CHAPTER 56

SPLASH - A MODEL FOR FORECASTING TROPICAL STORM SURGES

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ABSTRACT

A significant portion of the damage by hurricanes is the storm surges. The National Weather Service has developed a dynamical-numerical model to forecast hurricane storm surges. The model is used operationally for prediction, warning, and planning purposes.

The model requires fixed oceanographic and real time meteorological input data. The oceanographic data were prepared for the Gulf and East coasts of the U.S. and are stored as an essential part of the program. Meteorological data for any tropical storm are supplied by the forecasters or planners using the model.

The model was applied to hurricane Camille 1969. Comparison between the observed and computed surges for Camille was satisfactory for prediction purposes.

INTRODUCTION

Coastal high waters (commonly called surge) generated by tropical storms can cause a significant fraction of the total storm damage. Because the potential for destruction can be enormous, it is useful to have at hand an estimate of the height of the potential surge and the extent of the coastal areas that can be affected by the flooding. Such an estimate can be given by a numerical model such as SPLASH.

What is SPLASH? SPLASH is an acronym for "Special Program to List Amplitudes of Surges from Hurricanes." It is the name of a computer program for a dynamical surge model to predict hurricane storm surges. The program is used operationally at the National Weather Service (NWS).

SPLASH is a numerical-dynamical model to predict storm surges generated by tropical storms (Jelesnianski 1972, 1974, 1976). The model solves the linearized transport equations of motion with storm driving forces on the surface and bottom stress. The model uses an input basin truncated from the ocean which contains coastal areas of interest. We use a truncated basin of proper size so that numerical computations can be performed at reasonable cost and yet not compromise on the dynamics of the open coast surge.

A very useful adjunct of the SPLASH model is a shoaling curve. (The meaning of shoaling correction will become clear in later parts of the paper.) The shoaling curve indicates the relative increase (or decrease) of the surges if a storm's landfall position changes along the coast. This is important because the surge varies as bathymetry varies along the basin, and bathymetry relative to the storm will vary as landfall is varied. For application purposes, the shoaling curve serves as a powerful tool to determine how surges change if the landfall point is varied. Also, with the aid of the shoaling curve, dangerous and ill-conditioned situations can be anticipated without resorting to extensive computer runs. For planning purposes, a shoaling curve is most effective to obtain added information with a minimum number of computer runs.

SPLASH is used operationally at the National Hurricane Center of NWS in Miami. In this paper, we will discuss the model, the basin, input data, a shoaling correction, and applications of the model. The program is applicable for the Gulf and East coasts of the U.S., from Brownsville, Texas, to Shinnecock Inlet, Long Island, N.Y. This stretch of coast is approximately 300 miles long. Recently, we extended the application of SPLASH to the New England area up to the U.S.-Canadian border.

The SPLASH product is also used to estimate flooding potentials in the coastal areas of the U.S. and Puerto Rico (Jelesnianski and Barrientos 1973). This work is being done by the National Oceanic and Atmospheric Administration (NOAA) as a reimbursable project for the Federal Insurance Administration of the Department of Housing and Urban Development to fix flood insurance rates. A discussion of the NOAA procedure to compute storm tide frequencies is in Myers (1975).

SPLASH MODEL

The SPLASH model has been partially documented in three publications, the mathematical technique in Jelesnianski (1967), and three operational techniques to run and interpret the results for forecasting purposes, Jelesnianski (1972, 1974, 1976). The mathematical techniques are adapted from Platzman (1963). The tropical storm model used to generate surges is discussed in Jelesnianski and Taylor (1973).

SPLASH is a dynamic model which numerically solves the linearized transport equations of motion in a basin bounded by a curvilinear parallel surface;

the curved coastline is a vertical wall and the remaining three boundaries are open to the sea. Initially, the sea in the basin is assumed at rest. Driving forces from the storm are applied on the water's surface; also, a time-history formulation of the bottom stress is utilized.

Initially, the storm is set at zero strength and then allowed to grow to maturity in a continuous but rapid manner. Initial positioning of the storm is unimportant, if on reaching maturity the storm lies in deep water beyond the continental shelf. For storms traveling more or less parallel to the coast and along the continental shelf, initial placement must be at least sufficiently distant from the area of interest so that the surge has time to form; this can be determined by empirical tests through variation of initial storm placement, growth time of storm to maturity, etc.

The grid distance used in our numerical computations must be fine enough to portray not only the storm surge but also the driving forces of the storm. The grid length may be determined by empirical tests.

On the two lateral, open boundaries, the boundary condition used is $\partial V/\partial y=0$; where V is the component of transport along the coastal y-coordinate. This boundary condition is arbitrary and used purely for convenience. In any case, reflections from these boundaries eventually corrupt the interior of the basin. However, if the boundaries are placed sufficiently far from an area of interest along the coast, there will be a time interval before the area is corrupted by reflections from the boundaries. The placement of these side boundaries are determined by empirical tests.

The deep water open boundary is placed somewhat arbitrarily, near the juncture of continental shelf and slope. In deep water away from coastal influences, the dynamic surge is small and corresponds very closely to the inverted barometer effect. The boundary condition used is $h=h_0$; where h_0 is the static height of the surface.

BASIN AND STORM DATA

The dynamic model, SPLASH, computes storm surges via numerical computations for particular storms in particular basins. A basin is described by two-dimensional depth fields, coastal boundaries, local and geographical references, and geographical orientation. To acquire basin data, we used the National Ocean Survey marine charts with scale 1:500,000. The chart delineates coastlines, the continental shelf, dept contours in shallow water, and spot depths in deep water. Detailed descriptions of preparing basin data are presented in our two reports to the Federal Insurance Administration (Barrientos and Jelesnianski, 1973; Barrientos and Chen, 1974).

For orientation purposes regarding the basin, the observer is at sea and facing the coast. The coast to his right will be considered relative north, to his left relative south. Crossing angles of the storm's path to this oriented coast will be described as follows: A storm moving from relative north has a crossing angle of 0°, moving normal to the coast from sea, a crossing angle of 90°, exiting (moving from land to sea), a crossing angle of 270°, etc.

Figure 1 positions pre-selected stations on the East and Gulf coasts of the U.S. used by the SPLASH operational model to indicate approximate positions of basin centers. Some of the location names are abbreviated. The abbreviations are exactly as used in the model for routine operations at NOAA's National Hurricane Center. The stations are 100 miles apart (more or less) and are situated at (or near) the center of the various basins.

To refine the technique for planning and flood insurance study, we find it necessary to add additional basins between the stations (Figure 1); i.e., basins are now overlapped every 50 miles instead of every 100 miles. Geographical locations of the basin centers are included in the basin data. We have not identified the additional basins with any new cities because we want to keep these reference cities to a minimum.

Due to computer core limitations and economics of machine operations, it is impossible to consider an entire ocean as a basin. Open boundaries are therefore used as an artifice in the model. (The basin used is 600 x 72 statute miles in size and grid length is 4 miles. Thus, total grid points are 1/2(151 x 20) = 1510 for each basin.) A more detailed description of basin preparations is in the report of Barrientos and Jelesnianski (1973).

Two versions of the dynamical model are in use. SPLASH I to compute storm surges for landfalling (or exiting) storms only, and SPLASH II for storms moving along the coast. SPLASH requires input meteorological parameters that have to be supplied by weather forecasters. The data for a computer run are shown schematically in Figure 2. In SPLASH I, these are: (a) the pressure drop, $\Delta p = p_\infty - p_o$, where p_∞ is the ambient pressure outside the influence of the storm and p_o is the central pressure of the hurricane; (b) the radius of maximum wind R; (c) the vector storm motion, U_s/Θ, where U_s is the storm speed of translation Θ is the compass (meteorological) storm direction of motion; and (d) landfall point referenced to stations or cities (Figure 1).

The landfall point is important, for it determines which basin will be used in the model. SPLASH I deals with a steady state storm, of constant size and intensity, and constant, linear, vector storm motion. This idealization in SPLASH I has been proved useful in actual operations and climatological studies.

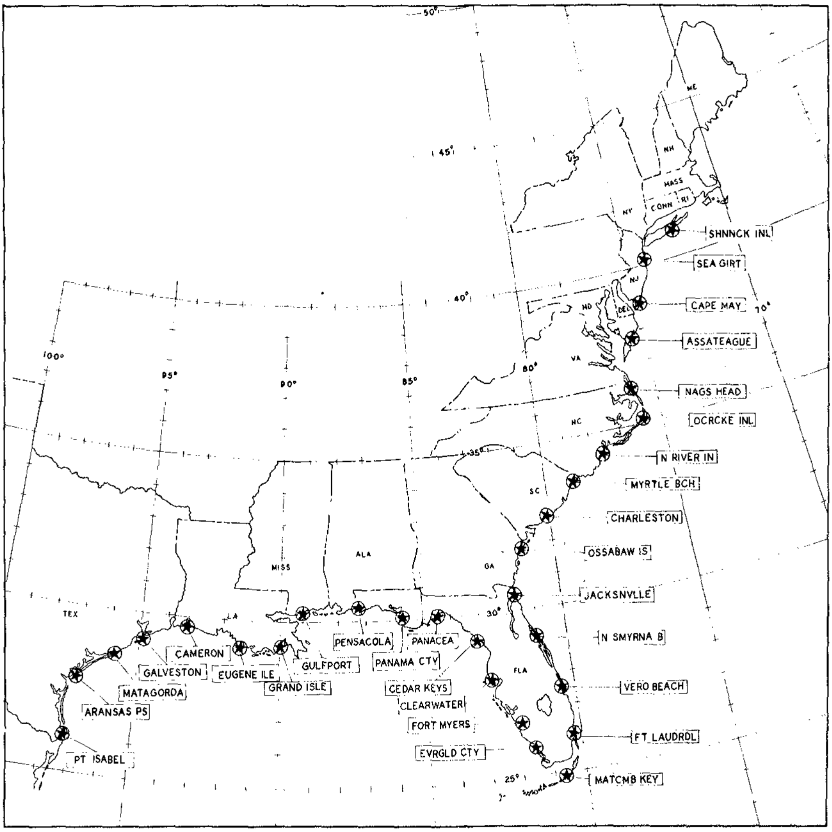

Fig. 1. Selected stations on the East and Gulf coasts of the U.S., used by the SPLASH operational model to indicate positions of basin.

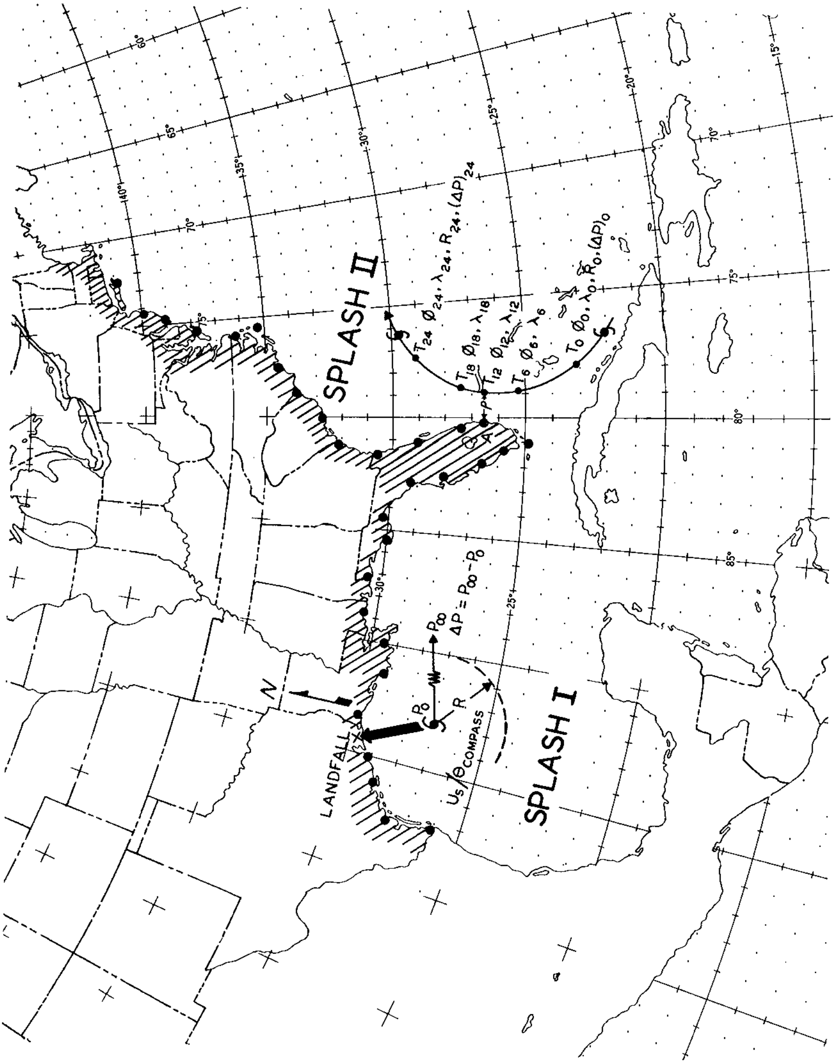

Fig. 2. A schematic representation of the use of the SPLASH programs and input meteorological data.

In contrast, SPLASH II deals with variant conditions of the storm and its track; i.e., a nonsteady state storm. The storm track is quite general; it can landfall (or exit--moving from land to sea) at any angle with the coastline, move parallel to the coast, be bow-shaped, etc. The speed of the storm can be variable along the storm track and even remain stationary. Note that SPLASH I is a special case of SPLASH II. For this program, the weather forecaster supplies a 24-hour track segment (Figure 2). The track is defined by latitude, ϕ, and longitude, λ, for five points on the track staggered six hours apart for a 24-hour period. These input latitudes and longitudes define the track, and the speed of propagation of the storm, i.e., vector storm motion. Other input data are the size of the storm, that is the radius of maximum wind, at initial and final time of the 24-hour period; also, the intensity or pressure drop at initial and final time of the 24-hour period. Both the size and the pressure drop can vary with time. The storm track is very important in the surge computations. A slight shift of the track either toward the coast, or toward the sea, can make a significant difference in coastal surges (Jelesnianski and Barrientos, 1975). Several dynamic phenomena, such as resonance and wave transients, can be generated by storms with generalized motions (Jelesnianski, 1974).

With the basin data and input meteorological parameters, peak surges, profiles, and envelopes of high water along the coast are computed by the SPLASH model.

SHOALING CORRECTIONS

A very important property derived by SPLASH is a normalized shoaling correction. It is a powerful tool to correct surge computations along the coast if the landfall point is shifted.

A shoaling curve for both the East and Gulf coasts is derived from the ratio of the peak surge computed in a local basin to that of the peak surge computed in a standard basin. A shoaling correction curve in a particular basin indicates the change in the coastal surge envelope* as it is displaced by a change in landfall point. The change of the surge envelope is due to changes in the bathymetry of the continental shelf with respect to landfall point. We used a standard storm and standard vector motion in the computations. (A standard storm has a maximum wind speed of 100 mph.) Peak surges computed by the SPLASH model with a standard storm in local basins are normalized with the peak surge computed in a standard basin. A standard basin has a continental shelf sloping linearly at 3 feet per mile, with a depth of 15 feet at the coast; its coast is a straight line, and the depths

*Envelope means the plot of the coastal high water heights during passage of a storm. Highest surges at various points along the coast don't occur simultaneously.

vary in one dimension only. This standard basin may be considered as the mean depth field averaged throughout the continental shelf of the Gulf and East coasts.

We define the standard vector motion to be perpendicular to the coast with a speed of 15 mph from sea to land. Hurricanes, of course, ordinarily do not landfall precisely normal to the coast, but for the purpose of computing shoaling curves our approach is the most convenient. Another alternative is to compute shoaling curves for various track angles to the coast. This kind of approach however would require voluminous amounts of data and staggering computer expense.

Storm surges are related to storm size (radius of maximum wind). For the same maximum wind, the larger storm will give larger surges, up to a critical size. Storm size is even more important for storms moving along the coast (Jelesnianski, 1974; Jelesnianski and Barrientos, 1975).

For convenience in our derivation of shoaling curves, we form the storm's pressure drop so that maximum winds are 100 mph; this wind is maintained for any storm size and also for latitude of real basins on the coast. We can follow this procedure because the storm model accommodates these parametric values (Jelesnianski and Taylor, 1973). In previous work, we found that peak surges along the coast depend only mildly on latitude, but to some extent on radius of maximum wind (storm size). Thus, we computed two reference peak surges in the standard basin with a standard storm for two storm sizes, or radii of maximum winds, of 15 and 30 miles. These two peak surges are used to scale maximum surges computed with the same storms in real basins.

To produce peak surges for standard storms along the Gulf and East coasts, we made SPLASH runs on all 50 basins for two storm sizes: 15 and 30 miles radii of maximum wind. We then plotted the resulting peak surges on the coast. For each basin, we chose a minimum of three landfall points: at the center of the basin baseline, and 16 miles on either side of the center. In complicated locations, e.g., Mississippi Delta, Cape Fear, and Sandy Hook, we made more runs to get better resolution for the shoaling curve. For landfall on either side of the basin center, the track was made normal to the true coastline.

In addition to the location of peak surges for each storm size, we successively plot a portion of the computed envelope on either side of the peak surge. Figure 3 is an example of the process. We plot only a portion of each envelope that is within about one storm radius on both sides of the peaks. We now hand draw an envelope of peak surges, that is, an envelope of surge envelopes. This is done separately for the two storm sizes. The final envelope of peak surges is an unscaled shoaling curve.

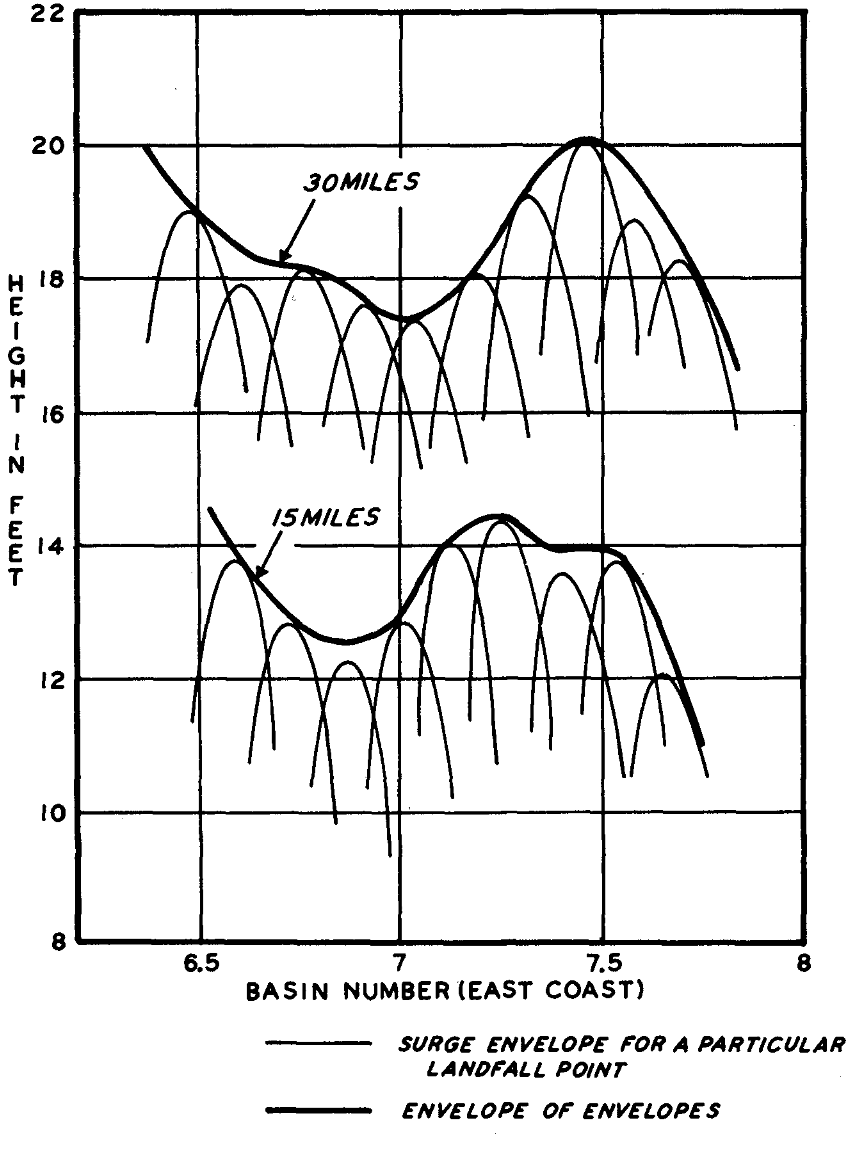

Fig. 3. Analysis of the envelope of surge envelopes to arrive at shoaling curves. The upper envelope is for storm size of 30 miles, the lower for storm size of 15 miles.

In Figure 3, some peak surges are not on the shoaling curve because subjective adjustments of the envelope were made considering the bathymetry of the continental shelf. If more runs of the SPLASH program were made at closer spacings along the coast, then peak surges would have been computed to fit the shoaling curve. The shoaling curve was based on all individual envelopes as shown in Figure 3.

We don't want to be constrained to peak surge values generated by standard storms only. Hence, the shoaling curve must be scaled locally for each basin if it is to be useful in the SPLASH model. The procedure for scaling is now discussed.

The peak surge computed for a standard storm along the coast is a function of the slope of the continental shelf. Hence if we scale the final envelope of Figure 3 according to the peak surge generated by a standard storm in a standard basin, then we reduce the final envelope to a common denominator. We call such a scaled, final envelope a shoaling curve. The shoaling curves for the Gulf and East coasts are shown in Figures 4a and 4b for both 15- and 30-mile storm sizes. The curved coasts are extended linearly for convenient display. The ordinate is the shoaling factor or surge potential (the ratio of peak surge on any point of the coast to that of peak surge on a standard basin).

Also included in Figures 4a and 4b are depth contours on the continental shelf. There is close correlation between the shoaling curve and depth contour, i.e., the shallower the shelf the higher the potential. This is illustrated in Eugene Isle in the Gulf and Ossabaw Island in the East coast. The surge potential is small between Pensacola and Panama City in the Gulf and on the east coast of Florida due to the narrow shelves in these areas.

The shoaling curve varies by a factor of about four on both coasts. The highest surge potential on the Gulf coast is higher than on the East coast for both storm sizes. We can conclude that for the same storm, the Gulf coast has higher storm surge potential than the East coast. However, we point out that storms are not necessarily the same on the Gulf and Atlantic shelves.

To correct a computed surge envelope for alternate landfall points, we have designed an individual shoaling correction curve for each basin. The basin shoaling correction curve is composed as follows: (1) Read from Figure 4a the shoaling value at the center of each basin. (2) Along the shoaling curve of Figure 4a for a given basin, divide the shoaling factors by the shoaling value from (1), for a shoaling correction curve. The value of the correction is unity at basin center. Because the coastal distances

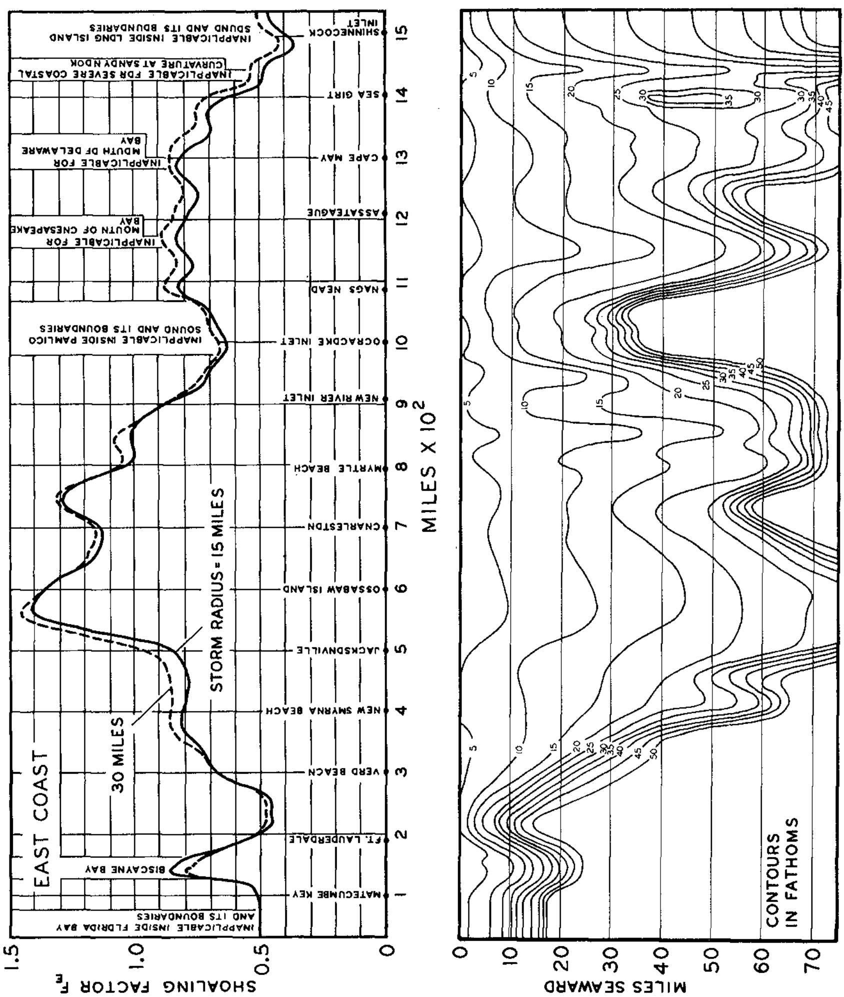

Fig. 4a. Shoaling correction curves along the Gulf coast.

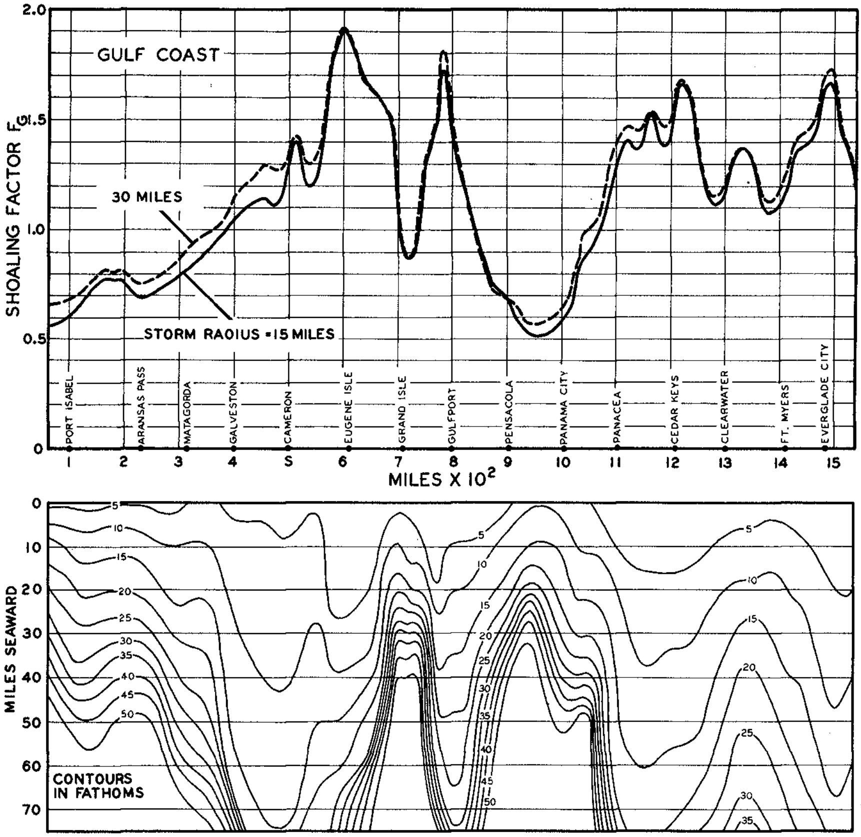

Fig. 4b. Shoaling correction curves along the East coast.

represented by abscissa distances on Figure 4a are curvilinear lengths, whereas the SPLASH model calculations are for equidistant coastal points on a tangent to the coast (a baseline), then the correction curve must be compressed to the linear lengths along the baseline.

After local shoaling corrections are computed, they are stored in the SPLASH program for instant use. The basin shoaling corrections are part of the basin data. The corrections operate on a computed surge envelope; if landfall point is hypothetically shifted on the coast, then the computed envelope is also shifted and operated on by the shoaling curve to correct for changing bathymetry.

The basin shoaling corrections are included in the SPLASH program for each of the 58 basins in the Gulf and East coasts. The program is used operationally at the National Hurricane Center, NWS and by the Office of Hydrology, NWS, NOAA, to compute outer coast surges with climatological input data for flood insurance projects.

APPLICATION TO HURRICANE CAMILLE 1969

To run the SPLASH program in NOAA, users will feed the computer with necessary meteorologic data as shown in Figure 2. For users without access to NOAA computers, we have an earlier version of the program available at the National Technical Information Service. The program includes the file of basin data.

To illustrate the SPLASH program we show a verification run for hurricane Camille 1969. Camille was probably the most devastating hurricane to hit the coast of the U.S. The important result of SPLASH is shown in Figure 5 for Camille.

On the top of Figure 5, the input data that the forecaster supplied are repeated for a visual check. The next group of data are the correction factors for the pressure drop. This is useful to correct the computed surges without rerunning the program. We gave corrections for ± 10 mbs deviation of pressure drop.

We also predict the astronomical tides, above MSL, for various stations near the Landfall point. In operational use, the forecaster's may modify the computed surges accordingly. We don't add the astronomical tide to the storm surges because it is very hard to phase the two waves together.

The main output of the SPLASH program is the surge envelope indicated by asterisks in Figure 5. The symbol * represents the landfall point of

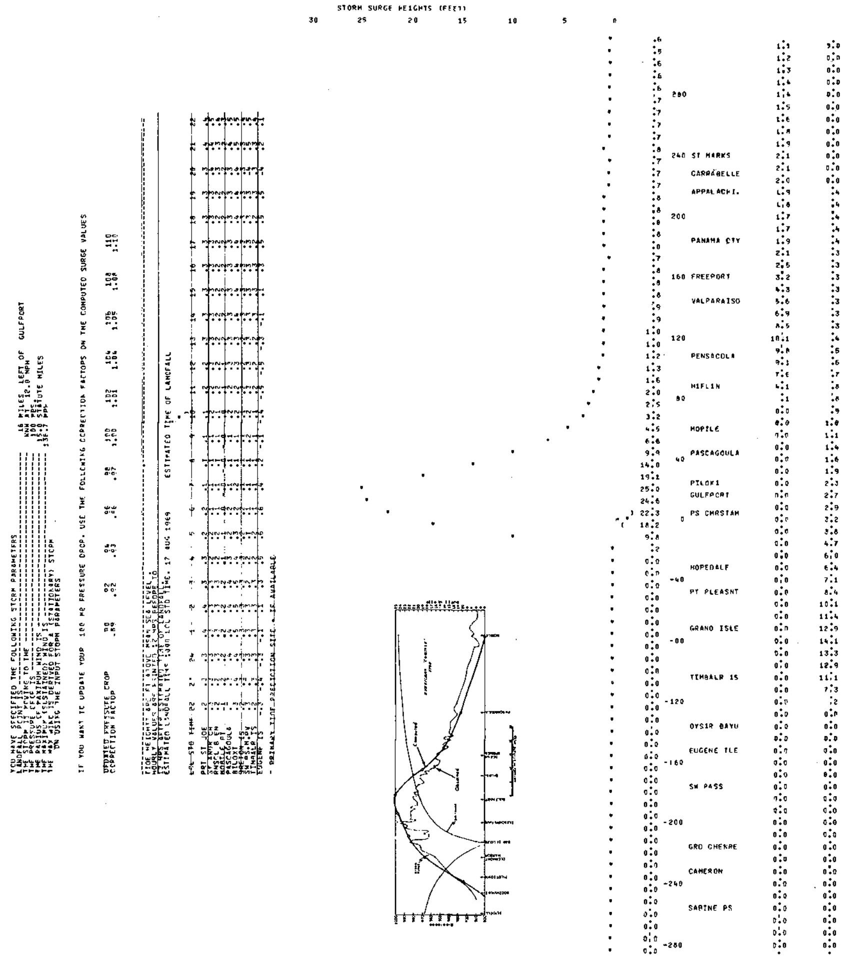

Fig. 5. A verification run of the SPLASH program for hurricane Camille 1969.

the hurricane. The peak surge generally occurs at a distance equal to the radius of maximum wind, R to the right of landfall. Below the graph, we print the values of the computed surge envelope. Note these values are the highest surges on the coast but not necessarily occurring at the same time. For Camille, the computed peak surge is 25.0 ft. We also print the stations along the coast for reference and the distances along the coast from landfall point.

The second row of numbers, from the bottom of Figure 5, is the surge envelope if the landfall is shifted 100 miles to the right; the first row is when landfall is shifted 100 miles to the left. It is possible to compute these surge values because of the shoaling correction factors.

The inset in Figure 5 shows a comparison of the observed surges and computed surges by SPLASH for Camille. Considering that the observations are taken at various distances from the coastline, we believe the comparison here is quite good. Also errors in measurements are very difficult to account for.

SUMMARY AND CONCLUSIONS

Rising coastal waters are generated by hurricane driving forces. These forces are low atmospheric pressure (inverted barometer effect) and wind force. Thus a rotating mound of water forms under a storm in deep water. If the variable momentum in the sea (i.e. rotating mound of water or vorticity) is transformed into divergence, then storm surges are further generated. The bathymetry or sloping depths of continental shelf and the coastal boundary are effective mechanisms to transform vorticity to divergence.

NOAA has an existing dynamical-numerical model to compute surges, called SPLASH. To compute surges with this model, basin data are stored for all basins of the Gulf and East coasts of the United States. Basin data consist of depth values at grid points, orientation of the basin with respect to north, local and geographical references, and shoaling corrections.

We have numerically computed surge envelopes at equally spaced landfall intervals of 16 miles, along the 3000-mile stretch of the Gulf and East coasts. At each landfall point, we made computer runs for two storm sizes, 15- and 30-mile storm radius. We then derived envelopes of peak surge to obtain shoaling curves. When the storm size is not 15 or 30 miles, then whichever of the two sizes is nearest to R is used, e.g., R = 25 the shoaling curve for R = 30 is used.

Finally, shoaling corrections were prepared for each basin in the SPLASH model.

The shoaling curves are used: (a) for comparing the peak surge potential at one location to another, along the Gulf and East coasts, provided the storm characteristics are the same; (b) for pointing out critical coastal areas to planners and developers; (c) for guiding climatologists in collecting and processing hurricane data; and (d) for giving meteorologists information on the isobathic effects on surge along coastal areas.

The shoaling correction curves, localized for each basin, are used even more extensively. In NOAA's work for flood insurance projects, a shoaling correction curve is used to redefine the surge envelope for variable landfall points along the coast, without additional computer runs. Shoaling correction is very convenient for the frequency method of NOAA for estimating flood potentials on the outer coast. In studies for a coastal county, the outer coast tide frequency curve is based on many hypothetical hurricanes determined from hurricane climatology. Because of shoaling corrections, it is not necessary to run the SPLASH program with these storms at successive landfall points on the coast; it is only necessary to run storms for one landfall point.

In operational use of SPLASH, we provide the forecasters with two additional surge envelopes based on landfall point left or right of the forecast landfall. Additionally, the peak surges for the 600-mile long basin are included in the output for any conceivable landfall point in the basin. We are able to provide this extra information because of shoaling correction curves.

We showed the SPLASH run for hurricane Camille 1969. The comparison between the observed and computed surges is quite good; although it is not perfect. Similar runs have been performed for many other historical storms.

Since there are many storm parameters which can be adjusted, as well as coefficients in the equations of motion, a model comparison against a single event does not constitute verification. Our model was verified against 43 actual recorded storms along the Atlantic and Gulf coasts and has been field tested for six hurricane seasons. The calibration for our model is in a global (not local) sense, and no attempt was made to force agreement between computed and observed results for particular storms in local regions. This is one reason why our verification for hurricane Camille is not perfect.

Simple versions of SPLASH are being used in the Philippines, India, and Hong Kong. SPLASH was modified for application to these countries because they don't have similar big computers as the U.S. They told us that satisfactory results were obtained in the SPLASH applications for their areas of the world.

ACKNOWLEDGMENTS

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