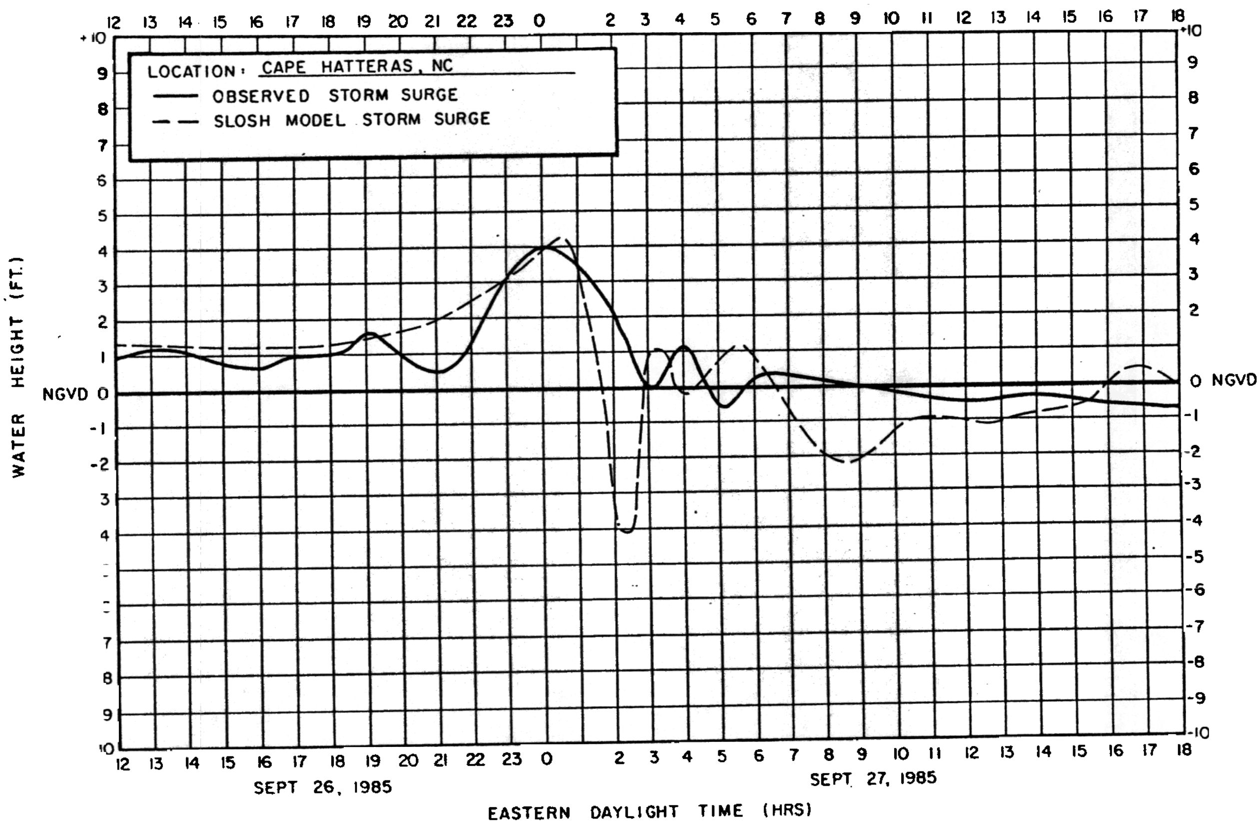
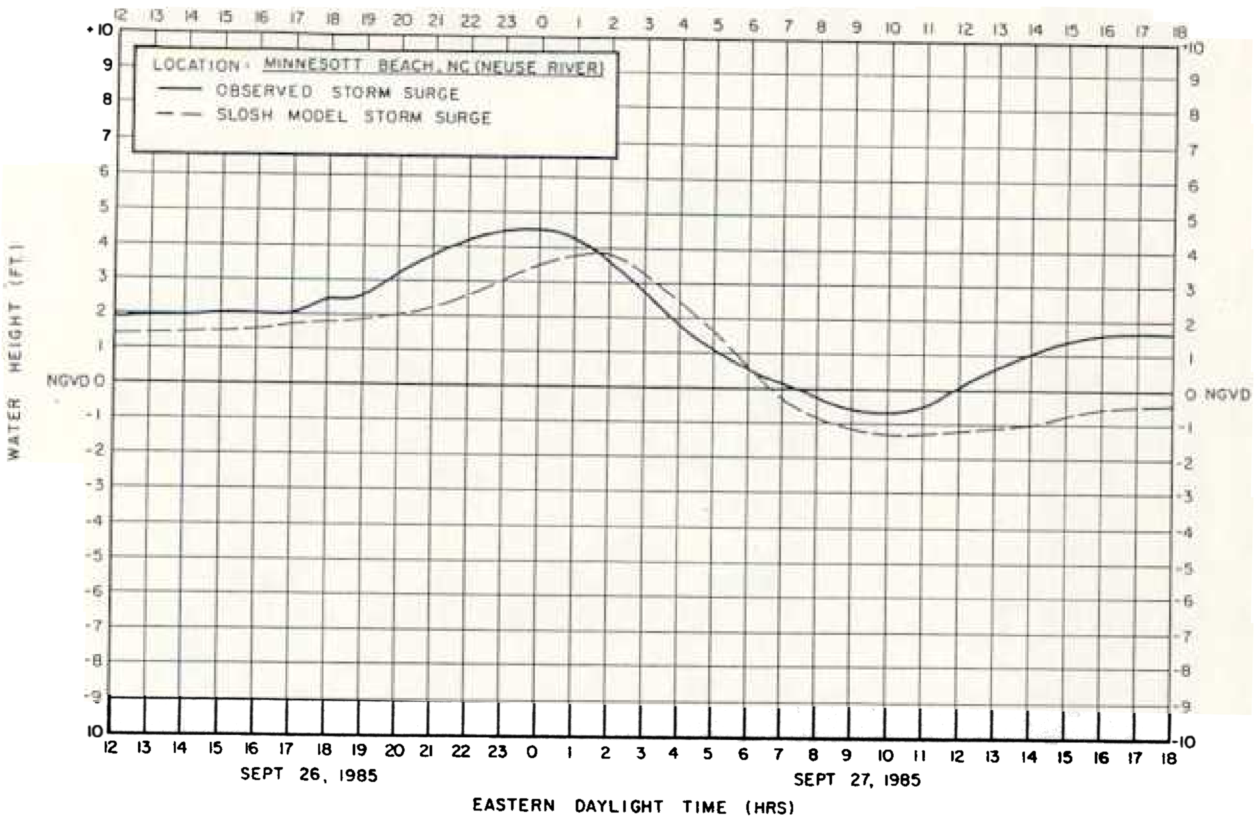


Figure 7a. Comparison of observed versus SLOSH model computed storm surge hydrographs for two locations in Figure 4.



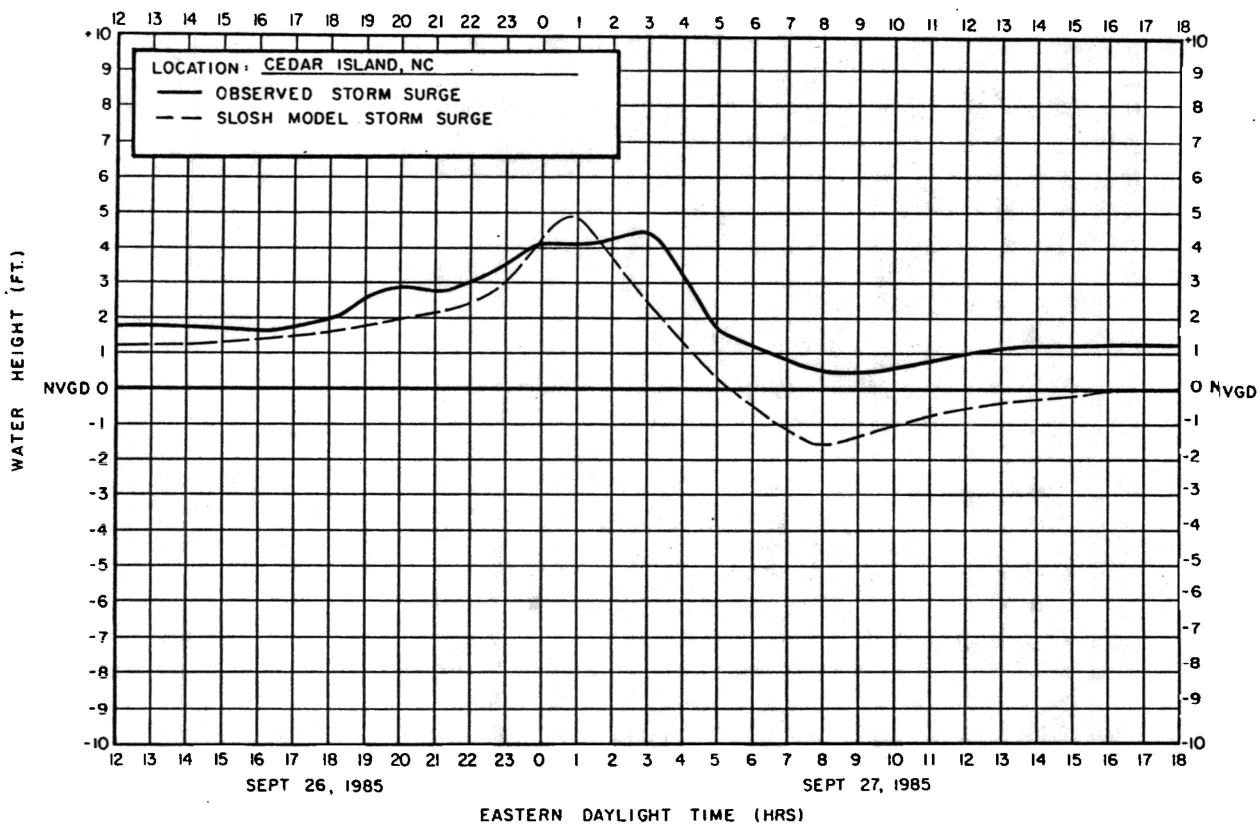
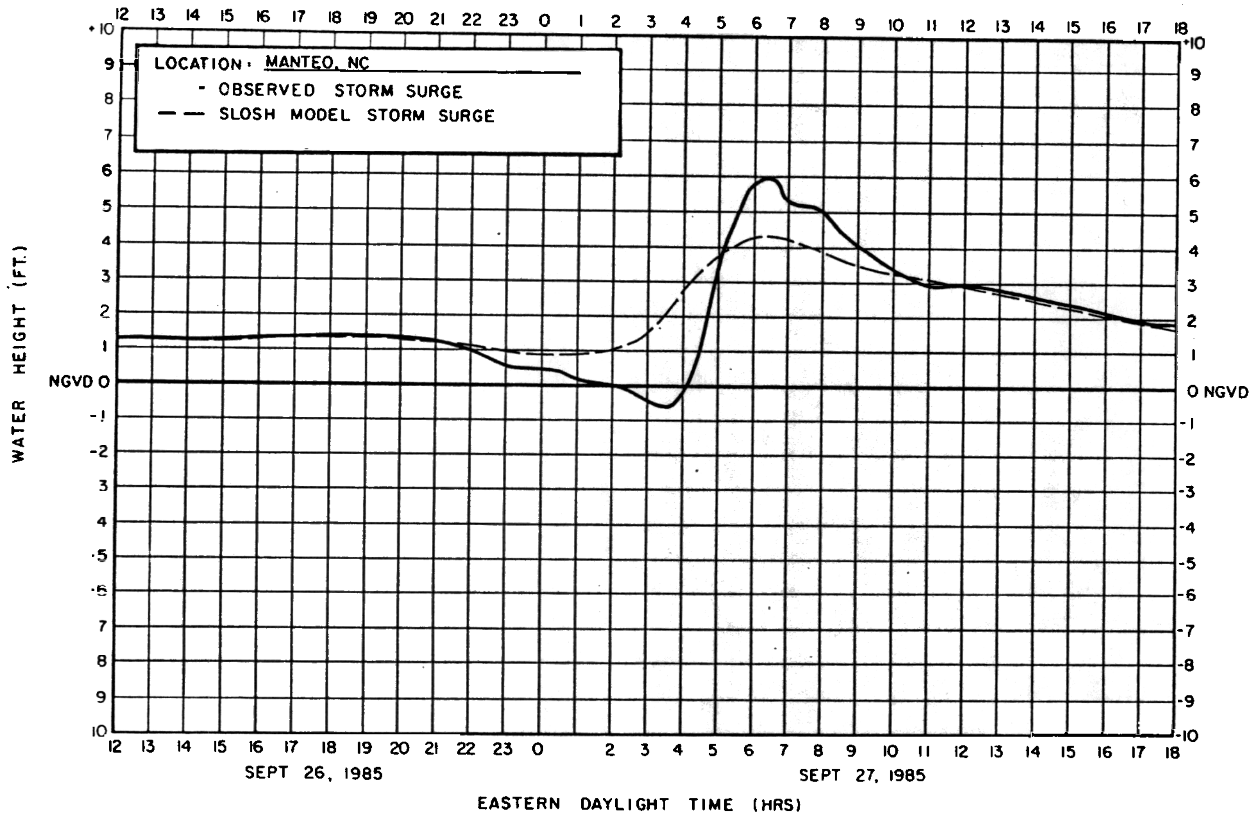


Figure 7b. Comparison of observed versus SLOSH model computed storm surge hydrographs for two locations in Figure 4.



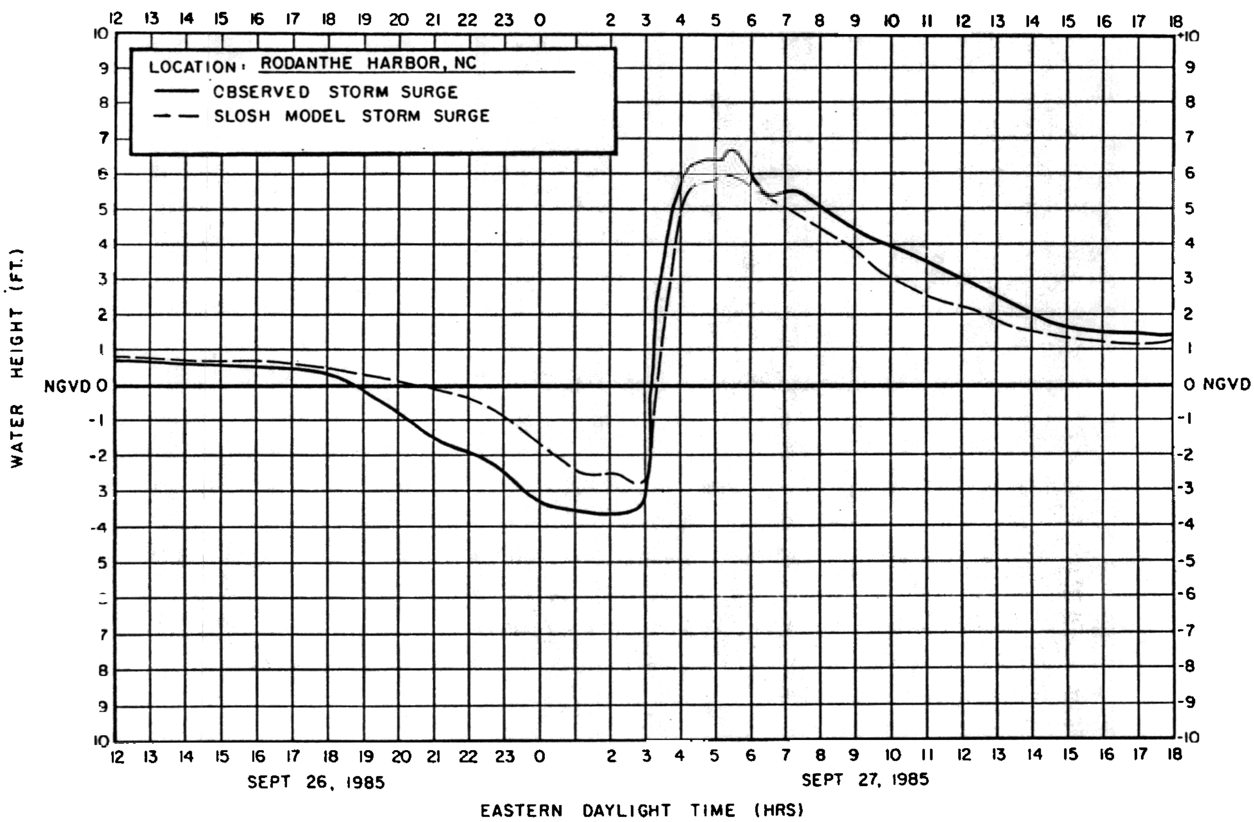
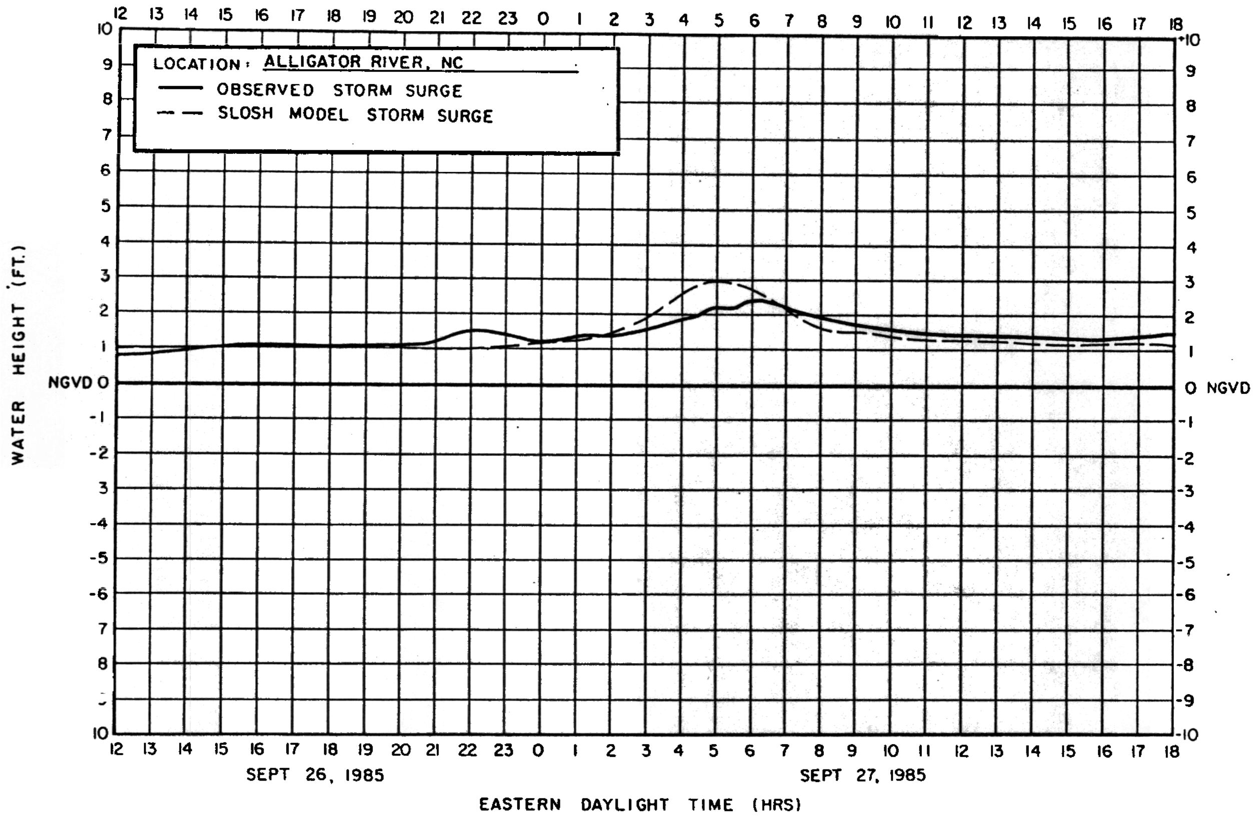


Figure 7c. Comparison of observed versus SLOSH model computed storm surge hydrographs for two locations in Figure 4.



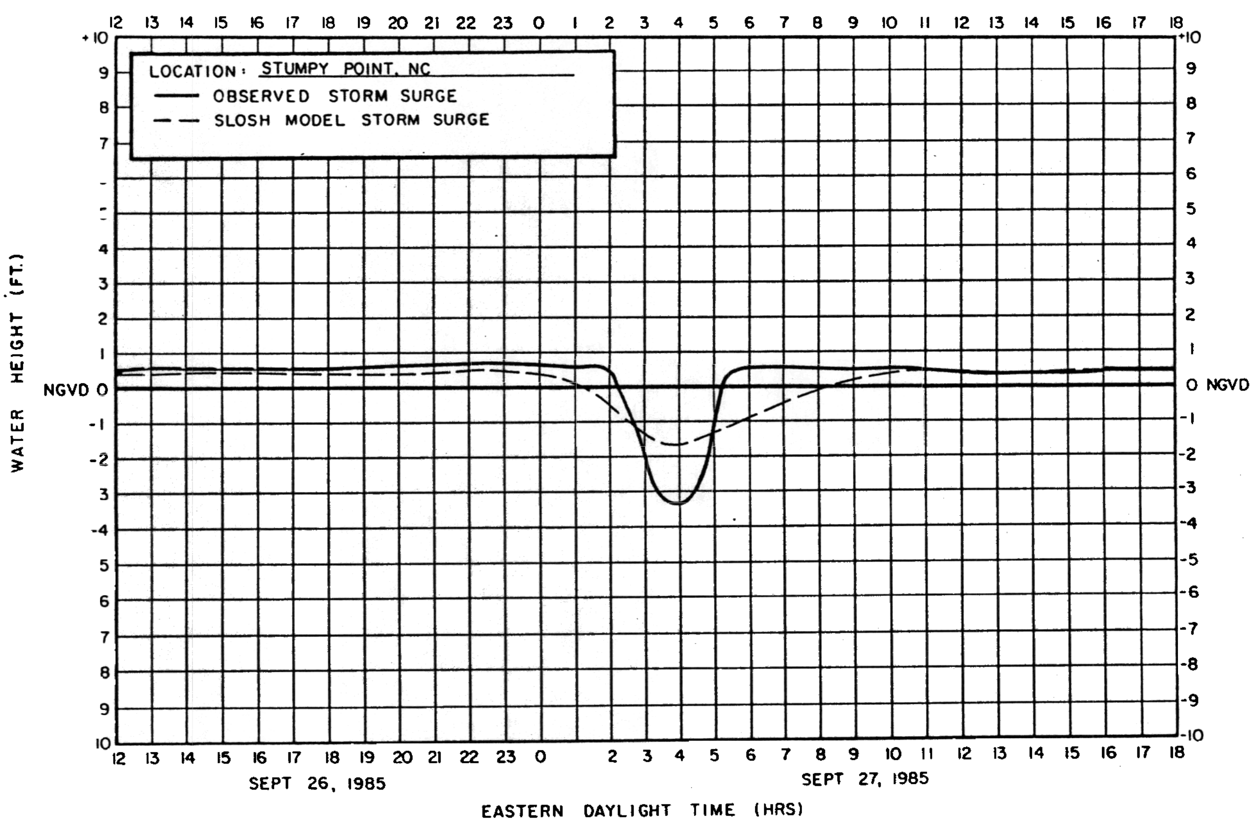
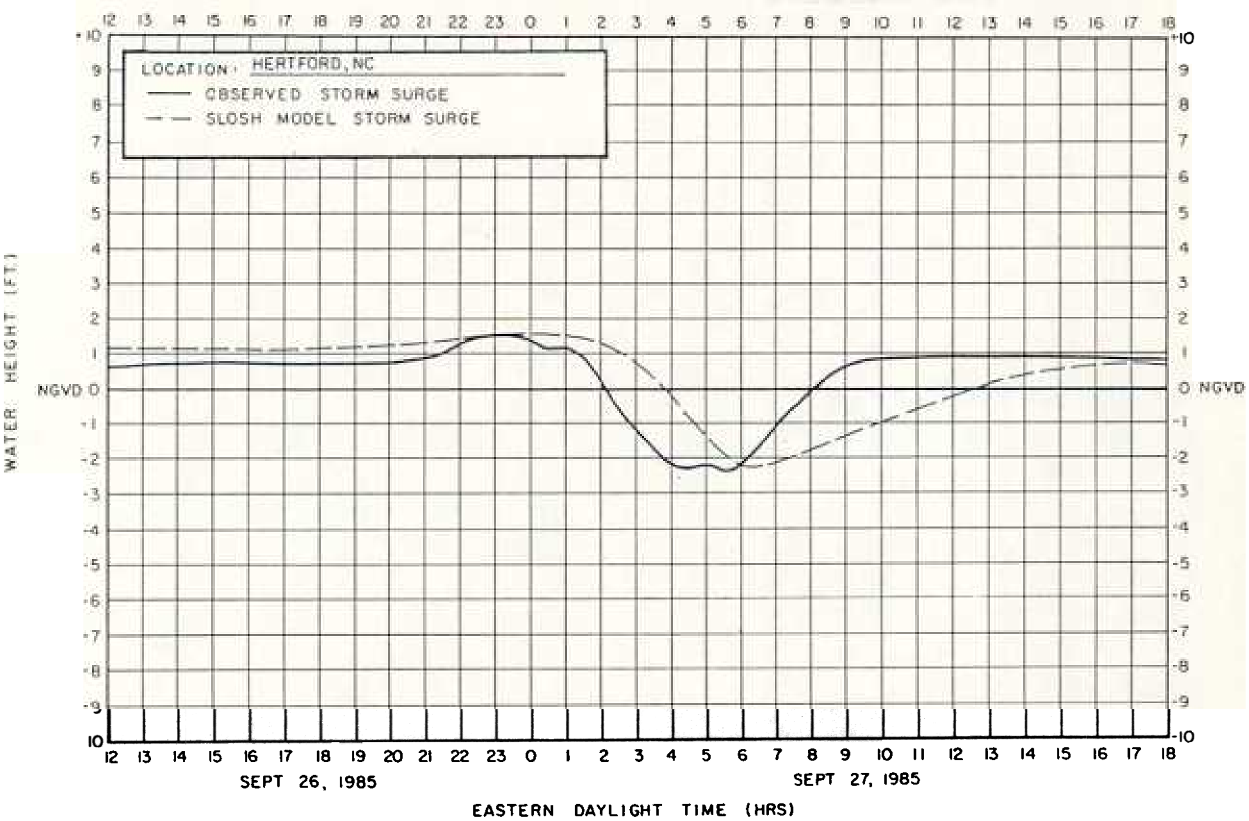


Figure 7d. Comparison of observed versus SLOSH model computed storm surge hydrographs for two locations in Figure 4.



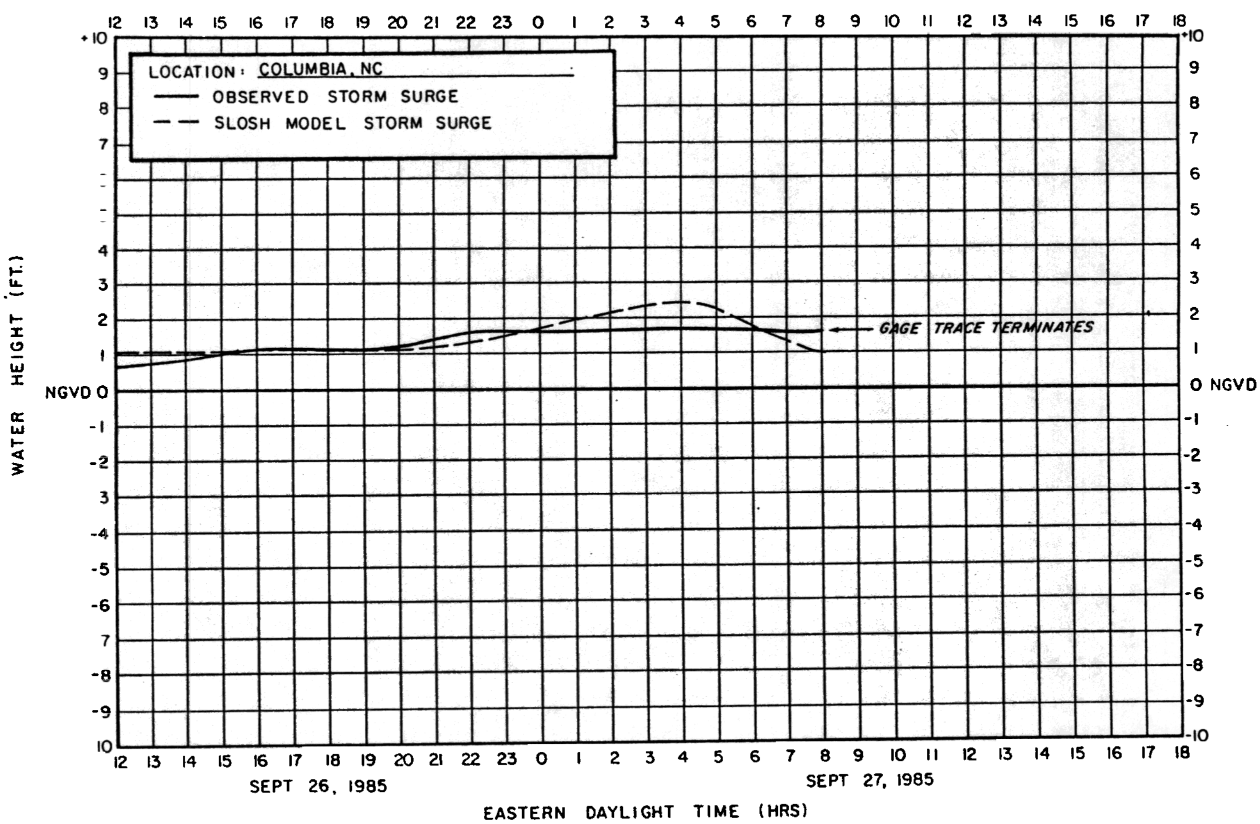


Figure 7e. Comparison of observed versus SLOSH model computed storm surge hydrographs for two locations in Figure 4.

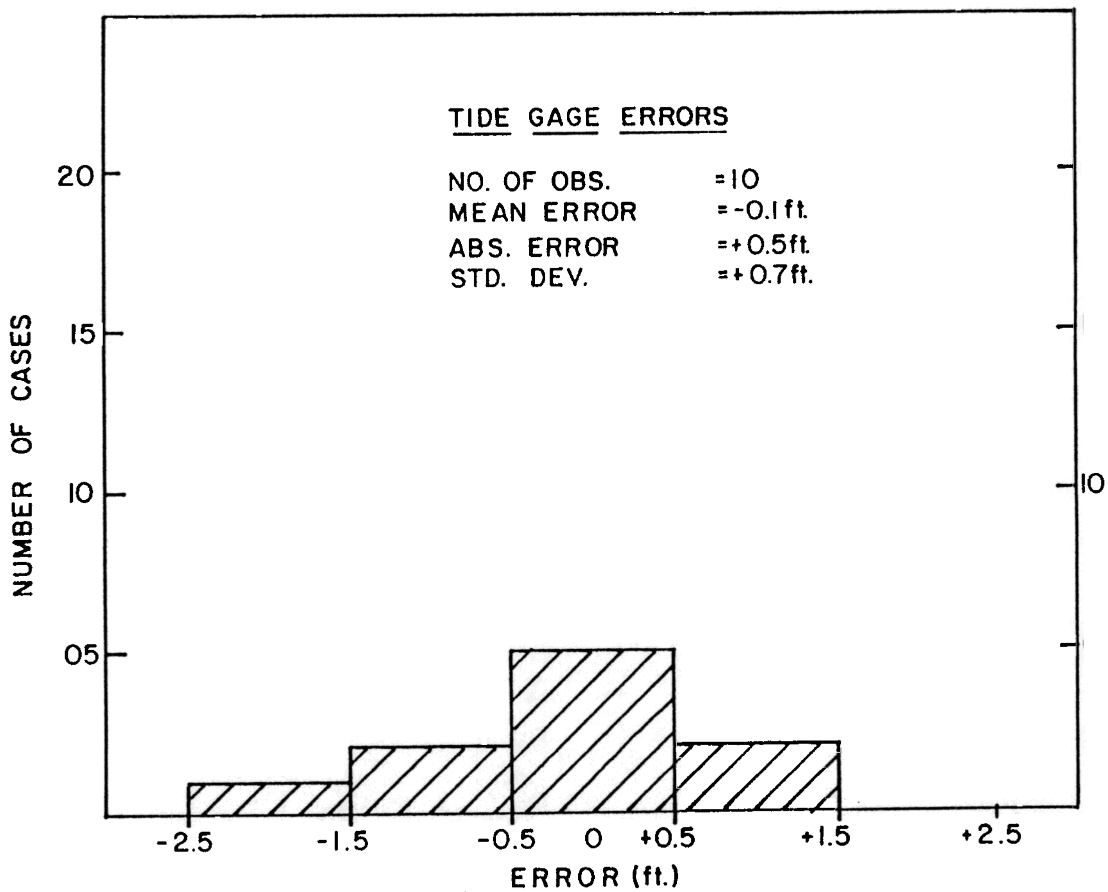


Figure 8. An estimate of the SLOSH model error distribution using tide gage data. This is a histogram with a class interval of 1.

5.2 Envelope of High Water (EOHW)

A useful product of the SLOSH model is a two-dimensional envelope of high water (EOHW). The EOHW represents the peak value of storm surge that was computed for each SLOSH grid square. Note that the EOHW is independent of time. Figure 9 shows the analyzed EOHW for Hurricane Gloria in the Pamlico Sound basin. Each labeled contour represents storm surge height. Spot values near shorelines and up rivers are also indicated. Storm surge values of less than or equal to 1 ft were not analyzed. Features of note are:

1. The 5.9 ft and 5.8 ft spot values located on the Outer Banks are Pamlico Sound shoreline maximums.

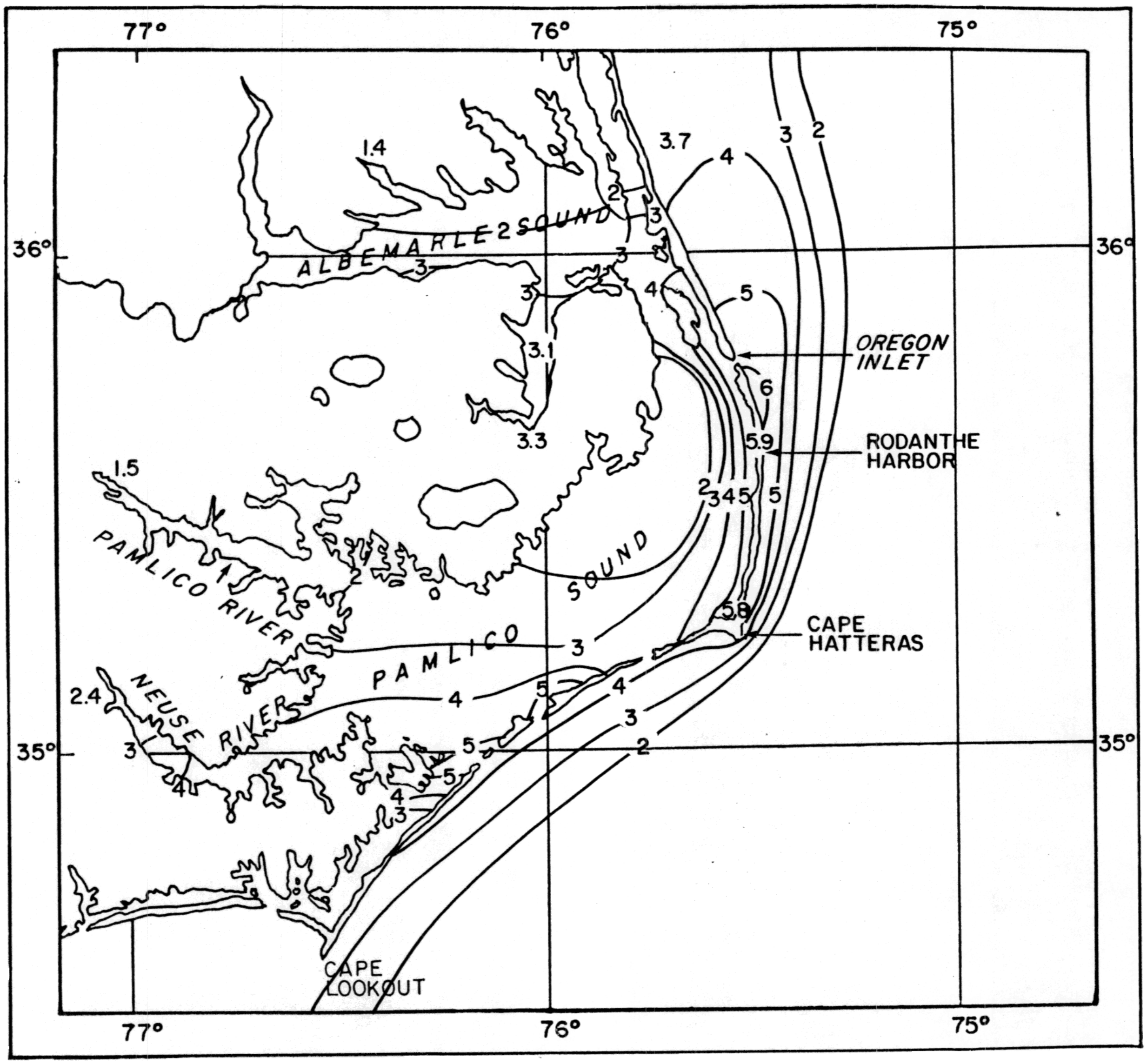


Figure 9. SLOSH model two-dimensional envelope of high water for Hurricane Gloria. Values represent magnitude of storm surge. Contour interval is 1 ft.

2. From Cape Hatteras northward to Oregon Inlet, the storm surge values on both the Atlantic and Pamlico Sound shorelines were between 5 and 6 ft.

3. The storm surge heights decrease up the Neuse and Pamlico rivers.

4. The storm surge was not localized at the shoreline but extended out on the continental shelf and into Pamlico Sound. For example, Figure 9 indicates a 5.9 ft storm surge at Rodanthe Harbor, but 3 miles west in Pamlico Sound it was still approximately 4 ft. Similarly, on the Atlantic shoreline near Rodanthe Harbor, the storm surge was nearly 6 ft and 3 miles to the east it was approximately 4.5 ft.

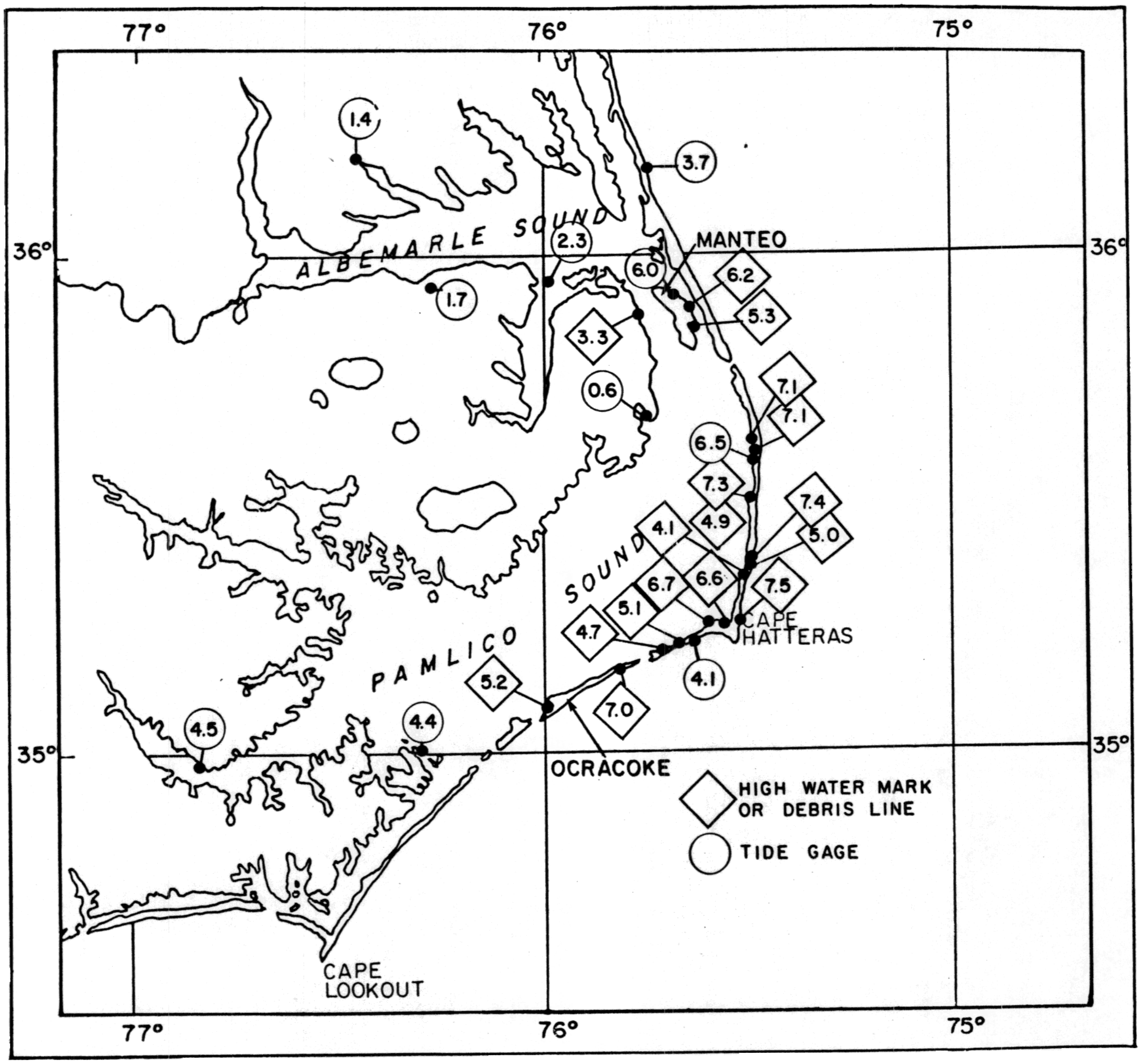


Figure 10. A diamond with a number indicates the location and value of a high water mark or debris line. A circle with a number indicates the location and value of a tide gage and peak storm surge height . Values are relative to the National Geodetic Vertical Datum in ft. N.G.V.D. is approximately equal to mean sea level.

5.3 High Watermarks and Debris Lines

In addition to obtaining the ten hydrograph traces for Hurricane Gloria, the Wilmington District of the Army Corps of Engineers also conducted a high watermark and debris line survey from Ocracoke, NC northward to Manteo, NC. All seventeen values obtained in the survey are located on or near the Pamlico Sound shoreline. Figure 10 shows the locations of the individual values which are plotted inside the diamond symbols. The values in the circles represent the peak storm surge taken from the observed storm surge hydrographs in Figures 7a through 7e.

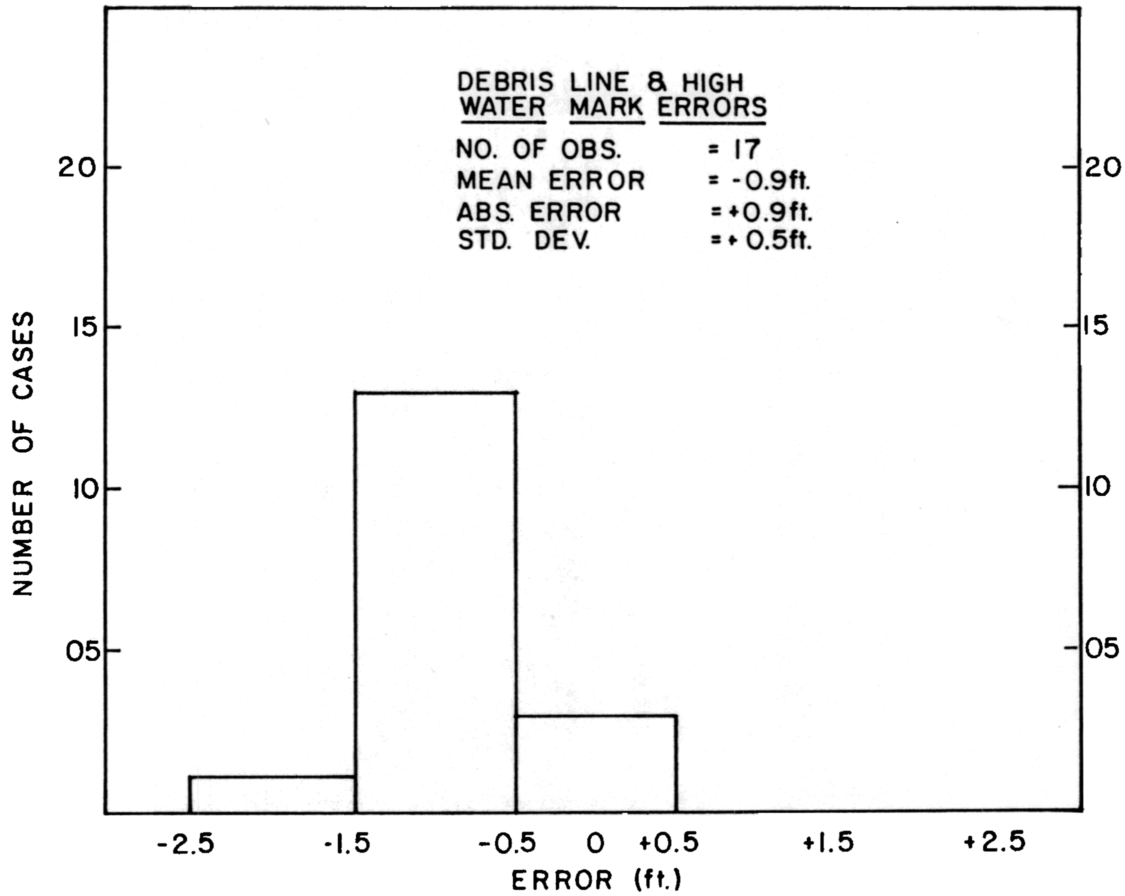


Figure 11. An estimate of the SLOSH model error distribution using high water mark and debris line data. This is a histogram with a class interval of 1 ft.

Each of the seventeen individually observed values was subtracted from its SLOSH model EOHW counterpart. As was done in Figure 8, the distribution of "errors" is displayed in Figure 11 which shows a dramatic shift of the error distribution in the negative direction when compared to Figure 8. This is also reflected in the mean error for both distributions. The debris line and high watermark values not only measure the storm surge but also reflect wave effects which are riding on top of the surge. Since the SLOSH model was designed to compute the still water height which contains no wave effects as observed by a tide gage, it is not surprising to find the differences reflected in Figures 8 and 11.

6. CONCLUSIONS

The Pamlico Sound SLOSH model, using Hurricane Gloria input data, produced acceptable peak storm surge results when compared with the observed data. Analysis of the observed Gloria hydrographic data at Cape Hatteras and Duck also shows the importance of phasing of the peak storm surge and the astronomical tide. During this event, these locations in the basin fortunately experienced peak storm surge near the time of low astronomical tide. In contrast, a peak storm surge arriving at high astronomical tide represents the "worst case" scenario.

Acknowledgments

The authors wish to thank William A. Birkemeier at the U.S. Army Corps of Engineers' Coastal Engineering Research Center Field Research Facility at Duck, North Carolina and Wallace H. DeMaurice, Official in Charge of the National Weather Service observing station near Cape Hatteras, North Carolina for their excellent data and support. Also, the support of Ken Old, Chief, Flood Plain Management Services of the Wilmington District Army Corps of Engineers and the support of both Will Brothers and Bob Buchanan of the North Carolina Division of Emergency Management is greatly appreciated. Outstanding drafting and typing services were rendered by Joan David and Sandra Potter respectively. Perceptive editorial readings were provided by Constance Arnhols, Miles Lawrence and Arthur Pike.

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