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DEPARTMENT OF COMMERCE
UNITED STATES OF AMERICA

SPLASH (SPECIAL PROGRAM TO LIST AMPLITUDES OF SURGES FROM HURRICANES)

Part Two. General Track and Variant Storm Conditions

Chester P. Jelesnianski

Systems Development Office
Silver Spring, Md.
March 1974

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UNITED STATES
DEPARTMENT OF COMMERCE
Frederick B. Dent, Secretary

NATIONAL OCEANIC AND
ATMOSPHERIC ADMINISTRATION
Robert M. White, Administrator

NATIONAL WEATHER
SERVICE
George P. Cressman, Director

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SPLASH
(SPECIAL PROGRAM TO LIST AMPLITUDES OF SURGES FROM HURRICANES)
PART TWO. GENERAL TRACK AND VARIANT STORM CONDITIONS

Chester P. Jelesnianski
Techniques Development Laboratory,
Systems Development Office, NOAA, Silver Spring, Md.

ABSTRACT. Part one, an operational computer program, has been expanded in part two to accommodate storms with generalized motions of not too great complexity. Examples are storms that move alongshore, recurve, remain stationary, accelerate, and landfall (exit). Also, storm strength and size are allowed to vary in a continuous monotonic manner with time. Surges generated by these generalized storms are complicated in space and time, and they can occur on an extensive coastline (hundreds of miles).

Five track positions (spaced at 6-hr increments on the storm path) and simple meteorological parameters are the meteorological input for the program. Detailed meteorological phenomena such as explosive deepening of storms, violent changes in storm track, and sudden accelerations of the storm are not considered.

In part two, we discuss--in a qualitative and heuristic manner--several strange dynamic phenomena generated by the storms with generalized motions. Several special examples are computed by the program and then interpreted for forecasting.

I. INTRODUCTION

In part one (Jelesnianski 1972, hereafter known as SPLASH I), operational techniques were developed to predict tropical storm surges on the open coast. Storms conveniently were restricted to strike the coast after/before traversing continental shelves, on a straight-line track, with constant speed, and with strength and size invariant with time.

In this follow-up report (part two, hereafter known as SPLASH II), we remove some of these restrictions. The prediction scheme is extended to accommodate storms that travel along coastlines, do not necessarily landfall (exit), follow curved tracks, recurve, become near stationary or slow moving, gently accelerate in speed, and vary <u>monotonically</u> with time in ly great to warrant the effort required to develop a stable finite-difference scheme for the resulting equations.

The natural surface of the basin is distorted into a rectangle; on the rectangular basin, we use a cartesian orthogonal grid system in our computations.[4] Because we assume gentle curvature[5] for the natural coast, our model basin[6] approximates the natural one only for small distances on either side of station. Therefore, we accept surge computations in the neighborhood of station but remain suspicious of computations at large distances from the basin's center. The depths in the basin vary in two dimensions and are read from marine charts.

B. Storm Tracks

Storm tracks are not always representable with simple analytic curves. If the track on the shelf is near normal to the coast, then it can be represented with a straight line.[7] If storms recurve or move alongshore, it is difficult to represent such a track linearly. Note:

1. For storms traveling linearly and near normal to a straight-line coast, a small variation in storm speed is more significant for surge values than a small variation in storm direction. Consequently, a mildly curvilinear track on the shelf can be represented by a straight line; however, the position of the storm with time--that is, storm speed--must be accurate.

2. For storms traveling linearly and near parallel to a straight-line coast, a small variation in storm direction is more significant for surge values than a small variation in storm speed. Thus, we must specify accurately the natural curvilinear track in space but less so in time (i.e., the storm speed[8] is not so critical in this case).

3. For intermediate linear tracks between normal and parallel to the coast, a small variation in any component of vector storm motion can affect surges significantly. Hence, for recurving or erratic storm tracks, we accurately must specify the natural curvilinear track--both in space and time.

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[4] We desperately need an orthogonal curvilinear coordinate system in our surge model that conforms to the natural coastline. This would be a most interesting future research project.

[5] By "gentle curvature," we mean smaller curvature than the size of the tropical storm.

[6] The "model basin" is a subbasin (600 mi x 72 mi) of the ocean.

[7] The average shelf width is about 70 mi; the track turns very little during shelf traverse, except in the case of a recurving storm.

[8] An exception occurs here if conditions are ripe to generate a kind of resonance phenomena (Jelesnianski 1970). The surge forecaster must understand that distance of the storm from the coast, relative to storm size, is an important factor. If the distance becomes greater than, say, one diameter (twice the radius of maximum winds), then the surges on the coast decrease rapidly with increasing distance.

4. For a storm track of sizeable length on the shelf, which is truncated and initialized on the shelf (all for computational convenience), there will be strange and fictitious surge phenomena with which to contend. This complication and others are discussed in appendixes II and III.

In our storm surge model, only a segment of the entire storm track is used. A curvilinear track on a weather chart must be described in space as a function of time (i.e., storm speed along a track); there are many ways of doing this, depending on the precision desired. We have devised a simple and direct scheme--at the expense of some accuracy--for the use of weather forecasters:

1. Isolate a small coastal section[9] for consideration; on it, select one of the 30 stations (fig. 10) nearest to the section's center.

2. Consider a segment of track for 24 hr of storm motion and locate its midpoint more or less abeam to station. Call the beginning of the segmented track T_0 to correspond with real time. Note: it is not required that the storm be exactly abeam to station at T_{12} hr or that T_0 be off the Continental Shelf either on land or sea; also, T_{12} need not be meteorological map times of, say, 00, 06, 12, or 18 hr. In fact, T_{12} can vary between 01 and 24 integer hours.

3. Ascertain latitude and longitude at 6-hr intervals on the track, beginning at T_0 and terminating at T_{24}; figure 1 shows these five points.

SPLASH transforms the points $T_0 \ldots T_{24}$, located on the spherical Earth, onto our model basin. This is done by orientating the plane surface of our model basin tangent to the spherical Earth at station and then projecting the track points on the sphere onto the surface of the basin;[10] details are not given here. It is possible to fit a quartic through the track points; however, no two people will read identical coordinates on a weather chart. Instead, the program fits a cubic curve--in the least squares sense--for the five points on the plane; the details are not given here.

Conceivably, track information could be required before T_0 or after T_{24}. To blindly extrapolate the truncated track is dangerous; instead, the program extends the cubic curve tangentially at T_0 and T_{24} (fig. 1); the details are not given here.

On the cubic track and its extrapolated extensions, the program interpolates for hourly storm positions and computes the linear distances between hourly positions. The storm is

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[9] By "small coastal section," we mean 100-200 mi in length.

[10] The plane is a polar stereographic projection. We have used a Mercator chart to position our model basin; the distortions from sphere to polar stereographic and to Mercator chart are small even at the ends of the model basin.

allowed to travel with linear vector motion along these directed segments at hourly speeds equal to the segment distance.

The program determines the closest approach of the storm to station to the nearest hourly storm position; it initializes computations 12 hr before and terminates computations 6 hr after the closest approach. For convenience, computations are limited to this 18-hr span. This limitation should be understood clearly, and the surge forecaster should not accept computed surge values on coastal segments adjacent to a component[11] of track motion that is not used; the only track used in the model is the 18-hr segment.

Because the curvilinear track is represented by a cubic, there are restrictions. We insist on civilized tracks; by this we mean no cusps, circular gyrations, or other tortuous motions. The user readily can determine (by eye) how well the discrete track points will describe the natural track. For exotic or uncivilized motion--say, for some unusual historical storms--a much more detailed description of the track is required (i.e., hourly storm positions); this can be incorporated in future models if such accuracy is desired.

C. Meteorological Parameters

A storm spending considerable time on the Continental Shelf may suffer changes in storm strength and size. There are many ways of representing variant storm parameters[12] in our surge model, depending on the precision desired. We have devised a very simple scheme--at the expense of some accuracy--for the use of weather forecasters:

1. Ascertain (observe or forecast) the pressure drop of the storm ($\Delta P = P_{00} - P_0$) and its size (R) at point T_0 (fig. 1).

2. Ascertain (forecast) the pressure drop of the storm and its size at point T_{24}.

The program fits a cubic through these two points so that:

1. The rate of change of ΔP and R are greatest at T_{12}.

2. The rate of change of ΔP and R are stationary at T_0 and T_{24}.

3. The rate of change of ΔP and R are monotonic with time.

4. The parameters remain constant before T_0 and after T_{24} to avoid large changes if extrapolations are required.

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[11] For a track normal to the coast, the component of the track on the coast is a point. In this case, the entire track is represented on the coast, and we accept surge computations throughout the entire coast of our model basin.

[12] In SPLASH I, we used the most simple procedure of invariant storm parameters.

Admittedly, this is a crude way to represent variable meteorology for the storm, but it is consistent with meteorological forecasting accuracy. A much more detailed description of the storm parameters--say, hourly values--can be incorporated easily in future models if such accuracy is desired.

Our storm model uses the storm parameters and track to compute driving forces on the sea's surface. Because the natural basin was translated into a rectangle, we translate the driving forces onto the model basin in like manner. This distorts the force fields, except in the vicinity of station.

III. STORM SURGE ENVELOPES AND COMPUTER DISPLAYS

Before discussing the computer products of SPLASH II, we should gather some experience on possible forms for coastal surges.

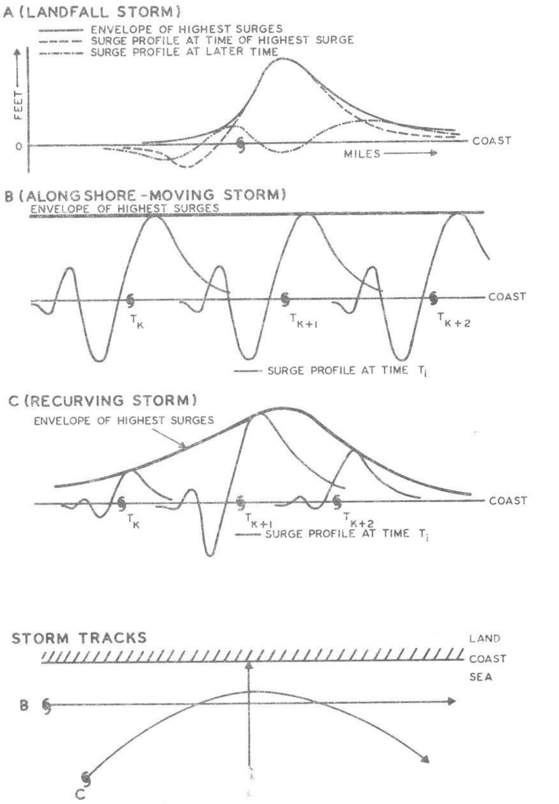

Figure 2.--Ideal storm surge envelopes for three types of storm tracks. The surge profile is a snapshot of coastal surges at time T_i. The symbol 🌀 on the coast means the landfall point of the storm on the coast or the abeam distance of the storm from the coast.

A. Idealized Surge Envelopes

One of the output products of SPLASH II is a coastal surge envelope of highest coastal waters. The envelope can be more complicated than any computed by SPLASH I for landfall storms. To acquaint the reader with several envelope forms, we conceptually have formed several ideal situations for:

1. A landfall storm with its track perpendicular to a straight-line coast [fig. 2 (A)].

2. An alongshore-moving storm [constant abeam distance of the track from the coast (B)].

3. A recurving storm [non-landfall (C)].

Storms Reaching Land

These landfall storms generate a surge profile that grows with time. A surge profile is a snapshot of coastal surges. The position of the highest surge on the profile remains stationary with time; eventually, it reaches peak surge amplitude at approximately the time of landfall.

For conceptual purposes, we can view the coastal surge profile at the time of peak surge as a string held or plucked by the storm at or near the time of landfall. Of course, things are not quite so simple as the mechanics of a plucked string; but the illustration is informative. Note that there are negative surges to the left of the storm. With passage of the storm, we now view the profile as a released string that forms two waves moving to the right and left, respectively. The form and speed of propagation of these two waves depend on the input meteorological parameters and basin used. To portray a convenient end product of this phenomena, we consider the envelope of all high water heights on the coast and call it the storm surge envelope. The form of the envelope along the coast represents the observed high water heights, irrespective of time of occurrence.

Alongshore-Moving Storms

The coastal surge profile at any given time can be viewed as a plucked string. Unlike landfall storms, however, the string cannot be released because the storm does not leave the coastal area; consequently, the profile moves along the coast with storm speed. The times T_i (fig. 2) are for abeam positions of the storm as it progresses along the coast. If the storm and ocean depths are invariable along the storm track, then the envelope of high waters is a line of constant surge height. We tacitly have assumed that the surge profile has reached a steady state, which of course does not happen readily in real life. For example, when a storm enters a continental shelf, there are initial and transient phenomena that take time to dissipate; also, there may be resonance phenomena with which to contend. These complexities are discussed in appendix II. On the extremity of surge profiles (behind the storm), we have drawn resurgences; this is to remind the reader that complicated dynamic phenomena can occur with alongshore-moving storms (see appendix II).

Recurving Storms

These have envelope features reminiscent of landfall and alongshore-moving storms. Surge profiles moving with storm speed along the coast sometimes act as a released string and at other times as a plucked string; the profiles can be more complicated than those portrayed in figure 2. The envelope is more elongated to the left because a storm moving toward shore generates larger surges than the storm moving away from shore.

The three idealized situations in figure 2, however, rarely occur so neatly in real life. Remember that all coasts and storm tracks are curvilinear to some extent, that the storm itself is not invariant with time, and that depth contours can vary considerably within basins. This means that all sorts of complicated envelopes occur with SPLASH II, and one easily can visualize complicated envelope forms when tracks and coastlines are other than those shown in figure 2.

B. Using the Computer To Display Coastal Storm Surges

SPLASH II is designed to display surges in space and time along a stretch of coast. The mechanism for running the program is described in appendix I. Note: SPLASH II is accessible for use in operational field forecasting.

To compactly display surges on the coast (without confusing the surge forecaster with reams of printed output) is desirable. To do this, we print out:

1. The envelope of coastal high water heights.

2. The coastal surges against time.

The two displays are slightly different from SPLASH I because we now consider arbitrary storm tracks and storms that vary in strength and size with time (i.e., we display time-history surges on the coast).

Displaying Storm Surge Envelopes by Computer Output

Figure 3 is an example of one part of a programmed computer output for SPLASH II. The graph (indicated by a line of stars) is an envelope of computed coastal high water heights, generated by a curvilinear storm track and achieved by utilizing variant storm parameters.

Here, we remind the reader that storm tracks crossing coastlines are admissible in the present model; however, if the track is not excessively curvilinear, if the angle of attack to the coast is not too acute, and if the parameters of the storm do not change drastically with time while the storm is on the shelf, then we recommend the use of SPLASH I. Note: SPLASH I is a simplified version of SPLASH II; furthermore, it is easier to run, use, and interpret.

Returning to figure 3, we find that the printed message (beginning the output) is a résumé of some storm parameters selected by the programmer.[13] Near the résumé, the ordinate or vertical scale of the graph is 20 ft. If the peak surge exceeds this, then the ordinate is rescaled to 40 ft. Meanwhile, the horizontal scale of the graph is only 320 mi long,[14] it represents the coast on a straight line. The dots on the scale are 4 mi apart. On alternate dots, the highest local surge heights are printed in feet. Just above, and on the middle of the scale, is a symbol -*-; this represents the center of the basin's coastline (note: it does not represent a landfall position, even if the storm does reach land or exits). Left and right of -*- , and below the dots, are linear distances in miles; below this are select-

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[13] The track positions and other storm information are printed separately; this informational output is not discussed here.

[14] We use a 600-mi coastline for computations but truncate the output to 320 mi so as not to confuse the surge forecaster with possible spurious waves at the top/bottom boundaries.

ed cities as they lie along the coast. The center of the horizontal scale is tangent to the natural coast; as such, it distorts and compresses distances on the curvilinear coast. This means that the printed distances away from the basin center are smaller than the actual curvilinear distances along the coast.

Within the envelope, only positive surges are printed; negative surges are displayed on the following output.

Below the cities are three special messages. These give storm positions (abeam to the coast) defined by:

1. STRT STM, for the storm initialization.

2. MATR STM, when the storm reaches maturity.

3. END COMP, when the computations are terminated.

These three messages are staggered; otherwise, they would fall on top of each other for a stationary storm or for a storm striking the coast on a track normal to the coast. In figure 3, the three messages are for a storm traveling up the coast; they reverse for a storm traveling down the coast. The computed surges on the coast are valid[15] on the coastal stretch between messages 2 and 3 (sometimes the storm travels so rapidly that none of the three messages will appear); on this stretch (at least), times to the nearest hour are printed for the occurrence of the computed peak surge on the coast. Variations on "time" printout for peak surges are discussed in appendix III; this is an important procedure when evaluating the importance of astronomical tide on the meteorologically induced surge.

At hourly increments beneath the displayed graph is a printout of astronomical tide levels for selected stations for 12 hr before and 12 hr after the storm makes its closest approach to the center of the coastline. The stations correspond to the cities listed on the graph. The tides are predicted in feet above MSL (mean sea level).

By "above MSL," we mean the tidal computations--for the rise and fall of the tide plus the annual variations of sea level--are with respect to a zero datum; thus, the computations can be added to any other datum. The datum used in the tide tables for the east coast and gulf coast stations is MLW (mean low water). The datum for contours on terrain charts is usually geodetic MSL; this does not always coincide with local MSL. For practical purposes, we can assume that the difference between geodetic and local MSL (unlike that between MSL and MLW)

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[15] This is not so for a landfall storm or for a recurving storm if the track of the mature storm begins and ends in deep water. In these cases, the diameter of the storm or the component of the significant track on the coast is a measure of coastal length affected by surges.

is very small; hence, our total tide--meteorological plus astronomical--can be compared directly with land contours for a measure of inland inundation.

We use a tide program developed by Pore and Cummings (1967). The specific application here was developed by Lt. R. Garwood, NOAA Commissioned Corps.

In principle, we could combine astronomical and meteorological tides for a total tide envelope. Although this appears to be a sensible procedure, such an envelope would be misleading. A display of this nature is meaningful only if we have an accurate knowledge of the storm track in space and time and an accurate knowledge of the meteorological parameters; we just cannot forecast meteorological occurrences to the accuracy required. Furthermore, it would not be meaningful to display envelopes including highest and lowest expected values for a range of meteorological accuracy with time; the range between the two envelopes could be so large that the information would be almost useless.

Displaying Time-History Coastal Surges by Computer Output

The envelope of highest surges on the coast can be misleading if transients are a problem (appendix II), that is, a near stationary storm might give envelope surge heights that are objectionable because of fictitious initialization phenomena. A time-history chart of coastal surges (fig. 4) is useful to interpret surge transients computed by the model.

Ideally, the chart should be contoured as in figures 13 and 17. However, not all installations have curve plotters to automatically contour such charts; but all installations do have a printer, and we output accordingly.

Figure 4 is a compact time-history chart of coastal surges output by printer. If so inclined, the user can draw equal height contours by hand.[16] The printed messages beginning the output are informational warnings to alert the forecaster to possible problem areas. The abscissa is a time scale incremented at hourly intervals. The coastal surges are printed at 0.5-hr intervals for a total of 17 hr; whereas the vertical scale--an exact replica from figure 3 for the coast--is orientated so that water is always to the right.[17] The computed surges are printed--in tenths of a foot--every 8 mi on the coast; at 0.5-hr printings, they have a 4-mi stagger.

The storm--abeam to the coast--is characterized by $ signs; because the printing is dense and compact, the storm position can be off by as much as 8 mi. The printed messages ending the output give pressure drop, storm size, storm distance abeam to the coast, storm speed, and maximum wind at each hourly interval.

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[16] This is an ordinary and normal procedure, at least for veteran weather forecasters with experience in drawing weather maps.

[17] For the uninitiated, the orientation on the western coast of Florida may be confusing.

IV. EXAMPLES AND SPECIAL CASES

In this section, we discuss several examples with real storm situations. Also, we consider some special cases that the surge forecaster may encounter. Note: the model cannot consider all conceivable situations; the surge forecaster at times will have to compromise or fit the meteorological situation and storm track to severe constraints imposed by the model.

A. Examples

The three examples that follow are of historical interest. For an effective test of the surge model, the meteorological data, storm tracks, and high water observations leave much to be desired.

To help interpret some weird oscillatory phenomena that can occur with generalized storm motion, we suggest that the reader recall or familiarize himself with possible forms of transients on the coast (appendix II).

Hurricane Helene, 1958

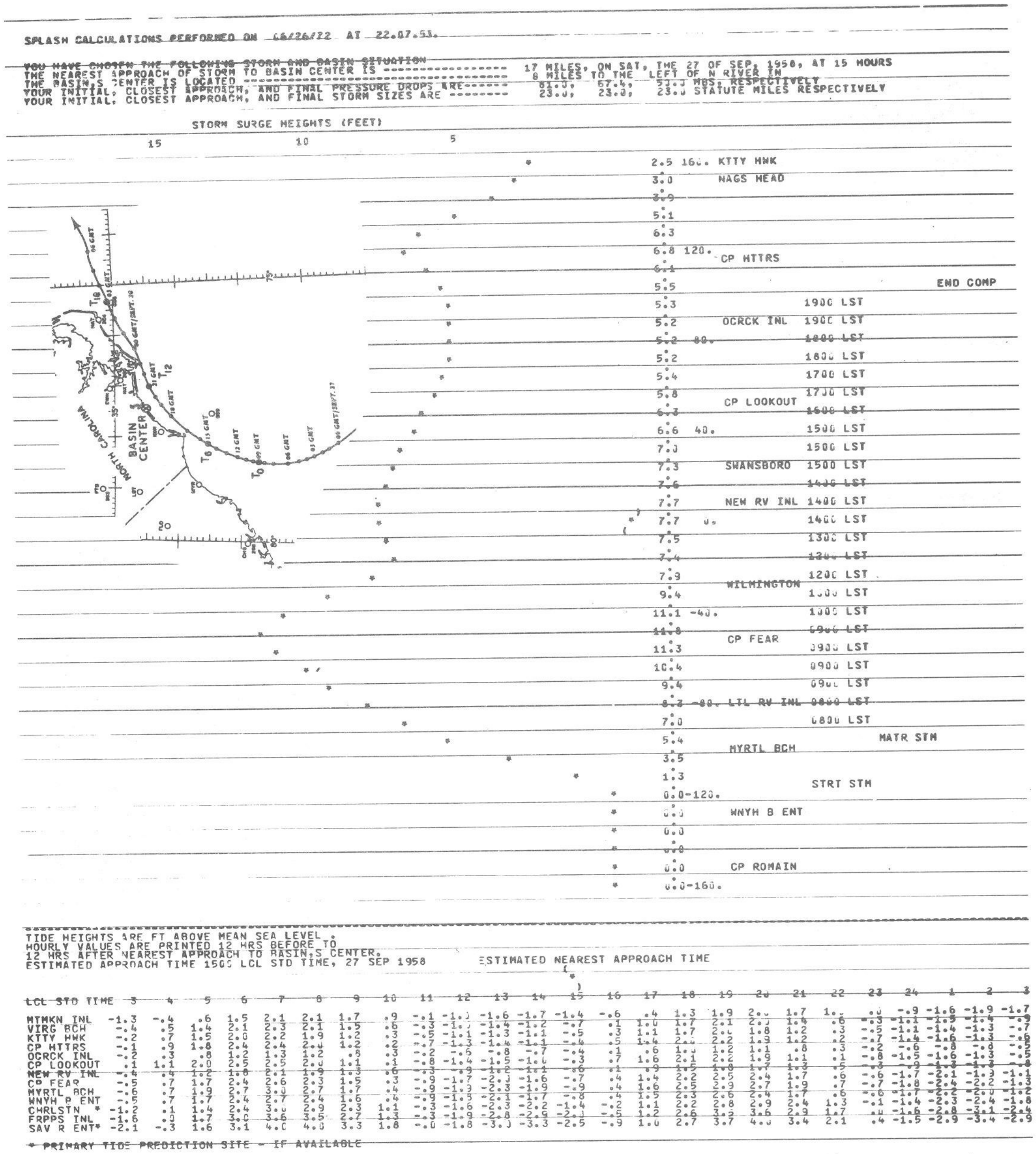
Here, we discuss coastal surges generated by a storm moving <u>up</u> the coast (fig. 3), which is in contrast to a storm moving <u>down</u> the coast as depicted in figure 5. (Note: the orientation is always with water to the right.)

In our presentation, we do not make comparisons with measured surges because--to date-- no studies or compilation of data has been accomplished. Although this is not a test of the model, it does provide an illustration of the type of surge forecast made by the model for this type of storm motion.

To illustrate the coastal surge for this storm, we compose the data deck of figure 11 (appendix I) and let SPLASH II print out figures 3 and 4. The storm parameters and track were assembled from the report by the Weather Bureau (1962). The track starts in deep water and then recurves while on the Continental Shelf (see the inset of fig. 3); this is an excellent situation for initialization, providing the storm is mature before it enters the Continental Shelf.

The storm decreased in intensity as it moved up the coast; meanwhile, the computed coastal surge generally decreased. We remark that two-dimensional depth patterns--as opposed to one-dimensional--play a significant roll in coastal surge generation; this can account for significant variations (bumps) on the coastal surge envelope. The upper surge at Cape Fear is due in part to:

1. The <u>local</u>, shallow ocean depths.
2. The short distance from the cape to the storm track.



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SPLASH CALCULATIONS PERFORMED ON  06/26/72  AT  22.07.53.

YOU HAVE CHOSEN THE FOLLOWING STORM AND BASIN SITUATION
THE NEAREST APPROACH OF STORM TO BASIN CENTER IS -----------------   17 MILES, ON SAT, THE 27 OF SEP, 1958, AT 15 HOURS
THE BASIN,S CENTER IS LOCATED ------------------------------------    8 MILES TO THE  LEFT OF N RIVER IN
YOUR INITIAL, CLOSEST APPROACH, AND FINAL PRESSURE DROPS ARE------   81.0,   67.4,   53.0 MBS, RESPECTIVELY
YOUR INITIAL, CLOSEST APPROACH, AND FINAL STORM SIZES ARE --------   23.0,   23.0,   23.0 STATUTE MILES RESPECTIVELY

                STORM SURGE HEIGHTS (FEET)

       15             10             5

                                                  2.5 160. KTTY HWK
                                                  3.0      NAGS HEAD
                                                  3.9
                                                  5.1
                                                  6.3
                                                  6.8 120. CP HTTRS
                                                  6.1
                                                  5.5                                  END COMP
                                                  5.3                 1900 LST
                                                  5.2      OCRCK INL  1900 LST
                                                  5.2  80.            1800 LST
                                                  5.2                 1800 LST
                                                  5.4                 1700 LST
                                                  5.8                 1700 LST
                                                  6.3      CP LOOKOUT 1600 LST
                                                  6.6  40.            1500 LST
                                                  7.0                 1500 LST
                                                  7.3      SWANSBORO  1500 LST
                                                  7.6                 1400 LST
                                                  7.7      NEW RV INL 1400 LST
                                                  7.7   0.            1400 LST
                                                  7.5                 1300 LST
                                                  7.4                 1200 LST
                                                  7.9                 1200 LST
                                                  9.4      WILMINGTON 1000 LST
                                                 11.1 -40.            1000 LST
                                                 11.8                 0900 LST
                                                 11.3      CP FEAR    0900 LST
                                                 10.4                 0900 LST
                                                  9.4                 0900 LST
                                                  8.3 -80. LTL RV INL 0800 LST
                                                  7.0                 0800 LST
                                                  5.4                           MATR STM
                                                  3.5      MYRTL BCH
                                                  1.3
                                                  0.0-120.            STRT STM
                                                  0.0      WNYH B ENT
                                                  0.0
                                                  0.0
                                                  0.0      CP ROMAIN
                                                  0.0-160.

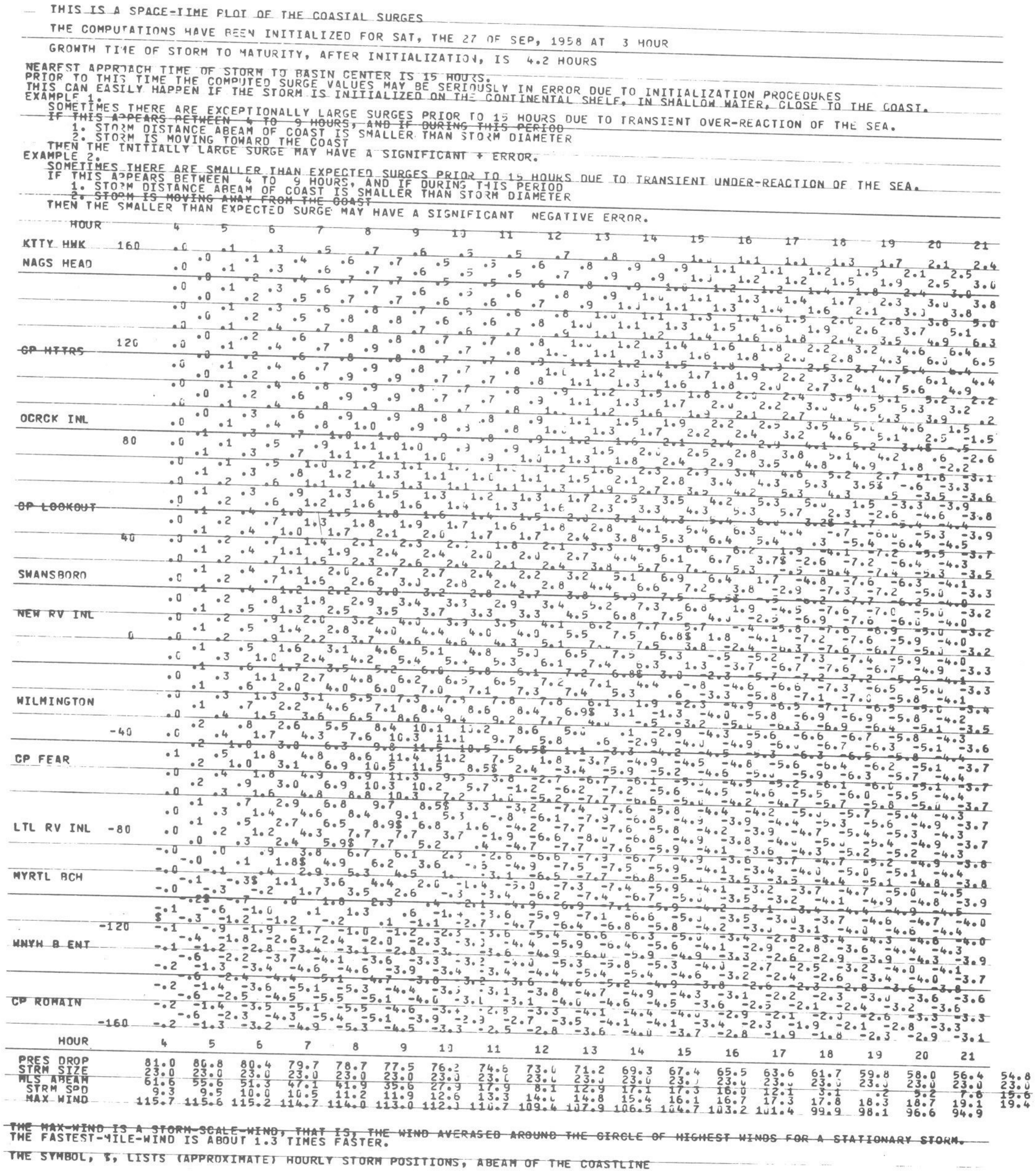
TIDE HEIGHTS ARE FT ABOVE MEAN SEA LEVEL .
HOURLY VALUES ARE PRINTED 12 HRS BEFORE TO
12 HRS AFTER NEAREST APPROACH TO BASIN,S CENTER.
ESTIMATED APPROACH TIME 1500 LCL STD TIME, 27 SEP 1958          ESTIMATED NEAREST APPROACH TIME
                                                                              *
LCL STD TIME   3    4    5    6    7    8    9   10   11   12   13   14   15   16   17   18   19   20   21   22   23   24    1    2    3

MTMKN INL   -1.3  -.4   .6  1.5  2.1  2.1  1.7   .9  -.1 -1.0 -1.6 -1.7 -1.4  -.6   .4  1.3  1.9  2.0  1.7  1.0   .0  -.9 -1.6 -1.9 -1.7
VIRG BCH     -.4   .5  1.4  2.1  2.3  2.1  1.5   .6  -.3 -1.0 -1.4 -1.2  -.7   .1  1.0  1.7  2.1  2.0  1.4   .6  -.3 -1.1 -1.5 -1.4  -.9
KTTY HWK     -.2   .7  1.5  2.0  2.2  1.9  1.2   .3  -.5 -1.1 -1.3 -1.1  -.5   .3  1.1  1.7  2.0  1.8  1.2   .3  -.5 -1.1 -1.4 -1.3  -.7
CP HTTRS     -.1   .9  1.8  2.4  2.4  2.0  1.2   .2  -.7 -1.3 -1.4 -1.1  -.4   .5  1.4  2.0  2.2  1.9  1.2   .2  -.7 -1.4 -1.6 -1.3  -.6
OCRCK INL    -.2   .3   .8  1.2  1.3  1.2   .8   .3  -.2  -.6  -.8  -.7  -.4   .1   .6  1.0  1.2  1.1   .8   .3  -.2  -.6  -.8  -.8  -.5
CP LOOKOUT    .1  1.1  2.0  2.5  2.5  2.0  1.1   .1  -.8 -1.4 -1.5 -1.0  -.3   .7  1.6  2.1  2.2  1.9  1.1   .1  -.8 -1.5 -1.6 -1.3  -.5
NEW RV INL   -.4   .4  1.2  1.8  2.1  1.9  1.3   .6  -.3  -.9 -1.2 -1.1  -.6   .1   .9  1.5  1.8  1.7  1.3   .5  -.3  -.9 -1.3 -1.3  -.8
CP FEAR      -.5   .7  1.7  2.4  2.6  2.3  1.5   .3  -.9 -1.7 -2.0 -1.6  -.7   .4  1.4  2.2  2.5  2.4  1.7   .6  -.6 -1.7 -2.1 -1.9 -1.1
MYRTL BCH    -.6   .7  1.9  2.7  3.0  2.7  1.7   .4  -.9 -1.9 -2.3 -1.9  -.9   .4  1.6  2.5  2.9  2.7  1.9   .7  -.7 -1.8 -2.4 -2.2 -1.3
WNYH B ENT   -.5   .7  1.7  2.4  2.7  2.4  1.6   .4  -.9 -1.5 -2.1 -1.7  -.8   .4  1.5  2.3  2.6  2.4  1.7   .6  -.6 -1.7 -2.2 -2.0 -1.2
CHRLSTN  *  -1.2   .1  1.4  2.4  3.0  2.9  2.3  1.1  -.3 -1.6 -2.3 -2.2 -1.4  -.2  1.1  2.2  2.8  2.9  2.4  1.3  -.1 -1.4 -2.3 -2.4 -1.8
FRPPS INL   -1.6   .0  1.7  3.0  3.6  3.5  2.7  1.3  -.3 -1.9 -2.8 -2.9 -2.0  -.5  1.2  2.6  3.5  3.6  2.9  1.7   .0 -1.6 -2.8 -3.1 -2.4
SAV R ENT*  -2.1  -.3  1.6  3.1  4.0  4.0  3.3  1.8  -.0 -1.8 -3.0 -3.3 -2.5  -.9  1.0  2.7  3.7  4.0  3.4  2.1   .4 -1.5 -2.9 -3.4 -2.9
* PRIMARY TIDE PREDICTION SITE - IF AVAILABLE
```

Figure 3.--Computer printout for the computed envelope of high waters on the open coast, generated by hurricane Helene, 1958. The storm is moving up the coast. The inset gives the storm track (Weather Bureau 1962). See also figure 10.

3. The initialization phenomena.

Note that the storm is constrained to reach maturity on the Continental Shelf shortly before passing Cape Fear; hence, it is possible that the very first computed transient from initialization may be too large. The time-history coastal surges (fig. 4) give the appearance of a wave packet (appendix II). The transients in this packet are suspicious at the beginning of



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THIS IS A SPACE-TIME PLOT OF THE COASTAL SURGES
THE COMPUTATIONS HAVE BEEN INITIALIZED FOR SAT, THE 27 OF SEP, 1958 AT  3 HOUR
GROWTH TIME OF STORM TO MATURITY, AFTER INITIALIZATION, IS  4.2 HOURS
NEAREST APPROACH TIME OF STORM TO BASIN CENTER IS 15 HOURS.
PRIOR TO THIS TIME THE COMPUTED SURGE VALUES MAY BE SERIOUSLY IN ERROR DUE TO INITIALIZATION PROCEDURES
THIS CAN EASILY HAPPEN IF THE STORM IS INITIALIZED ON THE CONTINENTAL SHELF, IN SHALLOW WATER, CLOSE TO THE COAST.
EXAMPLE 1.
   SOMETIMES THERE ARE EXCEPTIONALLY LARGE SURGES PRIOR TO 15 HOURS DUE TO TRANSIENT OVER-REACTION OF THE SEA.
   IF THIS APPEARS BETWEEN  4 TO  9 HOURS, AND IF DURING THIS PERIOD
      1. STORM DISTANCE ABEAM OF COAST IS SMALLER THAN STORM DIAMETER
      2. STORM IS MOVING TOWARD THE COAST
   THEN THE INITIALLY LARGE SURGE MAY HAVE A SIGNIFICANT + ERROR.
EXAMPLE 2.
   SOMETIMES THERE ARE SMALLER THAN EXPECTED SURGES PRIOR TO 15 HOURS DUE TO TRANSIENT UNDER-REACTION OF THE SEA.
   IF THIS APPEARS BETWEEN  4 TO  9 HOURS, AND IF DURING THIS PERIOD
      1. STORM DISTANCE ABEAM OF COAST IS SMALLER THAN STORM DIAMETER
      2. STORM IS MOVING AWAY FROM THE COAST
   THEN THE SMALLER THAN EXPECTED SURGE MAY HAVE A SIGNIFICANT  NEGATIVE ERROR.

     HOUR          4     5     6     7     8     9    10    11    12    13    14    15    16    17    18    19    20    21

     HOUR          4     5     6     7     8     9    10    11    12    13    14    15    16    17    18    19    20    21
 PRES DROP      81.0  80.8  80.4  79.7  78.7  77.5  76.2  74.6  73.0  71.2  69.3  67.4  65.5  63.6  61.7  59.8  58.0  56.4  54.8
 STRM SIZE      23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0  23.0
 MLS ABEAM      61.6  55.6  51.3  47.1  41.9  35.6  27.9  17.9   8.1  12.9  17.1  17.3  16.0  12.1   3.1    .2   5.2   7.6  15.6
  STRM SPD       9.3   9.5  10.0  10.5  11.2  11.9  12.6  13.3  14.0  14.8  15.4  16.1  16.7  17.3  17.8  18.3  18.7  19.1  19.4
  MAX WIND     115.7 115.6 115.2 114.7 114.0 113.0 112.0 110.7 109.4 107.9 106.5 104.7 103.2 101.4  99.9  98.1  96.6  94.9

THE MAX-WIND IS A STORM-SCALE-WIND, THAT IS, THE WIND AVERAGED AROUND THE CIRCLE OF HIGHEST WINDS FOR A STATIONARY STORM.
THE FASTEST-MILE-WIND IS ABOUT 1.3 TIMES FASTER.
THE SYMBOL, $, LISTS (APPROXIMATE) HOURLY STORM POSITIONS, ABEAM OF THE COASTLINE
```

Figure 4.--Computer printout for time-history surges on the open coast for hurricane Helene, 1958

computations but not so at the center of the basin.

The astronomical tide was high just before the storm passed Cape Fear and low when the storm passed the basin center; thus, the addition of astronomical tide can be an important factor in coastal surge forecasting.

Although the storm decreases in intensity, the coastal surge shows a rise as the storm approaches Cape Hatteras (similar in scope to Cape Fear). The computations are terminated before the storm passes the cape; therefore, the coastal surges and their envelope cannot be completed beyond the termination.

Note: high waters lead/lag the storm. Usually, high waters lead a storm moving up the coast and lag a storm moving down the coast. In figure 3, the nearest approach of the storm to the basin center was at 15 hr, and high waters occurred there at 14 hr; hence, high waters lead the storm by 1 hr. The lead/lag time is a function of storm speed and storm size.

Our model, however, is designed to compute surges at the center of the basin's coastline and a small distance (no more than 100 mi) on either side. If the user desires to complete the surge profile for longer distances on the coastline, then several runs must be made on advancing the storm track to neighboring basins in the model. Recall that our track is for 18 hr only in real time, for which about 4 hr are set for initialization. Consequently, at worst we can have only 14 hr of surge activity on the coast.

Hurricane Donna, 1960, Along the West Coast of Florida

Here, we discuss the time of high waters and coastal surges generated by a storm moving down the coast (fig. 5). This is in contrast to a storm moving up the coast as depicted in figure 3.

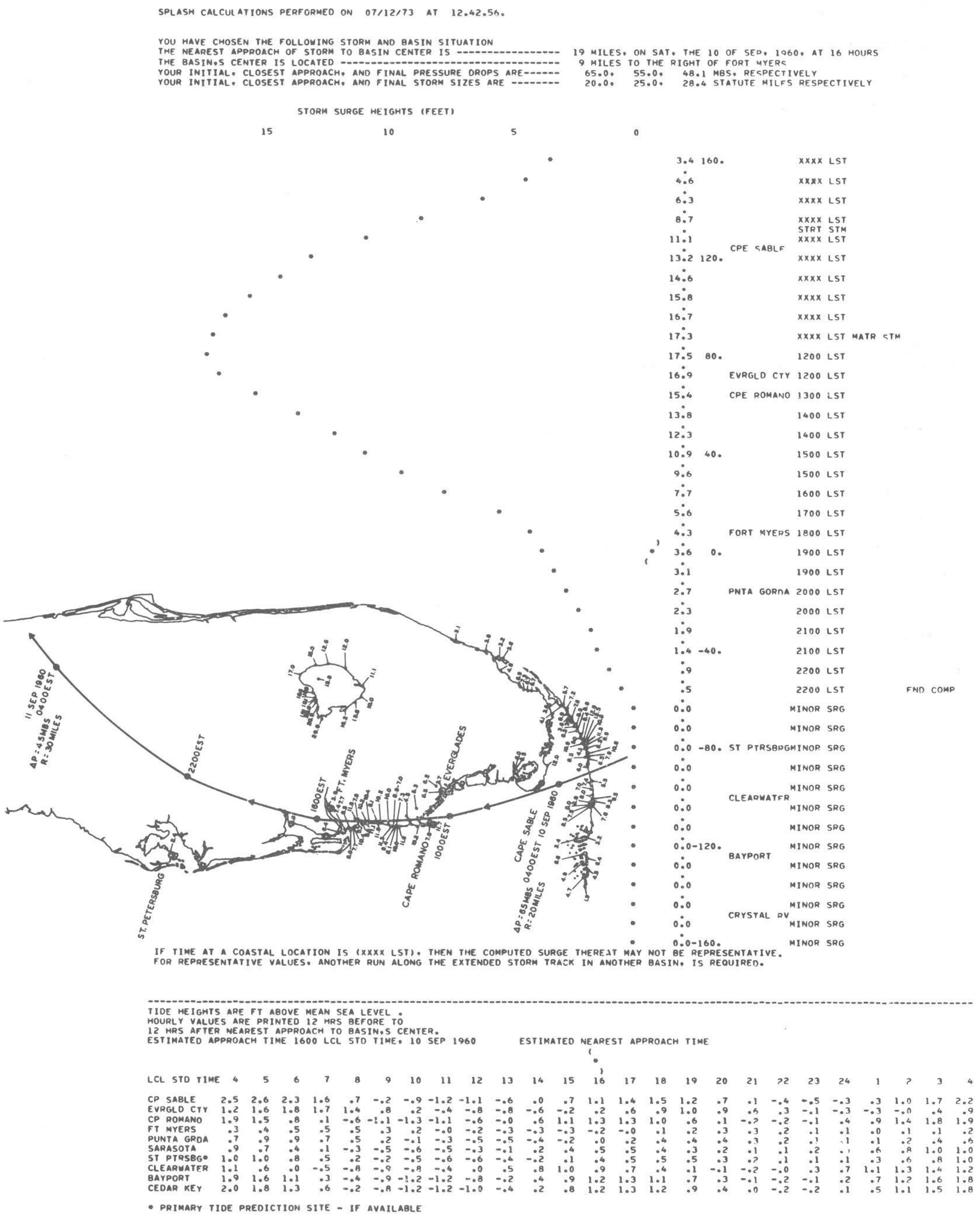
We must avoid disorientation when dealing with the east and west coasts of Florida (fig. 5). Meteorological orientation of storm tracks on compass North is not good enough; we also must orientate on direction relative to a coastline. For an alongshore-moving storm, try the following orientation scheme. If an observer has land to his left and sea to his right, then a storm track that:

1. Strikes the observer in the back is traveling up the coast (fig. 3).

2. Strikes the observer in the front is traveling down the coast (fig. 5).

Thus, an alongshore-moving storm passing Florida in a northerly direction is moving up the east coast and down the west coast. Do not permit confusion by this orientation or by SPLASH displays (in SPLASH envelope outputs, the observer is at sea and is facing land).

Consider the track of Donna, 1960 (fig. 5); the entire track along the U.S. coast runs from the tip of Florida to the New England States. To compute surges on all this coast requires an extraordinary computational effort; this is so because the SPLASH II model is restricted to segments of the U.S. coast with basins separated at 100-mi intervals. We show one computational effort on the western part of Florida where observed high water marks are available for comparison.



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SPLASH CALCULATIONS PERFORMED ON  07/12/73  AT  12.42.56.

YOU HAVE CHOSEN THE FOLLOWING STORM AND BASIN SITUATION
THE NEAREST APPROACH OF STORM TO BASIN CENTER IS -----------------  19 MILES, ON SAT, THE 10 OF SEP, 1960, AT 16 HOURS
THE BASIN.S CENTER IS LOCATED -------------------------------------  9 MILES TO THE RIGHT OF FORT MYERS
YOUR INITIAL, CLOSEST APPROACH, AND FINAL PRESSURE DROPS ARE------   65.0,   55.0,   48.1 MBS, RESPECTIVELY
YOUR INITIAL, CLOSEST APPROACH, AND FINAL STORM SIZES ARE --------   20.0,   25.0,   28.4 STATUTE MILFS RESPECTIVELY

                 STORM SURGE HEIGHTS (FEET)

        15               10               5                0

                                                   3.4 160.               XXXX LST
                                                   4.6                    XXXX LST
                                                   6.3                    XXXX LST
                                                   8.7                    XXXX LST
                                                                          STRT STM
                                                  11.1                    XXXX LST
                                                            CPE SABLF
                                                  13.2 120.               XXXX LST
                                                  14.6                    XXXX LST
                                                  15.8                    XXXX LST
                                                  16.7                    XXXX LST
                                                  17.3                    XXXX LST MATR STM
                                                  17.5  80.               1200 LST
                                                  16.9      EVRGLD CTY 1200 LST
                                                  15.4      CPE ROMANO 1300 LST
                                                  13.8                    1400 LST
                                                  12.3                    1400 LST
                                                  10.9  40.               1500 LST
                                                   9.6                    1500 LST
                                                   7.7                    1600 LST
                                                   5.6                    1700 LST
                                                   4.3      FORT MYERS 1800 LST
                                              )
                                                   3.6   0.               1900 LST
                                             (
                                                   3.1                    1900 LST
                                                   2.7      PNTA GORDA 2000 LST
                                                   2.3                    2000 LST
                                                   1.9                    2100 LST
                                                   1.4 -40.               2100 LST
                                                    .9                    2200 LST
                                                    .5                    2200 LST             FND COMP
                                                   0.0                   MINOR SRG
                                                   0.0                   MINOR SRG
                                                   0.0 -80. ST PTRSBRGMINOR SRG
                                                   0.0                   MINOR SRG
                                                   0.0                   MINOR SRG
                                                            CLEARWATFR
                                                   0.0                   MINOR SRG
                                                   0.0                   MINOR SRG
                                                   0.0-120.              MINOR SRG
                                                            BAYPORT
                                                   0.0                   MINOR SRG
                                                   0.0                   MINOR SRG
                                                   0.0                   MINOR SRG
                                                            CRYSTAL RV
                                                   0.0                   MINOR SRG
                                                   0.0-160.              MINOR SRG
IF TIME AT A COASTAL LOCATION IS (XXXX LST), THEN THE COMPUTED SURGE THEREAT MAY NOT BE REPRESENTATIVE.
FOR REPRESENTATIVE VALUES, ANOTHER RUN ALONG THE EXTENDED STORM TRACK IN ANOTHER BASIN, IS REQUIRED.
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TIDE HEIGHTS ARE FT ABOVE MEAN SEA LEVEL .
HOURLY VALUES ARE PRINTED 12 HRS BEFORE TO
12 HRS AFTER NEAREST APPROACH TO BASIN.S CENTER.
ESTIMATED APPROACH TIME 1600 LCL STD TIME, 10 SEP 1960        ESTIMATED NEAREST APPROACH TIME
                                                                         (
                                                                         *
                                                                         )
LCL STD TIME  4    5    6    7    8    9   10   11   12   13   14   15   16   17   18   19   20   21   ?2   23   24    1    ?    3    4

CP SABLE    2.5  2.6  2.3  1.6   .7  -.2  -.9 -1.2 -1.1  -.6   .0   .7  1.1  1.4  1.5  1.2   .7   .1  -.4  -.5  -.3   .3  1.0  1.7  2.2
EVRGLD CTY  1.2  1.6  1.8  1.7  1.4   .8   .2  -.4  -.8  -.8  -.6  -.2   .2   .6   .9  1.0   .9   .6   .3  -.1  -.3  -.3  -.0   .4   .9
CP ROMANO   1.9  1.5   .8   .1  -.6 -1.1 -1.3 -1.1  -.6  -.0   .6  1.1  1.3  1.3  1.0   .6   .1  -.2  -.2  -.1   .4   .9  1.4  1.8  1.9
FT MYERS     .3   .4   .5   .5   .5   .3   .2  -.0  -.2  -.3  -.3  -.3  -.2  -.0   .1   .2   .3   .3   .2   .1   .1   .0   .1   .1   .2
PUNTA GRDA   .7   .9   .9   .7   .5   .2  -.1  -.3  -.5  -.5  -.4  -.2   .0   .2   .4   .4   .4   .3   .2   .1   .1   .1   .2   .4   .6
SARASOTA     .9   .7   .4   .1  -.3  -.5  -.6  -.5  -.3  -.1   .2   .4   .5   .5   .4   .3   .2   .1   .1   .2   .[illegible]   .6   .8  1.0  1.0
ST PTRSBG*  1.0  1.0   .8   .5   .2  -.2  -.5  -.6  -.6  -.4  -.2   .1   .4   .5   .5   .5   .3   .2   .1   .1   .1   .3   .6   .8  1.0
CLEARWATER  1.1   .6   .0  -.5  -.8  -.9  -.8  -.4   .0   .5   .8  1.0   .9   .7   .4   .1  -.1  -.2  -.0   .3   .7  1.1  1.3  1.4  1.2
BAYPORT     1.9  1.6  1.1   .3  -.4  -.9 -1.2 -1.2  -.8  -.2   .4   .9  1.2  1.3  1.1   .7   .3  -.1  -.2  -.1   .2   .7  1.2  1.6  1.8
CEDAR KEY   2.0  1.8  1.3   .6  -.2  -.8 -1.2 -1.2 -1.0  -.4   .2   .8  1.2  1.3  1.2   .9   .4   .0  -.2  -.2   .1   .5  1.1  1.5  1.8

* PRIMARY TIDE PREDICTION SITE - IF AVAILABLE
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Figure 5.--Computer printout for the computed envelope of high waters on the open coast, generated by hurricane Donna, 1960, on western Florida. The storm is moving down the coast (water always to the right). The inset gives the storm track and measured high water marks from poststorm surveys (Harris 1963).

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   THIS IS A SPACE-TIME PLOT OF THE COASTAL SURGES

   THE COMPUTATIONS HAVE BEEN INITIALIZED FOR SAT, THE 10 OF SEP, 1960 AT  4 HOUR

   GROWTH TIME OF STORM TO MATURITY, AFTER INITIALIZATION, IS  4.0 HOURS

NEAREST APPROACH TIME OF STORM TO BASIN CENTER IS 16 HOURS.
PRIOR TO THIS TIME THE COMPUTED SURGE VALUES MAY BE SERIOUSLY IN ERROR DUE TO INITIALIZATION PROCEDURES
THIS CAN EASILY HAPPEN IF THE STORM IS INITIALIZED ON THE CONTINENTAL SHELF, IN SHALLOW WATER, CLOSE TO THE COAST.
EXAMPLE 1.
   SOMETIMES THERE ARE EXCEPTIONALLY LARGE SURGES PRIOR TO 16 HOURS DUE TO TRANSIENT OVER-REACTION OF THE SEA.
   IF THIS APPEARS BETWEEN  5 TO 10 HOURS, AND IF DURING THIS PERIOD
      1. STORM DISTANCE ABEAM OF COAST IS SMALLER THAN STORM DIAMETER
      2. STORM IS MOVING TOWARD THE COAST
   THEN THE INITIALLY LARGE SURGE MAY HAVE A SIGNIFICANT + ERROR.
EXAMPLE 2.
   SOMETIMES THERE ARE SMALLER THAN EXPECTED SURGES PRIOR TO 16 HOURS DUE TO TRANSIENT UNDER-REACTION OF THE SEA.
   IF THIS APPEARS BETWEEN  5 TO 10 HOURS, AND IF DURING THIS PERIOD
      1. STORM DISTANCE ABEAM OF COAST IS SMALLER THAN STORM DIAMETER
      2. STORM IS MOVING AWAY FROM THE COAST
   THEN THE SMALLER THAN EXPECTED SURGE MAY HAVE A SIGNIFICANT  NEGATIVE ERROR.
NOTE--THE COASTAL HIGH WATERS LAG THE STORM. HENCE, FOR A FAST MOVING STORM
THE COMPUTED SURGE MAY BE TOO SMALL AT TIME OF TERMINATION OF COMPUTATIONS.

      HOUR             5     6     7     8     9    10    11    12    13    14    15    16    17    18    19    20    21    22

             160      .2   1.0   2.3   3.3   3.3   2.5   1.3    .5    .2    .5    .8   1.1   1.0    .7    .5    .5    .6    .7
                         .6   2.0   3.4   3.9   3.5   2.3   1.1    .4    .4    .7   1.0   1.2   1.0    .7    .5    .6    .7
                      .3   1.5   3.3   4.4   4.4   3.4   2.1   1.0    .6    .6   1.0   1.2   1.2   1.0    .7    .6    .7    .8
                         .9   2.9   4.7   5.4   4.8   3.4   2.0   1.1    .8    .9   1.2   1.4   1.3   1.0    .8    .8    .9
                      .4   2.2   4.7   6.2   6.1   5.0   3.4   2.0   1.2   1.0   1.1   1.4   1.5   1.3   1.0    .9    .9   1.0
                        1.2   4.1   6.6   7.4   6.8   5.2   3.5   2.2   1.5   1.3   1.4   1.6   1.5   1.3   1.1   1.0   1.0
                      .4   2.8   6.3   8.4   8.5   7.2   5.3   3.6   2.4   1.7   1.5   1.6   1.7   1.6   1.4   1.2   1.1   1.2
                        1.2   4.8   8.6   9.9   9.2   7.5   5.5   3.8   2.6   1.9   1.7   1.8   1.8   1.6   1.5   1.3   1.3
                      .2   2.5   7.2  10.6  11.0   9.7   7.6   5.6   3.9   2.7   2.1   1.9   1.9   1.8   1.7   1.6   1.4   1.4
CPE SABLE            $    .5   4.2   9.4  12.1  11.7  10.0   7.7   5.7   4.0   2.8   2.2   2.0   2.0   1.9   1.8   1.7   1.5
             120     -.1   1.1   6.0  11.3  13.1  12.2  10.1   7.8   5.7   3.9   2.8   2.2   2.1   2.0   1.9   1.9   1.7   1.6
                        -.4   1.7   7.6  12.7  13.9  12.4  10.1   7.8   5.6   3.8   2.8   2.3   2.1   2.1   2.0   2.0   1.8
                     -.4   -.9   2.5   9.3  13.9  14.4  12.5  10.1   7.6   5.3   3.6   2.7   2.3   2.1   2.1   2.1   2.0   1.8
                      -1.2$  -1.3   3.7  10.8  14.8  14.7  12.5  10.0   7.3   5.0   3.4   2.6   2.3   2.2   2.2   2.2   2.0
                     -.6  -2.3  -1.4   5.2  12.4  15.7  14.8  12.4   9.6   6.8   4.6   3.2   2.5   2.3   2.3   2.3   2.2   2.1
                       -1.6 -3.5$   -.9   7.0  13.9  16.2  14.9  12.2   9.1   6.2   4.2   3.0   2.4   2.3   2.4   2.4   2.3
                     -.5  -3.1  -4.5    .2   9.0  15.2  16.6  14.8  11.7   8.4   5.6   3.8   2.8   2.4   2.4   2.5   2.4   2.2
                       -1.4  -4.8 -4.9$   1.7  10.7  16.0  16.8  14.4  10.9   7.5   5.0   3.4   2.6   2.4   2.5   2.6   2.4
                     -.4  -2.9  -6.5  -4.7   3.6  12.3  16.8  16.7  13.7   9.9   6.7   4.4   3.0   2.5   2.5   2.6   2.5   2.3
                       -1.1  -4.6  -7.5  -3.4   5.7  13.9  17.4  16.3  12.6   8.8   5.8   3.8   2.8   2.5   2.6   2.6   2.5
              80     -.3  -2.3  -6.4  -7.7  -1.6   7.7  15.3  17.5  15.4  11.3   7.6   5.0   3.3   2.6   2.5   2.6   2.6   2.3
                        -.8  -3.7  -7.8 -7.2$    .1   9.4  15.9  17.1  14.1   9.9   6.5   4.2   2.9   2.5   2.6   2.6   2.5
EVRGLD CTY           -.2  -1.7  -5.3  -8.9  -6.3   1.3  10.7  16.3  16.2  12.5   8.6   5.5   3.5   2.7   2.6   2.6   2.6   2.3
                        -.6  -2.9  -6.9  -9.5 -5.6$   2.8  11.6  16.0  14.9  10.9   7.2   4.5   3.0   2.6   2.6   2.6   2.5
CPE ROMANO           -.2  -1.3  -4.3  -8.4  -9.9  -4.6   4.0  12.3  15.4  13.3   9.4   6.0   3.8   2.7   2.6   2.6   2.6   2.2
                        -.5  -2.3  -5.9  -9.6  -9.8 -3.4$   5.5  12.8  14.5  11.8   8.1   5.0   3.2   2.6   2.6   2.6   2.4
                     -.1  -1.1  -3.6  -7.4 -10.5  -9.4  -1.8   6.9  13.0  13.4  10.3   6.8   4.2   3.0   2.7   2.7   2.6   2.2
                        -.4  -1.9  -5.0  -8.7 -11.1  -8.4   -.3   8.0  12.7  12.2   9.1   5.8   3.7   2.9   2.8   2.7   2.4
                     -.1   -.9  -3.0  -6.4  -9.7 -11.3  -7.1   1.5   8.9  12.2  11.1   7.9   5.0   3.4   2.9   2.8   2.6   2.2
                        -.3  -1.6  -4.3  -7.6 -10.5 -11.0 -5.4$   3.0   9.3  11.6  10.0   6.9   4.4   3.3   3.0   2.8   2.5
              40     -.1   -.8  -2.6  -5.4  -8.5 -11.0 -10.2  -3.5   4.3   9.5  10.9   8.9   6.0   4.1   3.3   3.0   2.8   2.3
                        -.3  -1.4  -3.5  -6.4  -9.2 -11.0  -8.7 -1.5$   5.3   9.4  10.1   7.8   5.3   3.9   3.3   3.0   2.6
                     -.1   -.6  -2.1  -4.5  -7.2  -9.7 -10.5  -6.9    .3   5.8   9.3   9.0   6.8   4.7   3.8   3.3   2.9   2.3
                        -.2  -1.1  -2.9  -5.3  -7.7  -9.7  -9.3  -4.8  1.6$   6.3   8.6   7.8   5.8   4.4   3.6   3.1   2.6
                     -.1   -.5  -1.7  -3.6  -5.9  -8.0  -9.3  -7.7  -3.0   2.6   6.3   7.7   6.7   5.1   4.0   3.4   2.9   2.2
                        -.2   -.9  -2.3  -4.2  -6.3  -8.1  -8.4  -6.1  -1.6  2.9$   5.9   6.6   5.7   4.5   3.6   3.1   2.5
                     -.1   -.4  -1.3  -2.9  -4.7  -6.6  -7.9  -7.3  -4.7   -.8   3.0   5.2   5.5   4.9   4.0   3.3   2.8   2.1
                        -.2   -.7  -1.8  -3.4  -5.2  -6.8  -7.5  -6.2  -3.7   -.2   2.7   4.5   4.8   4.3   3.5   3.0   2.4
FORT MYERS           -.0   -.4  -1.1  -2.3  -3.9  -5.5  -6.8  -6.7  -5.2  -3.0   -.0   2.4   3.9   4.3   3.8   3.2   2.6   1.9
                        -.1   -.6  -1.5  -2.8  -4.3  -5.8  -6.6  -5.9  -4.4  -2.4   .0$   2.2   3.6   3.9   3.4   2.9   2.2
               0     -.0   -.3   -.9  -2.0  -3.3  -4.7  -5.9  -6.1  -5.1  -3.9  -2.1    .0   2.0   3.4   3.6   3.1   2.5   1.8
                        -.1   -.5  -1.3  -2.4  -3.7  -5.0  -5.8  -5.6  -4.6  -3.6  -2.0  -.0$   2.0   3.2   3.3   2.8   2.2
                     -.0   -.3   -.8  -1.7  -2.8  -4.0  -5.2  -5.6  -5.0  -4.2  -3.4  -1.9    .0   2.1   3.1   3.0   2.5   1.7
                        -.1   -.5  -1.1  -2.0  -3.2  -4.3  -5.2  -5.2  -4.6  -4.0  -3.2  -1.9   .2$   2.2   2.9   2.7   2.1
PNTA GORDA           -.0   -.2   -.7  -1.5  -2.4  -3.5  -4.5  -5.1  -4.8  -4.3  -3.9  -3.3  -1.8    .5   2.2   2.7   2.4   1.7
                        -.1   -.4  -1.0  -1.8  -2.8  -3.8  -4.6  -4.9  -4.5  -4.1  -3.9  -3.2  -1.5    .8   2.2   2.5   2.1
                     -.0   -.2   -.6  -1.3  -2.1  -3.1  -4.0  -4.6  -4.6  -4.2  -4.1  -3.9  -3.1  -1.1   1.0   2.2   2.2   1.6
                        -.1   -.4   -.9  -1.6  -2.4  -3.3  -4.1  -4.5  -4.3  -4.1  -4.1  -4.0  -2.9  -.7$   1.2   2.0   1.9
                     -.0   -.2   -.6  -1.1  -1.8  -2.7  -3.5  -4.1  -4.3  -4.1  -4.1  -4.2  -4.0  -2.6   -.3   1.3   1.9   1.5
                        -.1   -.3   -.8  -1.4  -2.1  -2.9  -3.6  -4.1  -4.1  -4.0  -4.1  -4.3  -3.9  -2.1   .0$   1.4   1.6
             -40     -.0   -.2   -.5  -1.0  -1.6  -2.4  -3.1  -3.7  -4.0  -3.9  -4.0  -4.3  -4.4  -3.6  -1.6    .3   1.3   1.3
                        -.1   -.3   -.7  -1.2  -1.9  -2.6  -3.3  -3.8  -3.9  -3.8  -4.0  -4.4  -4.4  -3.2  -1.2   .5$   1.1
                     -.0   -.2   -.5   -.9  -1.5  -2.1  -2.8  -3.4  -3.7  -3.7  -3.8  -4.2  -4.6  -4.3  -2.7   -.8    .6    .9
                        -.1   -.3   -.7  -1.1  -1.7  -2.3  -2.9  -3.4  -3.7  -3.7  -3.8  -4.4  -4.6  -3.9  -2.2   -.4    .6
                     -.0   -.2   -.4   -.8  -1.3  -1.9  -2.5  -3.0  -3.5  -3.6  -3.6  -4.0  -4.6  -4.6  -3.5  -1.7   -.2    .4
                        -.1   -.3   -.6  -1.0  -1.5  -2.1  -2.6  -3.1  -3.4  -3.5  -3.7  -4.2  -4.7  -4.4  -3.1  -1.3   -.1
                     -.0   -.1   -.4   -.8  -1.2  -1.7  -2.2  -2.8  -3.2  -3.4  -3.5  -3.8  -4.5  -4.8  -4.2  -2.6  -1.0   -.1
                        -.1   -.3   -.6  -1.0  -1.4  -1.9  -2.4  -2.9  -3.3  -3.4  -3.6  -4.1  -4.7  -4.8  -3.8  -2.2   -.8
                     -.0   -.1   -.4   -.7  -1.1  -1.6  -2.0  -2.5  -3.0  -3.3  -3.4  -3.7  -4.4  -4.9  -4.7  -3.5  -1.9   -.7
                        -.1   -.3   -.5   -.9  -1.3  -1.7  -2.2  -2.6  -3.1  -3.3  -3.5  -3.9  -4.7  -5.0  -4.5  -3.1  -1.6
ST PTRSBRG   -80     -.0   -.1   -.4   -.7  -1.0  -1.4  -1.9  -2.3  -2.7  -3.1  -3.3  -3.6  -4.2  -4.8  -5.0  -4.2  -2.7  -1.4
                        -.1   -.2   -.5   -.8  -1.2  -1.6  -2.0  -2.4  -2.8  -3.1  -3.3  -3.7  -4.4  -5.0  -4.8  -3.8  -2.4
                     -.0   -.1   -.4   -.6  -1.0  -1.3  -1.7  -2.1  -2.5  -2.9  -3.1  -3.4  -3.9  -4.6  -5.0  -4.6  -3.4  -2.1
                        -.1   -.2   -.5   -.8  -1.1  -1.4  -1.8  -2.1  -2.6  -2.9  -3.1  -3.4  -4.1  -4.8  -4.9  -4.3  -3.0
                     -.0   -.1   -.3   -.6   -.9  -1.2  -1.5  -1.9  -2.2  -2.6  -2.9  -3.2  -3.6  -4.3  -4.9  -4.8  -4.0  -2.8
CLEARWATER              -.1   -.2   -.5   -.7  -1.0  -1.3  -1.6  -1.9  -2.3  -2.7  -3.0  -3.3  -3.8  -4.5  -4.9  -4.6  -3.7
                     -.0   -.1   -.3   -.6   -.8  -1.1  -1.4  -1.7  -2.0  -2.4  -2.8  -3.0  -3.4  -4.1  -4.7  -4.9  -4.4  -3.4
                        -.0   -.2   -.4   -.7   -.9  -1.2  -1.5  -1.8  -2.1  -2.5  -2.8  -3.1  -3.6  -4.3  -4.9  -4.9  -4.2
                     -.0   -.1   -.3   -.5   -.8  -1.0  -1.3  -1.6  -1.9  -2.2  -2.6  -2.9  -3.2  -3.8  -4.5  -5.0  -4.8  -4.0
                        -.0   -.2   -.4   -.6   -.9  -1.1  -1.4  -1.6  -2.0  -2.3  -2.7  -3.0  -3.4  -4.0  -4.7  -5.0  -4.6
            -120     -.0   -.1   -.3   -.5   -.7  -1.0  -1.2  -1.4  -1.7  -2.1  -2.4  -2.8  -3.1  -3.6  -4.3  -4.9  -5.0  -4.5
BAYPORT                 -.0   -.2   -.4   -.6   -.8  -1.1  -1.3  -1.5  -1.8  -2.2  -2.5  -2.8  -3.2  -3.8  -4.5  -5.0  -4.9
                     -.0   -.1   -.3   -.5   -.7   -.9  -1.1  -1.3  -1.6  -1.9  -2.3  -2.6  -2.9  -3.3  -4.0  -4.7  -5.0  -4.8
                        -.0   -.2   -.4   -.6   -.8  -1.0  -1.2  -1.4  -1.6  -2.0  -2.3  -2.7  -3.0  -3.5  -4.2  -4.8  -5.0
                     -.0   -.1   -.3   -.5   -.7   -.9  -1.1  -1.2  -1.4  -1.7  -2.0  -2.4  -2.7  -3.1  -3.6  -4.3  -4.8  -4.9
                        -.0   -.2   -.4   -.5   -.7   -.9  -1.1  -1.3  -1.5  -1.8  -2.1  -2.5  -2.8  -3.2  -3.8  -4.4  -4.8
                     -.0   -.1   -.2   -.4   -.6   -.8  -1.0  -1.1  -1.3  -1.5  -1.8  -2.2  -2.5  -2.8  -3.3  -3.9  -4.5  -4.7
CRYSTAL RV              -.0   -.2   -.3   -.5   -.7   -.9  -1.0  -1.2  -1.4  -1.6  -1.9  -2.2  -2.6  -2.9  -3.4  -4.0  -4.5
                     -.0   -.1   -.2   -.4   -.6   -.7   -.9  -1.1  -1.2  -1.4  -1.7  -2.0  -2.3  -2.6  -3.0  -3.5  -4.1  -4.5
                        -.0   -.1   -.3   -.5   -.6   -.8  -1.0  -1.1  -1.2  -1.4  -1.7  -2.0  -2.3  -2.6  -3.0  -3.6  -4.1
            -160     -.0   -.1   -.2   -.4   -.5   -.7   -.8  -1.0  -1.1  -1.2  -1.5  -1.7  -2.0  -2.3  -2.7  -3.1  -3.6  -4.1

      HOUR             5     6     7     8     9    10    11    12    13    14    15    16    17    18    19    20    21    22

 PRES DROP          64.9  64.6  64.1  63.5  62.8  61.9  60.9  59.8  58.7  57.5  56.2  55.0  53.8  52.5  51.3  50.2  49.1  48.1  47.2
 STRM SIZE          20.1  20.2  20.4  20.7  21.1  21.6  22.1  22.6  23.2  23.8  24.4  25.0  25.6  26.2  26.8  27.4  27.9  28.4  28.9
 MLS ABEAM          -4.9   3.0   7.0   7.1   2.6  -2.5  -2.4   -.4    .7  -4.9 -13.7 -18.7 -21.7 -25.1 -31.1 -36.5 -43.8 -52.8 -58.8
  STRM SPD          10.6  10.6  10.6  10.6  10.6  10.6  10.7  10.8  10.9  11.1  11.3  11.6  11.8  12.1  12.5  12.9  13.3  13.7  14.2
  MAX WIND         106.5 106.0 105.5 104.7 103.8 102.7 101.5 100.2  98.8  97.3  95.8  94.2  92.7  91.1  89.6  88.2  86.8  85.5

THE MAX-WIND IS A STORM-SCALE-WIND, THAT IS, THE WIND AVERAGED AROUND THE CIRCLE OF HIGHEST WINDS FOR A STATIONARY STORM.
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Figure 6.--Computer printout for time-history surges on the open coast for hurricane Donna, 1960

Let SPLASH II print out figures 5 and 6 (pp. 16 and 17). The track and storm parameters were determined subjectively from data from such sources as bulletins and advisories; they may disagree from other available values.

Before discussing the surges from the abbreviated storm track, we should indicate a few significant differences in surge generation for a storm moving up/down the coast:

1. A storm moving down the coast can generate larger surges than one moving up the coast.

2. High waters lag a storm moving down the coast but lead a storm moving up the coast. Note: a large storm moving slowly has a significant lag/lead time.

3. A storm moving down the coast is most critical for surge generation with a track slightly seaward (an abeam distance less than storm size), whereas a storm moving up the coast is most critical for a track slightly landward.

4. A storm moving down the coast has negative surges along the coast in front of the storm, whereas a storm moving up the coast has positive surges along the coast in front of the storm.

At the coast center (fig. 5), the peak surge occurred at 1900 LST, whereas the storm was abeam to this center at 1600 LST. Thus, high waters lag the storm by about 3 hr; this large lag time is due to a slow-moving storm, 10-12 mi/hr (fig. 6).

The printed times XXXX LST in the display serve to warn the user that the computed surges are unrepresentative because of initialization; a message to this effect is given at the end of the printed display. These times were not shown in previous figures such as figure 3, but they are used in operational outputs of the SPLASH II model.

At Everglades City, the computed surge of 16.9 ft becomes 16 ft with the addition of the astronomical tide. At first sight, this seems to be in serious disagreement with observed high water marks of 8.5 (and 9.7) ft at Everglades City. This city, however, is about 5 mi inland from the coast--across tidal flats--where we expect decreasing surge heights. As further evidence of this decrease, notice the high water mark of 6.2 ft about 10 mi inland and abeam to Everglades City. In fact, all inland high water marks--relative to coastal high water marks--appear to show a rapid decrease with distance inland. Perhaps, an alongshore-moving storm has less potential to push water inland as compared with a storm landfalling normal to the coast.

The high water marks on the coast between Cape Romano and Fort Myers agree more or less with the computed values and agree sufficiently well for forecasting.

Notice that the storm passes Fort Myers far inland; thereafter, the computed surges are small. Warning: secondary effects such as sea-level anomolies, breaking wave setup, tilt of sea within bays/estuaries, and local effects inside broken coast features are not considered by the SPLASH model. These plus the astronomical tide must be supplied by the surge forecaster from any available source.

The special message MINOR SRG at the times position occurs only with storms moving down the coast. It alerts the surge forecaster that surges may be minor (i.e., if the projected track continues far from shore and secondary effects are not significant). At END COMP and beyond (fig. 5), the computed surges are negative for the computational run; they cannot become positive until the storm passes. Whenever the message MINOR SRG occurs, it means that the computed surge has remained negative for the run and we do not know what the positive values will be when the storm passes. The surge forecaster must evaluate the possibility of surges becoming significant at a later time (i.e., making another run by extending the track into another basin).

The 1944 Storm

This storm is a severe test for SPLASH II, for there are storm accelerations along the curvilinear track, exceptional storm celerity, huge and dramatic changes in pressure drop, and large changes in storm size with time. The computed surge envelope and time-history coastal surges are shown in figures 7 and 8. The meteorological data for this storm were assembled from the report by the Weather Bureau (1960). We remind the reader that, in the operational model, storm parameters and storm motion are varied with time in a continuous manner; hence, rapid fluctuations in a short time span are not accommodated.

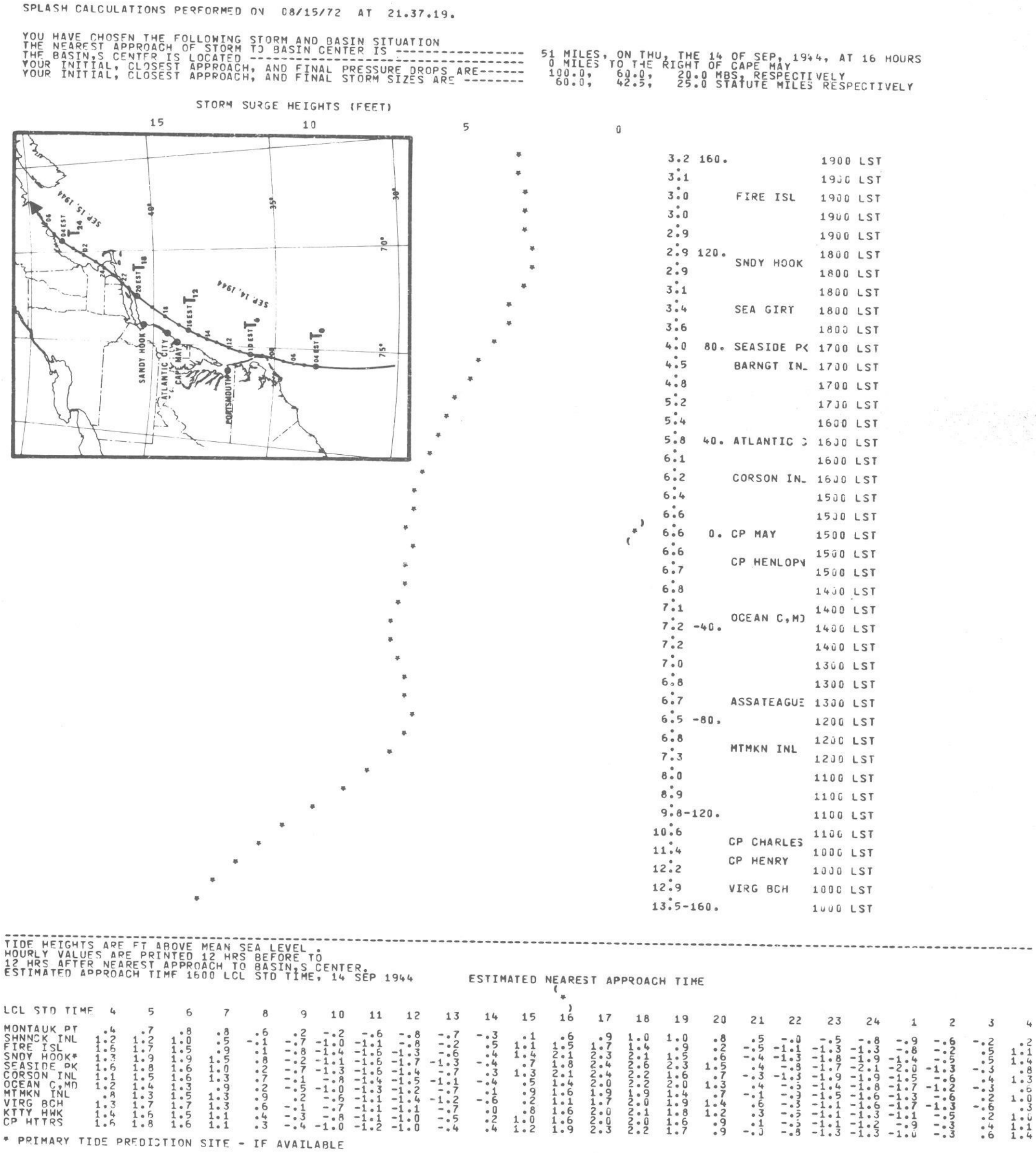
On figure 7, the messages STRT STM, MATR STM, and END COMP do not appear; this is due to a rapidly moving storm (30-35 mi/hr) whereby initialization and termination of computations occur outside our area of interest. The observed track of the storm is displayed in the inset; notice the detail in space and time. Our model just cannot fabricate all the detail with the five points $T_0 \ldots T_{24}$. Because the pressure drop decreases as the storm moves along the coast, the envelope of coastal surges decreases accordingly. The storm is initialized in deep water, but our computations compel a growth to maturity while the storm traverses the Continental Shelf;[18] this means that the initial transient surge may be too large.

In figure 8, we insert three tide-gage readings--less astronomical tide--for comparison and explanatory purposes (Harris 1963). For our area of interest (the coastal neighborhood at the center of the basin's coastline), there are no observations of high water marks. The computed surge leads all three gages; this occurs in part because:

1. Our model track does not reflect the details of the observed track.

---

[18] We could compel the storm to reach maturity before traversing the shelf if the basin is extended to accommodate a long track; but then, the action of the track with a curving coastline is not properly accounted for in our model.



```
SPLASH CALCULATIONS PERFORMED ON  08/15/72  AT  21.37.19.

YOU HAVE CHOSEN THE FOLLOWING STORM AND BASIN SITUATION
THE NEAREST APPROACH OF STORM TO BASIN CENTER IS -----------------  51 MILES, ON THU, THE 14 OF SEP, 1944, AT 16 HOURS
THE BASIN,S CENTER IS LOCATED -------------------------------------  0 MILES TO THE RIGHT OF CAPE MAY
YOUR INITIAL, CLOSEST APPROACH, AND FINAL PRESSURE DROPS ARE-------  100.0,   60.0,   20.0 MBS, RESPECTIVELY
YOUR INITIAL, CLOSEST APPROACH, AND FINAL STORM SIZES ARE --------   60.0,   42.5,   25.0 STATUTE MILES RESPECTIVELY

                    STORM SURGE HEIGHTS (FEET)
              15                10                5                0

                                                       3.2 160.                  1900 LST
                                                       3.1                       1900 LST
                                                       3.0        FIRE ISL       1900 LST
                                                       3.0                       1900 LST
                                                       2.9                       1900 LST
                                                       2.9 120.                  1800 LST
                                                                  SNDY HOOK
                                                       2.9                       1800 LST
                                                       3.1                       1800 LST
                                                       3.4        SEA GIRT       1800 LST
                                                       3.6                       1800 LST
                                                       4.0  80.   SEASIDE PK     1700 LST
                                                       4.5        BARNGT IN.     1700 LST
                                                       4.8                       1700 LST
                                                       5.2                       1700 LST
                                                       5.4                       1600 LST
                                                       5.8  40.   ATLANTIC C     1600 LST
                                                       6.1                       1600 LST
                                                       6.2        CORSON IN.     1600 LST
                                                       6.4                       1500 LST
                                                       6.6                       1500 LST
                                                   (*) 6.6   0.   CP MAY         1500 LST
                                                       6.6                       1500 LST
                                                                  CP HENLOPN
                                                       6.7                       1500 LST
                                                       6.8                       1400 LST
                                                       7.1                       1400 LST
                                                                  OCEAN C,MD
                                                       7.2 -40.                  1400 LST
                                                       7.2                       1400 LST
                                                       7.0                       1300 LST
                                                       6.8                       1300 LST
                                                       6.7        ASSATEAGUE     1300 LST
                                                       6.5 -80.                  1200 LST
                                                       6.8                       1200 LST
                                                                  MTMKN INL
                                                       7.3                       1200 LST
                                                       8.0                       1100 LST
                                                       8.9                       1100 LST
                                                       9.8-120.                  1100 LST
                                                      10.6                       1100 LST
                                                                  CP CHARLES
                                                      11.4                       1000 LST
                                                                  CP HENRY
                                                      12.2                       1000 LST
                                                      12.9        VIRG BCH       1000 LST
                                                      13.5-160.                  1000 LST
-----------------------------------------------------------------------------------------------------
TIDE HEIGHTS ARE FT ABOVE MEAN SEA LEVEL .
HOURLY VALUES ARE PRINTED 12 HRS BEFORE TO
12 HRS AFTER NEAREST APPROACH TO BASIN,S CENTER.
ESTIMATED APPROACH TIME 1600 LCL STD TIME, 14 SEP 1944      ESTIMATED NEAREST APPROACH TIME
                                                                        (
                                                                        *
                                                                        )
LCL STD TIME  4    5    6    7    8    9   10   11   12   13   14   15   16   17   18   19   20   21   22   23   24    1    2    3    4

MONTAUK PT    .4   .7   .8   .8   .6   .2  -.2  -.6  -.8  -.7  -.3   .1   .6   .9  1.0  1.0   .8   .5  -.0  -.5  -.8  -.9  -.6  -.2   .2
SHNNCK INL   1.2  1.2  1.0   .5  -.1  -.7 -1.0 -1.1  -.8  -.2   .5  1.1  1.5  1.7  1.4   .9   .2  -.5 -1.1 -1.3 -1.3  -.8  -.2   .5  1.1
FIRE ISL     1.6  1.7  1.5   .9   .1  -.8 -1.4 -1.6 -1.3  -.6   .4  1.4  2.1  2.3  2.1  1.5   .6  -.4 -1.3 -1.8 -1.9 -1.4  -.5   .5  1.4
SNDY HOOK*   1.3  1.9  1.9  1.5   .8  -.2 -1.1 -1.6 -1.7 -1.3  -.4   .7  1.8  2.4  2.6  2.3  1.5   .4  -.8 -1.7 -2.1 -2.0 -1.3  -.3   .8
SEASIDE PK   1.6  1.8  1.6  1.0   .2  -.7 -1.3 -1.6 -1.4  -.7   .3  1.3  2.1  2.4  2.2  1.6   .7  -.3 -1.3 -1.9 -1.9 -1.5  -.6   .4  1.3
CORSON INL   1.1  1.5  1.6  1.3   .7  -.1  -.8 -1.4 -1.5 -1.1  -.4   .5  1.4  2.0  2.2  2.0  1.3   .4  -.5 -1.4 -1.8 -1.7 -1.2  -.3   .6
OCEAN C,MD   1.2  1.4  1.3   .9   .2  -.5 -1.0 -1.3 -1.2  -.7   .1   .9  1.6  1.9  1.9  1.4   .7  -.1  -.3 -1.5 -1.6 -1.3  -.6   .2  1.0
MTMKN INL     .8  1.3  1.5  1.3   .9   .2  -.6 -1.1 -1.4 -1.2  -.6   .2  1.1  1.7  2.0  1.9  1.4   .6  -.3 -1.1 -1.6 -1.7 -1.3  -.6   .3
VIRG BCH     1.3  1.7  1.7  1.3   .6  -.1  -.7 -1.1 -1.1  -.7   .0   .8  1.6  2.0  2.1  1.8  1.2   .3  -.5 -1.1 -1.3 -1.1  -.5   .2  1.0
KTTY HWK     1.4  1.6  1.5  1.1   .4  -.3  -.8 -1.1 -1.0  -.5   .2  1.0  1.6  2.0  2.0  1.6   .9   .1  -.5 -1.1 -1.2  -.9  -.3   .4  1.1
CP HTTRS     1.6  1.8  1.6  1.1   .3  -.4 -1.0 -1.2 -1.0  -.4   .4  1.2  1.9  2.3  2.2  1.7   .9  -.0  -.8 -1.3 -1.3 -1.0  -.3   .6  1.4
* PRIMARY TIDE PREDICTION SITE - IF AVAILABLE
```

Figure 7.--Computer printout for the computed surge envelope of high waters on the open coast, generated by the September 1944 storm. The inset gives the storm track (Weather Bureau 1960).

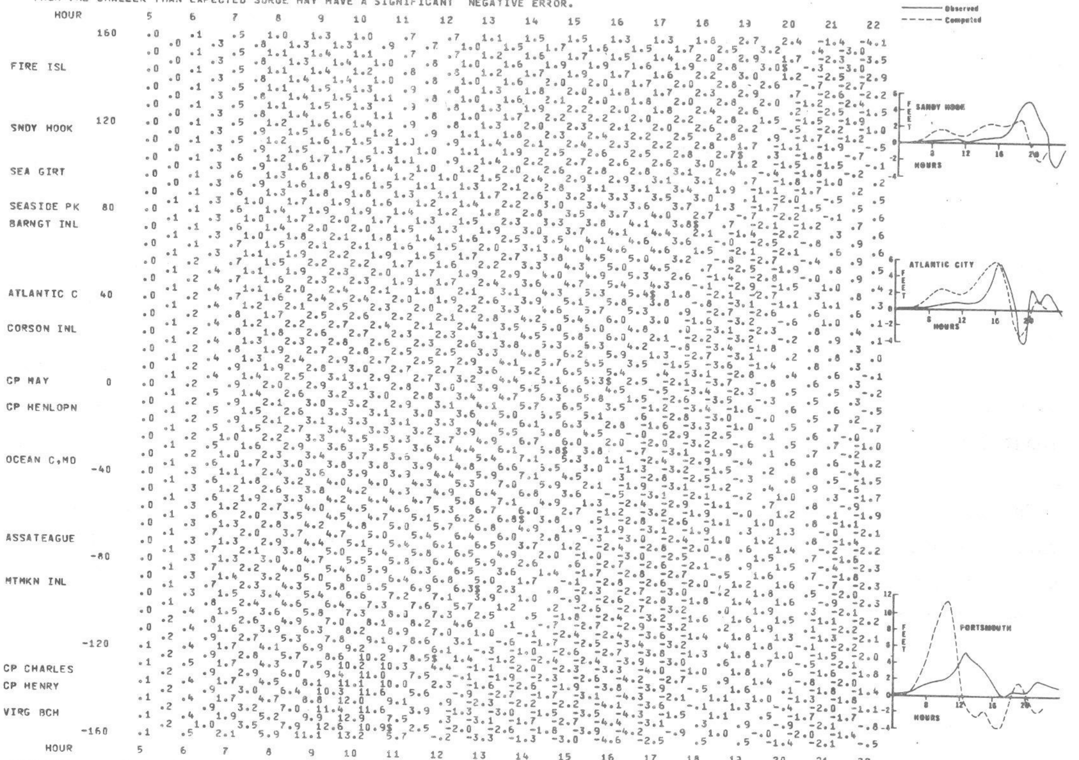
2. The model storm size decreases monotonically and continuously with time and does not reflect the details of the actual storm. [We remind the reader that the observed meteorological values are best estimates from available data; we do not know how well they represent actual meteorology. There are strong objections to the <u>extreme</u> initial size and pressure drop of the storm given in the report by the Weather Bureau (1960).]

```
THIS IS A SPACE-TIME PLOT OF THE COASTAL SURGES

THE COMPUTATIONS HAVE BEEN INITIALIZED FOR THU, THE 14 OF SEP, 1944 AT 4 HOUR

GROWTH TIME OF STORM TO MATURITY, AFTER INITIALIZATION, IS  4.0 HOURS

NEAREST APPROACH TIME OF STORM TO BASIN CENTER IS 16 HOURS.
PRIOR TO THIS TIME THE COMPUTED SURGE VALUES MAY BE SERIOUSLY IN ERROR DUE TO INITIALIZATION PROCEDURES
THIS CAN EASILY HAPPEN IF THE STORM IS INITIALIZED ON THE CONTINENTAL SHELF, IN SHALLOW WATER, CLOSE TO THE COAST.
EXAMPLE 1.
   SOMETIMES THERE ARE EXCEPTIONALLY LARGE SURGES PRIOR TO 16 HOURS DUE TO TRANSIENT OVER-REACTION OF THE SEA.
   IF THIS APPEARS BETWEEN  5 TO  9 HOURS, AND IF DURING THIS PERIOD
      1. STORM DISTANCE ABEAM OF COAST IS SMALLER THAN STORM DIAMETER
      2. STORM IS MOVING TOWARD THE COAST
   THEN THE INITIALLY LARGE SURGE MAY HAVE A SIGNIFICANT + ERROR.
EXAMPLE 2.
   SOMETIMES THERE ARE SMALLER THAN EXPECTED SURGES PRIOR TO 16 HOURS DUE TO TRANSIENT UNDER-REACTION OF THE SEA.
   IF THIS APPEARS BETWEEN  5 TO  9 HOURS, AND IF DURING THIS PERIOD
      1. STORM DISTANCE ABEAM OF COAST IS SMALLER THAN STORM DIAMETER
      2. STORM IS MOVING AWAY FROM THE COAST
   THEN THE SMALLER THAN EXPECTED SURGE MAY HAVE A SIGNIFICANT  NEGATIVE ERROR.
```



```
     HOUR          5      6      7      8      9     10     11     12     13     14     15     16     17     18     19     20     21     22
PRES DROP        99.6   98.4   96.6   94.1   91.0   87.5   83.6   79.3   74.7   69.9   65.0   60.0   55.0   50.1   45.3   40.7   36.4   32.5   29.0
STRM SIZE        59.8   59.3   58.5   57.4   56.1   54.5   52.8   50.9   48.9   46.8   44.7   42.5   40.3   38.2   36.1   34.1   32.2   30.5   28.9
MLS ABEAM       130.1  116.3   16.0    5.1   -3.0   11.1   36.2   45.8   43.2   38.5   42.6   48.7   42.4   42.4   54.7   42.8    8.8  -14.5  -16.7
 STRM SPD        30.3   30.6   30.9   31.3   31.8   32.3   32.7   33.2   33.7   34.1   34.5   34.8   35.2   35.4   35.6   35.8   35.9   35.9   35.9
 MAX WIND        99.1   98.8   98.3   97.6   96.7   95.5   94.2   92.7   90.9   88.9   86.6   84.1   81.3   78.4   75.2   71.8   68.4   64.9

THE MAX-WIND IS A STORM-SCALE-WIND, THAT IS, THE WIND AVERAGED AROUND THE CIRCLE OF HIGHEST WINDS FOR A STATIONARY STORM.
THE FASTEST-MILE-WIND IS ABOUT 1.3 TIMES FASTER.

THE SYMBOL, $, LISTS (APPROXIMATE) HOURLY STORM POSITIONS, ABEAM OF THE COASTLINE
```

Figure 8.--Computer printout for time-history surges on the open coast for the September 1944 storm. The three insets compare observed/computed surges at three tide-gage stations; only the Atlantic City gage lies on the open coast; the other two are within bays.

The gage at Portsmouth is on a tributary within Chesapeake Bay; it does not lie on the open coast. The computed time-history surge abeam to Portsmouth has the same character as the observed surge but is out of phase about 2 hr and has a drastically different amplitude. We should not be startled by this because:

1. The initial, computed transient surge on the coast may be too large.

2. The mouth of a bay is not an open coast.

3. Surges within a bay can be significantly different from the open coast surge, and it

takes time for the coastal surge to move into the bay.

4. The coastline is curvilinear, and Portsmouth is more than 100 mi from the center of the basin's coastline.

5. The storm strength and size--abeam to Portsmouth--are exceptionally large, and small errors in meteorology can mean significant errors in computed surge on the open coast.

The gage at Atlantic City is near the center of the basin's coastline and lies on the open coast; we expect useful results in this region where we have designed our model to be most functional. The gage became inoperative between 1600 and 1700 EST, and we do not know exactly how high the waters were. The initial high surge computed at 0900 EST is due to initialization phenomena with an exceptionally large and powerful storm growing to maturity while on the Continental Shelf. We emphasize that small changes in storm track and parameters can give significant changes in the computed surge; moreover, by juggling the meteorology and storm track slightly (all within observational accuracy), we can compute surges that agree with observed values more closely than shown. Note: the computed surge leads the storm by about 1 hr.

The gage at Sandy Hook lies on an extended spit near the entrance of a bay. The coast takes a sharp 90° turn at Long Island. This dramatic curvature of the open coast warns that our model computations may be suspect. We qualitatively can explain the smaller computed surge values as:

1. The pressure drop of the storm abeam to Sandy Hook may have been too small (the model changes pressure drop monotonically with time and ignores complicated detail).

2. The curvature of the coast--an inside corner--generates larger surges than a straight-line coast.

3. The details of the storm track are not present in our model track.

4. Sandy Hook is more than 100 mi from the center of the basin's coastline.

For a more comprehensive computation of surges on other portions of the coast besides the neighborhood of Cape May, we suggest the track be segmented about coastal points of interest (i.e., several computational runs in several basins). An example of this is shown in the next section.

B. Slow-Moving Storms (Special Cases)

For fast-moving storms, we compute surges only on a segment of coast affected by the storm; but for slow-moving storms, we must improvise and compromise to compute surges on a comparable coastal segment. This is so because our model is limited in real time.

To discuss the mechanics of the model for slow-moving storms, we manufacture a hypothetical storm with the following properties:

1. The storm traverses the Continental Shelf at a slow speed (less than 8 mi/hr).

2. The storm's closest approach to the coast occurs near Miami, Fla., where the Continental Shelf is almost nonexistent.[19]

3. The storm's strength and size (ΔP=100 mb and R=15 mi) are invariant along the track.

Note: we do not use a historical storm, simply because no adequate meteorological data have been analyzed; we do not know how well the model will work in real life, but it does present a severe trial with property 2. Note also that it is the nature of surge generation to be sensitive to placement of track relative to the coast; hence, published tracks based on operational weather charts may not be adequately precise for our model. A much more exhaustive analysis, utilizing all available data after the fact, will give a more representative track.

The upper part of figure 9 shows three computed surge envelopes generated by the hypothetical storm. The bottom part shows the storm track on the sea. The coast has been straightened for convenient display. It takes more than 2 days for the storm to traverse the hypothetical track. Our model is limited to 18 hr of real time (less growth time to storm maturity); hence, we segment the track into three areas of interest:

1. The first segment, A to B, about Matecumbe Key.

2. The second segment, C to D, about Fort Lauderdale.

3. The third segment, E to F, about Vero Beach.

The valid portions on the coast lie between A' and B', C' and D', and E' and F' (i.e., they lie between MATR STM and END COMP.

The first segment is initialized in deep water while the storm is traveling toward the coast, and the storm is mature in deep water before affecting the coast. We, therefore, have no serious problems with initial transients (see appendix II). The point B' on the envelope relates the abeam position of the storm at the end of the computations. The envelope on the coast is valid to B' and possibly farther to the right according to how the storm lags high waters. We do not suspect the surge about A' and farther to the left because the mature storm enters the shelf similarly to a landfall storm.

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[19] We need to investigate surge generation inside small shelf widths, contiguous to a steep (vertical) continental slope. This would be an interesting future research project.

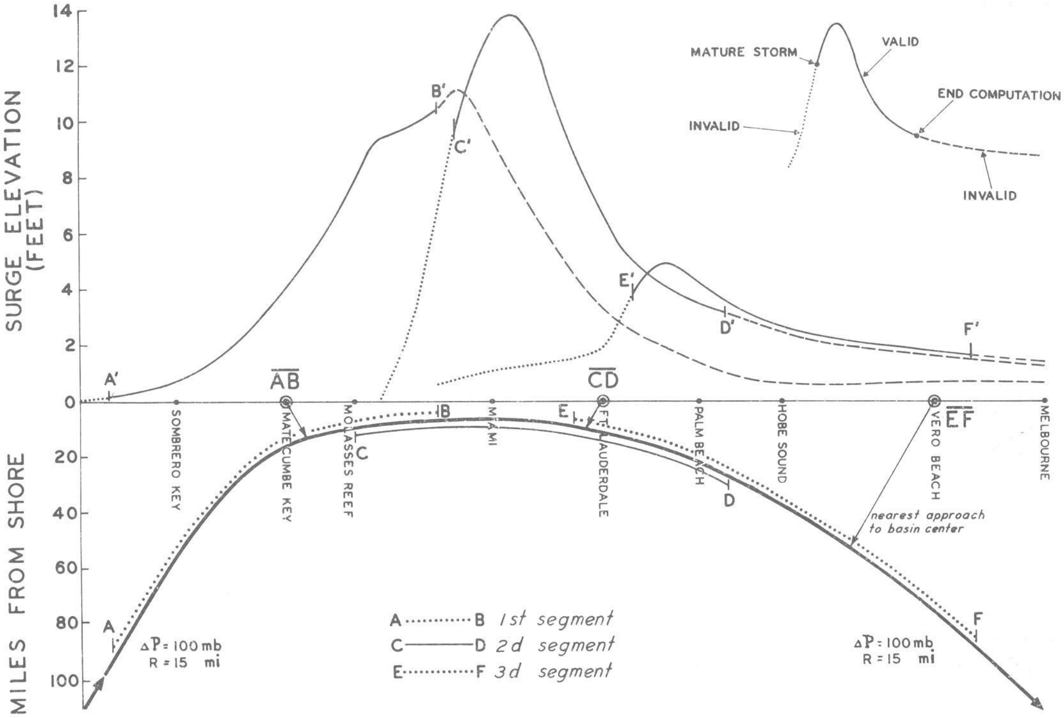

Figure 9.--Three coastal envelopes of high waters, computed on overlapping segments of a track for a slow-moving storm

The second segment is initialized on the shelf while the storm is traveling toward the coast, and the storm grows to maturity while affecting the coast. We may have serious problems with initial transients in this case, and the peak surge on the envelope could then be too large. The points C' and D' on the envelope relate the abeam positions of the storm when it becomes mature and at the end of the computations. The envelope is valid from C' to D'; however, we suspect the surges may be too small at C' and then too large at its peak value because the basin is in the process of adjusting itself to initialization phenomena; also, the surges may be valid to the right of D' because the storm lags high waters and because the storm then exits the Continental Shelf.

The third segment is initialized on the shelf while the storm is traveling away from the coast, and the storm grows to maturity while affecting the coast. The point E' on the envelope relates the abeam position of the storm when it becomes mature; the envelope is valid from E' outward to the right. We have the same problems with initial transients (as in the second segment), and the height of the peak surge on the envelope is suspect. We do not suspect the surges about F' and farther to the right because the mature storm is departing the shelf similarly to an exiting storm.

To compute coastal surges on either side of a segmented track is impossible. The surge forecaster must realize that the ends of a surge envelope, generated by a segmented track, is suspect; exceptions of course are for mature storms that enter or depart the shelf as a landfall or exiting storm. Note: the central region of the surge envelope generated by a segmented track is not suspect unless the storm is near stationary (see appendix II). All this must be taken into account when composing a composite surge envelope for several track segments.

A simple procedure for slow-moving storms would compute with a real time interval that spans the entire track affecting the coast. However, this may require not only a long computational effort but also a prohibitively long coastline (i.e., a large basin). There is also the problem of long-term accumulative errors from open boundary conditions. We will need to study radiation conditions for open boundaries and apply a curvilinear coordinate system conformal to the natural coast before performing long time computations in a basin truncated from the ocean.

V. SUMMARY AND CONCLUSIONS

We extend an operational SPLASH to accommodate storms that travel alongshore, recurve, remain stationary, or follow a curvilinear track. Also, the strength and size of the storm is allowed to vary with time along the storm's track, but in a restricted manner (i.e., variations proceed monotonically with time).

Such complicated storm conditions can generate a weird assortment of transients that are difficult for the surge forecaster to interpret; moreover, the coastal surge is sensitive in some cases to even small errors in track position and meteorological parameters. An example is a storm traveling near parallel to a coast; the coastal surge is then sensitive to small changes in the track direction, relative to the coastal orientation.

The peak surge generated by landfall storms is not unduly sensitive to storm size. For nonlandfall storms, however, storm size is important; this is so because the surge on the coast is a function of distance from the coast relative to storm size. The length of coast affected by surges can be extraordinarily long, if the component of track on the coast--while the storm is on the shelf--is large; for a storm traveling normal to the coast, the component of track on the coast degenerates into a point, and only a small length of coast is affected by surges.

At present, our model shifts the coast onto a straight line. This is a serious restriction when dealing with a naturally curvilinear coastline with strong curvature. Our computations are valid--at worst--about the center of our model basin. The length of coastline in our model is restricted. If the track on the shelf has a component on the coast longer than the basin's coastline, then we cannot compute for the entire coastline affected by the storm with only one computational effort; in this case, several computations are required in several basins.

Storms that threaten a coast with surges are dangerous when less than one diameter (twice the radius of maximum winds) from the coast; as this distance increases, the surge rapidly decreases. This puts a burden on the surge forecaster, for he must have an accurate account of the entire track (relative to a coastline) and not just initial and terminal points on the track.

Meteorology is a means to an end--not an end in itself--when forecasting surges. An acceptable meteorological forecast may not be completely satisfactory for surge prediction. As an example, suppose a storm is forecast to move up and parallel to a coast, but in fact moves (1) slightly to the left toward shallow water or (2) slightly to the right toward deep water, then the surges along the coast for the two nearly identical tracks can be as different as night and day.

Surge forecasting deals with oceanographic phenomena. Many critical situations can occur, and these are dependent on both the meteorology and the geography of the continental shelf (i.e., meteorology by itself does not tell if a critical situation arises). For example, suppose that, in a given basin, the track and all meteorological parameters are held fixed except for storm speed, then there is a given speed that produces the highest surge; similarly, this occurs for other parameters or combination of parameters such as vector storm motion (speed and direction). The forecaster must ask himself such questions as "What if the storm goes faster/slower, increases/decreases in size,and changes course to the right/left? Do such small changes--all within meteorological forecasting accuracy--take us into or out of a critical situation? If so, by how much?" To answer these questions, he will need to make several computational efforts and investigate the phenomena in some detail.

An alongshore-moving storm generates a smaller surge compared to a landfall storm (exceptions are storms traveling down a coast and generating resonance); however, a large fetch of coast (hundreds of miles) can be affected by the storm.

Our computations are valid only on the open coast; broken features (e.g., bays, sounds, estuaries, and intracoastal waterways) are not incorporated in the model. We emphasize that surge values on broken coastlines can be significantly different from open coast values; also, surges on broken coastlines are influenced differently for a landfall storm versus an alongshore-moving storm. If the storm track parallels the major axis of a broken coast feature, then the surges inside the region can be higher than the open coast surge. We remark that alongshore-moving storms generally do not parallel the major axis of estuaries, but they may for bays.

Some bays and estuaries are dangerous to communities if waters rise only a few feet. This can occur even if the storm does not generate a surge (long gravity wave) of any consequence. There are secondary effects on the sea surface that locally can produce a critical water level (by secondary effects, we mean rise of local waters from phenomena other than astronomical tide and storm surges).

One such secondary effect is local mean sea level. Recall that local mean sea level is a living thing--not invariant and not always corresponding to geodetic sea level or land-contoured charts. In the Gulf of Mexico, it is not unusual for local mean sea level to differ from geodetic mean sea level by as much as 2 ft (Harris 1958). The surge forecaster should keep a running account of predicted/observed astronomical tide for several days before a storm affects his area and thereby account for an anomolous rise (fall) of the sea level during hurricane conditions.

Another secondary effect on coastal sea level is the action of such factors as surf, swell, and breaking waves (i.e., short gravity waves). It is well known that wave setup can occur on the coast with a train of breaking waves. Observations and laboratory studies of these phenomena--in the absence of surface driving forces and a forming storm surge--show that the setup can be significant. We cannot specify how much the setup will be in localized situations or the details of its variations on the sea surface (note: wave setup in one part of the sea implies wave setdown in another part). We remind the reader that if the surge on the coast is significant, then the drag coefficient in our model implicitly may account for some of the short-gravity wave setup on the coast (i.e., wave setup is important in the absence of a significant meteorological surge).

A secondary effect that can occur inside a bay or estuary--but not along the open coast--is a quasi-steady state slanted or tilted sea. An alongshore-moving storm, producing winds predominantly in one direction for a long time duration, can tilt the sea in a closed or partially closed basin; the tilt along the open coast is much smaller because the scale length of the coast is much larger than the bay's major axis. The tilt within the basin can occur even with weak winds. We cannot specify, at this time, how much the sea tilts because each bay (estuary) has its own particular reaction to a given storm.

These secondary effects--and many others of a subtle nature--are small except for critical situations. The surge forecaster must be aware that at times they can conspire together to produce a significant rise of water that is not explained with available surge models.

In SPLASH I, we developed nomograms to predict peak storm surges that are generated by storms which landfall (exit). Pertaining to these storms, the meteorological parameters and storm track are invariant. In principle, we also could design nomograms for the complicated storms and tracks of this report; however, they would have questionable value since they would be misleading and difficult to interpret. The problem is that there are many extra parameters and conditions with which to contend (e.g., variant storm strength and size, curvilinear track and variant speed on the track, complicated two-dimensional bathymetry with respect to the track, and transients). The surge is sensitive to groupings of these conditions, and this sensitivity cannot be incorporated directly with simple nomograms (i.e., the nomograms are not independent of each other). Instead of trying to accommodate so many specialized features in a few nomograms, we suggest that each particular storm situation be explored with the numerical surge model as the occasion arises.

The printed output of SPLASH I gives simple correction factors for small conceptual changes in storm parameters and landfall position; this is to aid the surge forecaster in planning his surge prediction. We do not give such gratuitous information in the printed output of SPLASH II because the surge at times is sensitive to small changes in meteorological parameters and storm track (i.e., the dynamics of surge generation can change drastically).

The surge model is neutral on the user's selection of storm parameters and storm track; it makes no protest unless certain bounds are exceeded. This means that almost any number (for, say, the peak surge at a given coastal location) can be computed depending on meteorological input data. Because data from past storms at any selected point on the coast are sparse or even nonexistent, the way is open for any individual to supply processed data from climatology. We point out that the model is no better than the quality of the data used. The user should be careful and suspicious of broad, highly smoothed data from long stretches of space about the coastal area of interest; these may no longer be representative of meteorological conditions for particular problems under study.

The operational computer output engineered in this study is a useful tool. As such, it should be considered as only an aid for the prediction of, or planning for, storm surges. This output is not a substitute for experience and judgment. We advise that there are inherent weaknesses in the dynamic model used here and there always will be uncertainties in the meteorological input data; the user judiciously must apply his knowledge so as not to support or strengthen these inadequacies.

ACKNOWLEDGMENTS

I am deeply indebted to Albion Taylor for his many helpful suggestions, technical help in designing the computer program, and the many friendly hours of discussion on storm surge hydraulics. Also, special thanks are in order to Herman Perrotti for the graphic art.

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APPENDIX I. DATA DECK FOR SPLASH II

The operational SPLASH is stored on tape. We use the same procedure given in SPLASH I (Jelesnianski 1972) for operational runs; however, the input data--the data deck--of SPLASH II is somewhat different.

The data deck consists of 2 title cards, followed by 10 storm data cards, and terminated by 4 time cards for astronomical tide predictions.[20] The two title cards are self explanatory, but the form and style of the storm and time cards require some explanations.

The first storm data card uses 1 of 30 stations (fig 10). Choose that station nearest to the center of a coastal region of interest. The station letters begin on the first space of the card, never exceed 10 spaces, and are punched exactly as printed in table 1, spaces and all; any spaces beyond the 10th space can be used for comments. Here, we use an A10 format.

Each of the next five storm data cards list both latitude and longitude at times T_0, T_6, T_{12}, T_{18}, and T_{24} on the storm track (i.e., track positions at 6-hr intervals). The position at T_{12} should be more or less abeam to station. Use the first 10 spaces of a card for

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[20] The data deck is organized with one piece of information on each card. It is unnecessary to space the deck with so many cards; if desirable, however, we could compactly organize the deck by updating the program.

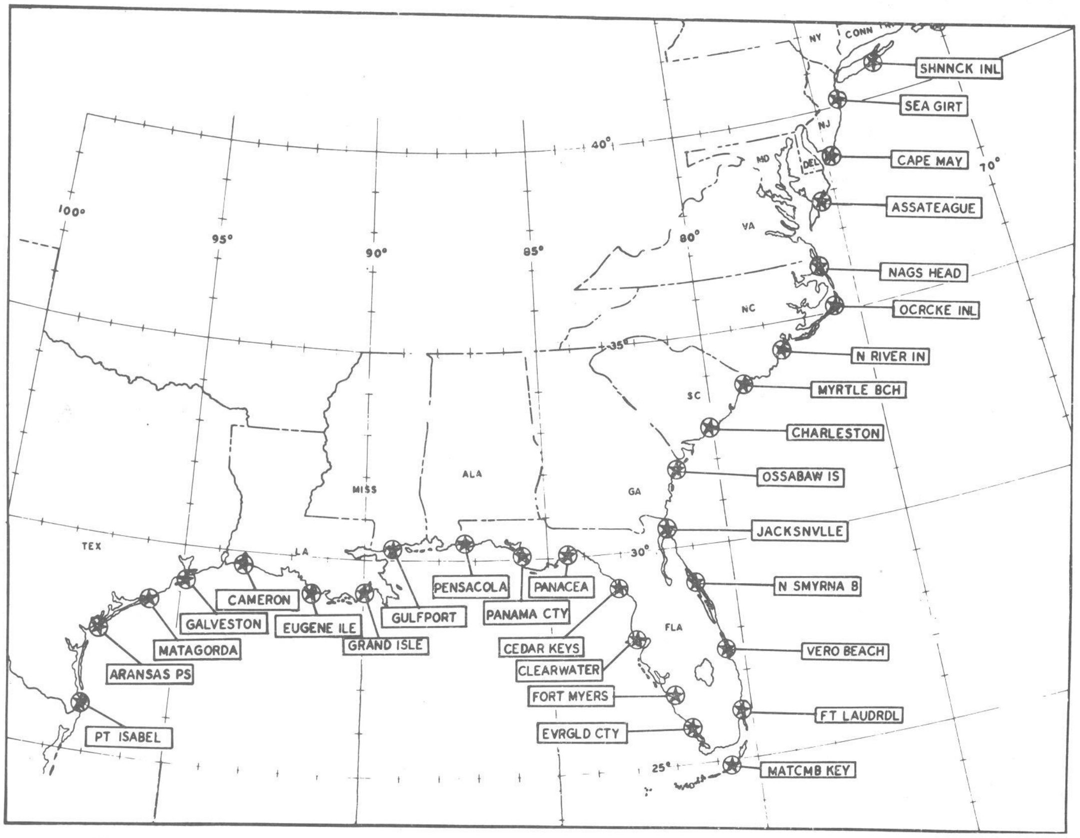

Figure 10.--Selected stations on the gulf and east coasts. See also table 1.

Table 1.--Preselected coastal stations.* See also figure 10.

Gulf stations	Latitude (° 'N)	Longitude (° 'W)	East Cst Stats	Latitude (° 'N)	Longitude (° 'W)
PT ISABEL	26 05	97 10	MATCMB KEY	24 55	80 39
ARANSAS PS	27 50	97 03	FT LAUDRDL	26 07	80 06
MATAGORDA	28 21	96 24	VERO BEACH	27 39	80 21
GALVESTON	29 16	94 48	N SMYRNA BCH	29 02	80 54
CAMERON	29 46	93 19	JACKSNVLLE	30 20	81 24
EUGENE ILE	29 21	91 24	OSSABAW IS	31 46	81 04
GRAND ISLE	29 13	90 01	CHARLESTON	32 44	79 51
GULFPORT	30 15	89 00	MYRTLE BCH	33 41	78 53
PENSACOLA	30 20	87 11	N RIVER IN	34 32	77 20
PANAMA CTY	30 07	85 42	OCRCKE INL	35 04	76 01
PANACEA	29 59	84 19	NAGS HEAD	36 01	75 39
CEDAR KEYS	29 11	83 02	ASSATEAGUE	37 54	75 20
CLEARWATER	27 59	82 49	CAPE MAY	38 55	74 54
FORT MYERS	26 29	82 10	SEA GIRT	40 08	74 02
EVRGLD CTY	25 45	81 30	SCNNCK INL	40 51	72 28

*These location abbreviations are exactly as used for input to SPLASH.

latitude and the next 10 spaces for longitude; use degrees and fractions (not minutes and seconds). All spaces beyond can be used for comments; Here, we use a 2F10.5 format.

Each of the next two storm-data cards list pressure drop (ΔP in mb) of the storm at times T_0 and T_{24}. Note that $10.0 \leq \Delta P \leq 140.0$ in the program. Use the first five spaces of the data card; any spaces beyond can be used for comments. Here, we use an F5.1 format.

Each of the next two storm-data cards list storm size (in mi) at times T_0 and T_{24}. The storm size R is the radius of maximum winds. Note that $10.0 \leq R \leq 60.0$ in the program.[21] Use the first five spaces of the card; any spaces beyond can be used for comments. The size can be in decimals if desired. Here, we use an F5.1 format.

For the first time card, use the nearest integer hour for T_0--the first of five storm positions--from 0100 to 2400. Use the first four spaces of the card and let the last two spaces be zeros; any spaces beyond can be used for comments. Here, we use an I4 format.

For the next time card, use the day for T_0, from day 01 to day 31. Use the first two spaces of the card; any spaces beyond can be used for comments. Here, we use an I2 format.

For the next time card, use the month of T_0. Use the first three letters of the month in the first three spaces of the data card; any spaces beyond can be used for comments, including the complete spelling of the month. Here, we use an A3 format.

For the next time card, use the year of T_0. The years can lie between 1900 and 1999 for past-present-future predictions of astronomical tide. Use the first four spaces of the data card; any spaces beyond can be used for comments. Here, we use the I4 format.

An example of a punched data deck is shown in figure 11; the deck is set in the small program as shown in SPLASH I (Jelesnianski 1972). The cards must be in sequence. If N jobs are to be executed, then set N data decks in the small program; separate each data deck with an end of record (EOR) card. Behind the last data deck, insert an end of file (EOF) card.[22]

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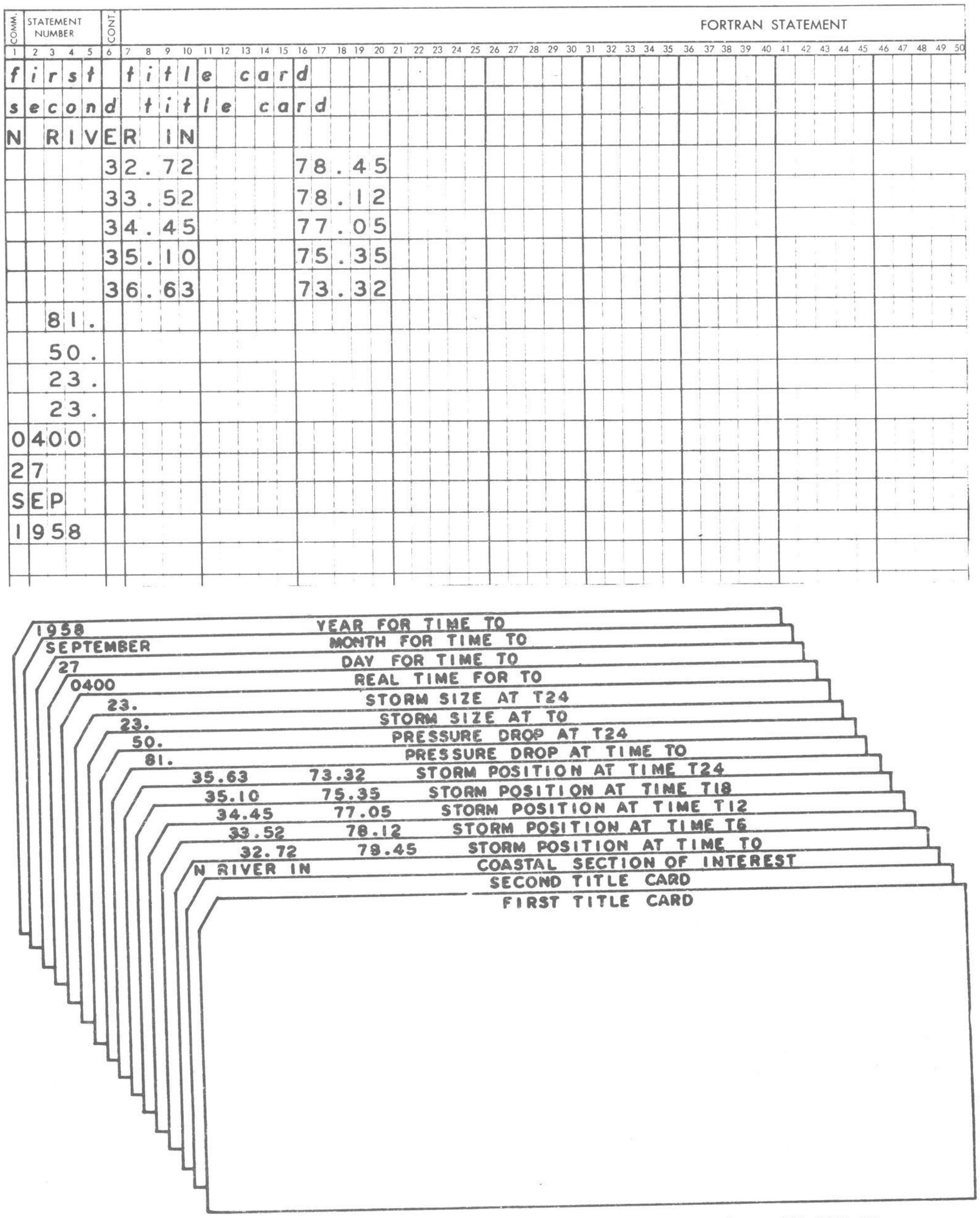
[21] It is doubtful if such a large storm as 60 mi can be represented adequately by our model.

[22] A CDC 6600 EOR card is one with the 7, 8, and 9 holes punched in column 1, and an EOF card has the 6, 7, 8, and 9 holes punched in column 1.



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first title card
second title card
N RIVER IN
     32.72     78.45
     33.52     78.12
     34.45     77.05
     35.10     75.35
     36.63     73.32
  81.
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  23.
  23.
0400
27
SEP
1958
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Figure 11.--Data deck inserted for an operational run after SPLASH II

APPENDIX II. INITIALIZATION PROCEDURES AND TRANSIENT PHENOMENA

Tropical storms have a life cycle of days to weeks; during this time, the storm can traverse an entire ocean. It is unreasonable, uneconomical, and (more to the point) unnecessary to compute for such time and space. The coastal storm surge is significant only while the storm is on the Continental Shelf; therefore, we restrict computations to this space and time span. But even this restriction is not always practical; for example, a stationary or very slow moving storm with an extraordinarily long time span on the shelf cannot be followed in the model for the full time span before interference arises from the artificial boundaries. In such special cases, we must improvise to fit natural conditions and compromise to fit our computational capabilities.

Ideally, in our model the storm track should begin far inland or on deep water away from the shelf; it should terminate on deep water or far inland. An excellent example is a storm striking the coast from sea to land (or land to sea), traveling normal to the coast, and moving rapidly. The significant portion of track is that segment traversing the Continental Shelf and small additional increments on both ends of this segment; there are no serious problems in surge generation with this truncated track (i.e., larger segments of track do not alter the significant surge computed with our model).

A storm track near normal to the coast traverses ocean depth contours that <u>change with time relative to the storm</u>; an alongshore-moving storm, however, traverses depth contours[23] that are <u>invariant</u> with time. Such different shelf traverses should alert the surge forecaster to expect significant differences in surge generation; in fact, for stationary, slow moving, recurving, or alongshore-moving storms, we will be faced with peculiar transient effects that are difficult to resolve. By "transients," we mean specialized or periodic surge phenomena superimposed on a general or equilibrium surge. There are several forms of transients depending on storm initialization, vector storm motion, storm size, and basin characteristics--say, the slope of the ocean bottom.

In this section, we concentrate on <u>specialized</u> transients. We do not wish to introduce complications due to varying storm parameters or ocean bathymetry. Consequently, for illustrative purposes in this section, the bathymetry of the basin will be one dimensional; and the strength, size, and motion of the storm will be invariant with time.

We want to convey some important dynamic differences in surges generated by an alongshore-moving storm, a stationary storm, and one traversing the shelf normal to the coast. It is important for the surge forecaster to have a clear understanding of these differences to judge how to use computed results.

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[23] We assume a nearly one-dimensional ocean depth profile off the coast; for two-dimensional depth profiles, the depth variation alongshore (compared to normal to shore) is generally small.

An invariant storm in a one-dimensional basin, stationary or moving alongshore, eventually will form an equilibrium surge under the storm.[24] Everything becomes steady state after a sufficient time transpires. We point out, however, that the term "sufficient time" is very loose; prior to it, we may have serious complications in surge generation. The surge does not jump at once to steady state but may, for example, overshoot or undershoot.

To reach a steady state takes time--sometimes a lot of time. During the developing stage, many forms of transients can occur. Several examples that follow will serve to bring out some of these forms;[25] our explanations for them will be crude, for they are tentative and hypothetical. The transients do have some similarities to special pendulum motions; but overall, they are considerably more complicated.

In the SPLASH II model, some of the transients are realistic, others fictitious. Those arising with rapidly moving storms are more realistic than others (e.g., those caused initially by a stationary storm in the middle of a basin). The fictitious transients are the price paid for programming and economic convenience. Although we point out the role of transients in the following topics for guidance, this is not exhaustive, and the user is not relieved of the responsibility of judging the output of the surge model for operational use.

A. Alongshore-Moving Storms

These can generate a rich variety of transients, simply periodic and otherwise. We want to illustrate some without complications from a varying storm or its track with time, curving coastlines, shelf bathymetry varying in two dimensions, and reflections from false boundaries. To do this--at least partially--we shall consider one-dimensional bathymetry, a straight-line coast, and a storm that has invariant parameters and parallels the coast at a constant speed. At times, we will ignore the coriolis force and bottom stress to bring out certain transients in their full effectiveness.

Resonance

On the sea, there are many possible wave patterns that, for example, form, move, spread, and dissipate; thus at any coastal point, the sea level can oscillate with time. There is an interesting periodic phenomenon in storm surge generation; we want to see how this very special case of resonant waves[26] will appear as a function of time at coastal points. For

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[24] The track of the storm lies on a constant depth contour.

[25] In these examples, the SPLASH model will be used for computations; the only exceptions are special long runs in real time and exceptions for particular cases where we want to ignore coriolis and bottom stress.

[26] In storm surge resonance, there is a finite-length wave train on the sea with fronts perpendicular to the coast. The length of the wave train grows with time because energy from the storm passes across the sea in an orderly manner.

simple conceptual presentation, we shall take many liberties and make no pretext for rigor.

The deciding factor for storm surge resonance is harmony between (1) storm speed parallel to the coast, (2) storm size, and (3) basin slope. A sloped basin can form a hierarchy of waves on the sea with passage of a storm. We want to explore conditions that will excite a resonant wave. There will be at least one wave in the hierarchy--*with phase or travel speed equal to storm speed*--that has potential for resonance; however, only if the storm size is proper can this wave be excited.

Note that the basin is not limited to only one resonant wave. The speed of the storm determines the wave for a given basin, and higher speeds mean longer waves; this situation is called dispersion (a relation between wave celerity and length). There is also the added complication of higher modes, which is characteristic of waves in a dispersive medium; for our purposes, only the fundamental mode need be considered. Evidence--empirical and observational--appears to bear out that the fundamental mode can be excited in storm surges.

We also want to display resonant properties in a direct way for easy reference; we will not do this for the entire sea surface, but we shall do so for the coast. Figure 12 is an example. In this figure, the origin for the coast is set on the bottom. C_p is a phase speed for the traveling resonant waves; it is also shown as a speed line for the storm, that is, the position of the storm abeam to the coast with time (note that constant speed means a straight line on the time-space diagram). C_g is a theoretical value for group velocity of the resonant waves. Resonant wave activity is restricted between the two lines. The middle panel illustrates the storm on the sea. The upper panel gives time-history surges at point A on the coast.

Now, consider a storm traveling at a given *speed* parallel to a straight-line coast; let the basin have one-dimensional depths representative of Atlantic City off the New Jersey coast. Choose a *small* storm to generate resonance (the strength of the storm and the distance from the coast are not relevant to our purposes at this time). Also, for this particular case, ignore coriolis and bottom stress in computations; this is done purposely to prevent damping the wave and altering its period. We now can compare numerical resonant wave period and wavelengths with an analytic solution.

The space-time diagram of figure 12 displays heights of surge at each point on the coast and at each time after initialization. The contours give the surge height in feet. In addition, the position of the storm abeam to the coast is plotted with time. For example, the entire line AB refers to the point on the coast 350 mi from the end. At 9 hr, the hurricane center (marked with 🌀) passes abeam to point A on the coast; and at that time, the height of the peak surge was slightly more than 8 ft.

Consider the upper panel of figure 12 as portraying sea-level time history before, during, and after storm passage for point A on the coast. We discriminate the first wave that passes

A from all others. It is a forced wave that follows the storm, and we call it the directly generated surge associated with the storm center; it always exists whether there is resonance or not.[27] Any following waves are free waves, and we call them resurgences (whether resonant or not). The resurgences of figure 12 are resonant waves; they travel parallel to the coast at storm speed and cannot overtake the directly generated surge.

Note: there are various analytic solutions for this type of phenomena--Munk et al.(1956), Greenspan (1956), and Reid (1958); the solutions are for a constant slope basin with zero coastal depths, and all ignore bottom stress. It is possible to expand on these solutions with geometrical optics techniques that consider general, monotonically decreasing, one-dimensional depth basins with finite sea depths on the coast (Jelesnianski 1970). With this technique, the computed wavelength and period for the resurgences in figure 12 agree quite well with analytically derived values.

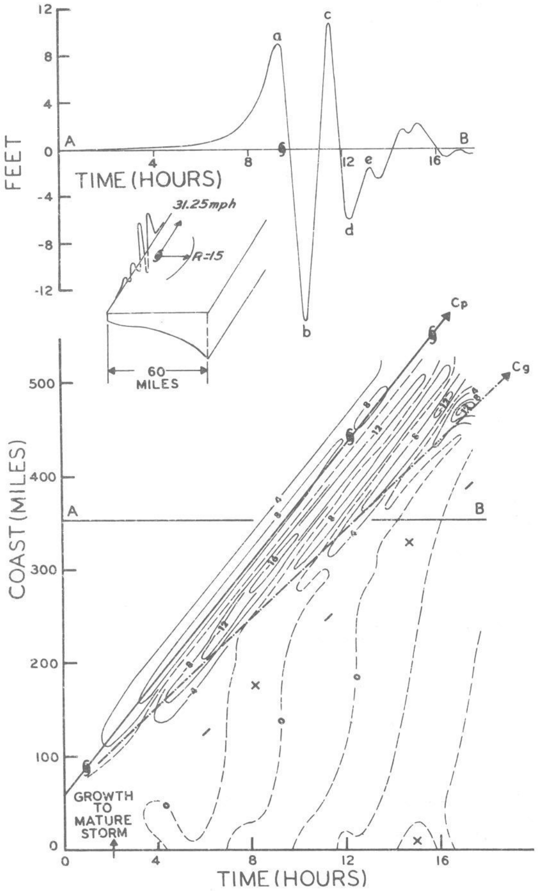

Figure 12.--Computed time-history surges for resonant waves on the open coast; coriolis and bottom stress are not included.

The duration of resonant activity, however, at any coastal point depends on storm duration on the shelf. The storm must spend time on the shelf--sometimes a lot of time--before resonance develops. Without bottom stress, the resurgences are of the same amplitude. In figure 12, only one resurgent wave affected coastal point A, but more resurgences do form above A where the storm spends more time on the shelf.[28]

After sufficient time passes, we call the directly generated surge a steady-state phenomenon. Now, the resonant resurgences can be transients or a part of steady state, depending on one's viewpoint. The extent of coastline affected by the train of resurgences grows with time, and this can be viewed as formation of transients; but when the train is fairly well developed

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[27] If the storm's speed and size and the basin slope are perfectly designed for resonance, then the directly generated surge is also a resonant wave.

[28] Computations are terminated when the storm strikes a false boundary in our model basin. The boundary forms spurious waves, and our computations are no longer appropriate.

and when bottom stress is absent, we are faced with resonant phenomena that do not dissipate with time. This gives the same type of surge action on any point of the coast passed by the storm, which can be viewed as a steady-state situation.

In figure 12, a time-history display of computed surges for the entire coast is contoured. Note that a sloping line on the space-time chart means invariant speed; C_p represents storm speed along the coast. Resonant waves, however, must travel along the coast with storm speed (i.e., phase speed C_p); this means that the surge contours must parallel the C_p line. This is an important property of resonant waves, and it is easy to spot on time-history plots. Now, the storm traveling parallel to the coast continuously will pour energy into the sea. This energy moves parallel to the coast at a particular speed C_g that, in wave mechanics, is called "group velocity;" we must bring in this term because we are dealing with a dispersive medium, the sea on a sloping basin.[29] But, the dispersive relation given by the resonance condition leads to C_g always smaller than C_p, at least when depths increase monotonically with distance from land. The important point we wish to bring out is that if resonance occurs, then the wave activity along the coast lies almost wholly between the region separated by the two speed lines; both lines coincide at storm initialization.[30] In figure 12, C_g is an analytically derived value (Jelesnianski 1970); it deliniates the computed resonant wave activity along the coast quite well. If the storm dissipates and if energy is no longer fed into the sea, then the finite resonant wave train spreads and diffuses across the sea even in the absence of friction. Note that the sea can dispose of energy concentrated in a relatively small volume by diffusing it into larger volumes.

Also note that this deliniation occurs only because we have ignored coriolis and bottom stress in the equations of motion. Since there is good agreement between the analytic and computed values for period, wavelength, and group velocity, we then have an independent test for our surge model with this special case. Note: this does not prove that our model is valid for all cases and conditions.

In real life, however, we should not ignore the coriolis and bottom stress:

1. Coriolis affects the period of resonant waves (Reid 1958).

2. Coriolis also affects the time position of the initial resurgence with respect to the directly generated surge.

3. Coriolis gives slightly different resonant periods for the same storm traveling up or down the coast (Reid 1958).

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[29] On the sea, it is possible to transmit energy from one volume to another at group velocity.

[30] We have been very careful to start the storm inside the basin--that is, the storm does not pass through a false boundary during initialization procedures. Also, the storm is allowed to grow quickly to maturity.

Bottom stress, however, does not greatly affect the amplitude of the directly generated surge, but it significantly will dampen resurgences; also, the periods are slightly altered.

Along the eastern seaboard, alongshore-moving storms usually are large. This means that the storm speed must be large to excite resonance; for such storms, the wavelengths and periods are larger than those shown in figure 12. It is questionable if large storms can attain sufficient speed to easily excite resonance along the eastern seaboard.

For operational convenience, the SPLASH model initializes storms 12 hr before reaching the center of the basin's coastline. At times, the storm will be initialized off the basin and passed through a false boundary in shallow water. This sets off spurious waves[31] at the boundary; but in almost all cases, it will not affect the computed surges along the center of the basin's coastline.

Figure 13 is an example of resonance computed by the SPLASH model where coriolis and bottom stress are retained. An invariant, intense, large storm travels rapidly up the coast of a standard one-dimensional basin (see the upper left insert). The storm crosses a false boundary at the bottom of the basin and sets off spurious waves; the waves spread but do not travel, and they have little effect at the center of the basin's coastline (i.e., if the basin length is enlarged, we still compute the same surges at the center of the basin). Notice how the coastal surge contours parallel the storm's speed line (excepting spurious waves); this is an excellent indication that resonance phenomena may be present. We do not draw a simple C_g line here, as in figure 12, because:

1. The storm was not initialized inside the basin.

2. The resurgences are dampened significantly by bottom stress.

3. The periods of the resurgences are altered by coriolis and bottom stress.

4. The computations were terminated before resurgences became fully developed.

The upper right panel gives a time-history surge for the center of the basin's coastline. Only one resurgence formed, and its amplitude--dampened by bottom stress--is small compared to the directly generated surge.[32] The lower left panel gives the envelope of peak surges along the coast, regardless of time occurrence for the peaks. Because the directly generated surge reaches equilibrium rather quickly, the envelope is a nearly straight line. The

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[31] Clearly, we need a radiation-type boundary condition that is transparent for a group of traveling waves in a sloping depth basin. This would be an interesting future research project.

[32] Recall that the amplitude value, relative to storm size, is a function of the storm's distance from the coast.

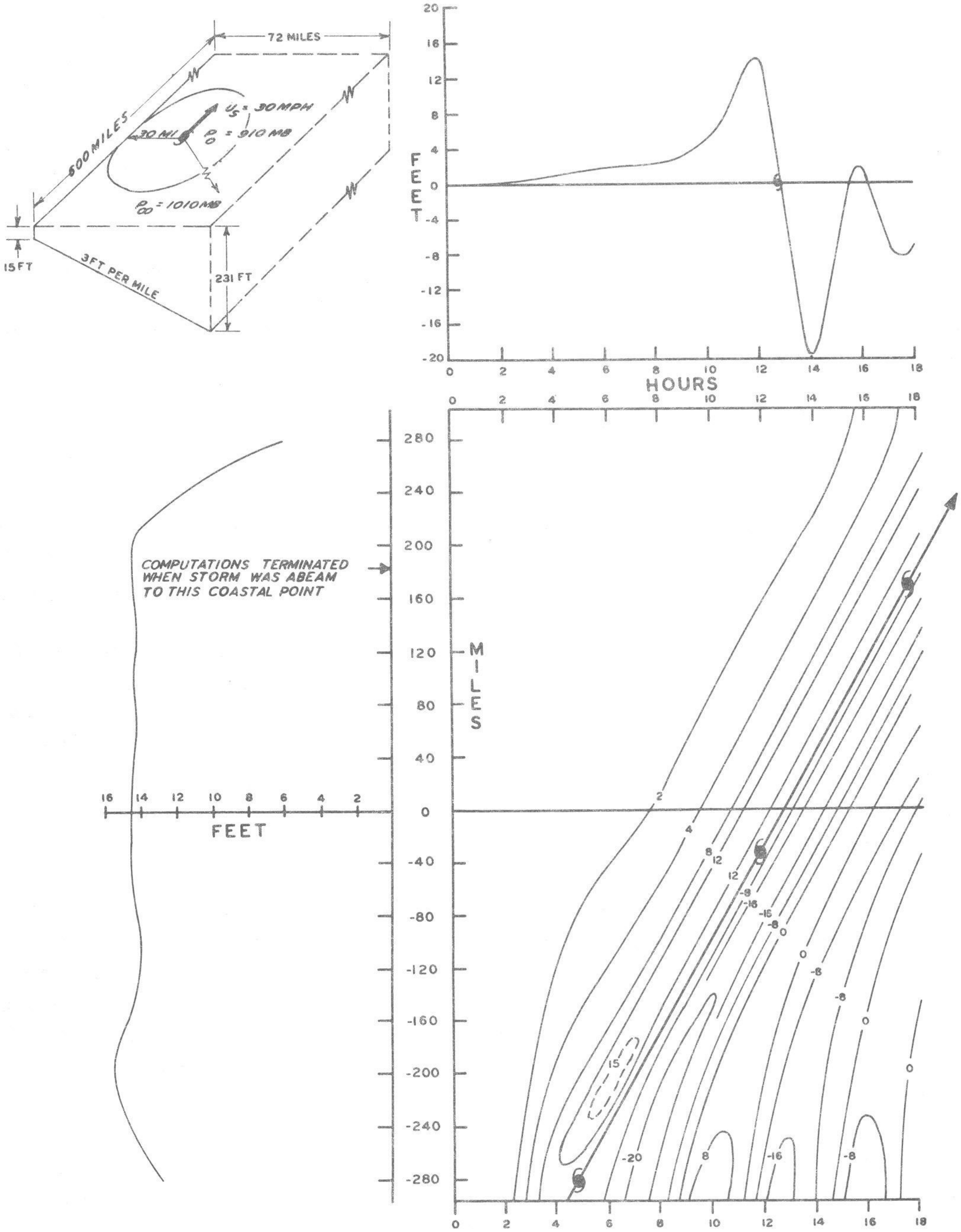

Figure 13.--Same as figure 12 except this is for a larger storm passing through the bottom of a standard basin and this includes coriolis and bottom stress. The group velocity of resonant waves is not shown, and the origin is set at the center of the coast. The upper panel gives time-history surges at the origin of the coast; and the left panel gives the envelope of high waters on the open coast.

straight-line envelope is formed by the directly generated surge; it also can occur for storm motions that do not generate resonance. Notice the effect of spurious waves and the termination of computations when the storm is about -200 mi and +185 mi, respectively, from the basin's center.

Transient Wave Packets Generated by an Alongshore-Moving Storm

A different phenomenon is that of initial or temporary transients which superimpose on, follow, or pass the directly generated surge. For simple conceptual presentation of this most complicated phenomenon, many liberties will be taken in the following discussion, and we make no pretext for rigor.

Suppose a storm travels alongshore--with storm speed, basin slope, and storm size not in harmony to generate resonance. What happens? Eventually, a steady-state directly generated surge follows the storm. Energy does not pass in an orderly manner across the sea; and it is disposed of by complicated processes such as work against the driving forces, friction, and diffusion across large volumes of the sea. Now, if such a storm enters the shelf from deep water or from land to sea, suddenly stagnates, or explosively intensifies on the shelf, then it will concentrate energy in a small volume of the sea while building up the directly generated surge; the initial concentration of energy occurs while the sea is adjusting itself to the suddenly imposed or varying driving forces. Wave mechanics treats concentrated energy in a small volume of sea by a discipline called "wave packets" (i.e., the concentrated energy in a small volume of the sea is composed of waves, of many different but nearly equal frequencies, that spread out with time across a large volume). Note that, for a sloping basin, the sea is a dispersive medium and energy can be disposed of even in the absence of friction and without doing work against driving forces.

Two principal speeds are connected with a wave packet (fig. 14), the phase speed C_p and the group speed C_g. In figure 14, the wave fronts are perpendicular to the coast, with amplitudes decreasing seaward. The envelope of the packet on the coast is a Gaussian-type curve, and the amplitude of the packet decreases seaward. The waves inside the packet move with phase speed C_p (not the speed of the storm), the envelope moves with group velocity C_g (i.e., the center of gravity of the packet), and $C_p > C_g$. The waves appear at one end, move through the packet, and disappear out the other end.

Phase speed refers in general to the speed of motion of the crests and troughs of waves, and group speed refers to the speed of motion of the packet as a whole. If C_p differs from C_g, the crests and troughs disappear as they pass through the front or rear of the packet. Both phase speed and group speed are defined in terms of wavelengths through a dispersion relation that relates frequency to wavelengths; the dispersion is defined by the type of wave motion and the geometry of the basin. For a given basin, C_p and C_g depend on a wavelength that is nearly proportional to the size of the storm (radius of maximum winds). The speed of the storm, however, may be greater than, equal to, or less than either C_p or C_g; various combinations of phase, group, and storm speeds can create surge patterns along the coast that are interestingly different.

For a conceptually simple wave packet on the shelf, with no energy entering it, there is a group of waves inside a surface envelope with crests normal to the shore (fig. 14). The amplitude of the waves decrease rapidly seaward. There is a sudden appearance of waves entering one end of the packet; while traveling at phase velocity C_p along the coast, they grow in amplitude to a maximum, then decrease, and finally disappear on exiting the other end. Meanwhile, the center of gravity of the packet is moving at a group velocity C_g, which is smaller than the phase velocity C_p. While all this is going on, the envelope of the wave packet is spreading and flattening out with time.

Note that we have used phase and group speeds to describe an idealized wave packet; this should not be confused with speed of the steady-state surge phenomena generated by a storm. The directly generated surge, which moves with storm speed, is separate and unrelated to the wave packet. Also note that, in resonance phenomena, the waves move with the phase speed equal to the storm speed, hence the two speeds are intimately related; in the idealized wave packet, the phase speed of waves has no relation to storm speed and, therefore, must be viewed separately.

The complicated space/time structure of the wave packet can superimpose on the directly generated surge; if the group velocity of the packet is greater than storm speed (the speed of the directly generated surge), then we have a most complicated surge on the coast. Figures 15 and 16 pictorially show these effects. To produce these effects, we have taken the basin of figure 12, enlarged the storm size (to inhibit resonance), and moved the track farther away from the coast; also, coriolis and bottom stress are ignored.

In figure 15, the effect of the wave packet on the directly generated surge is small; this is so because we have designed conditions whereby storm speed is roughly the speed of the center of gravity of the packet (i.e., the group velocity C_g). There are some minor spurious waves generated at the bottom boundary; their effects on coastal points farther up the basin are small. The collection of surge contours paralleling the storm's speed line is mainly the directly generated surge associated with and following the storm center; there may be some resonant effects near the end of the computations. The remaining bow-shaped contours are effects of the wave packet. Initially, the packet is obscured by the

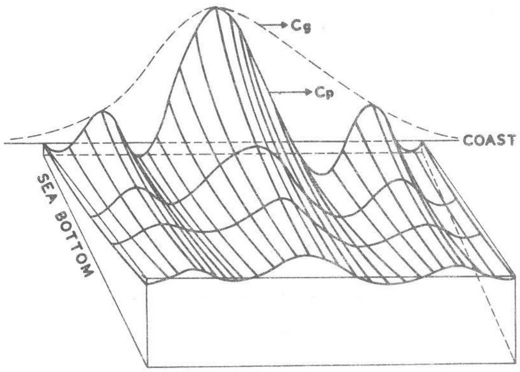

Figure 14.--Hypothetical wave packet on the Continental Shelf

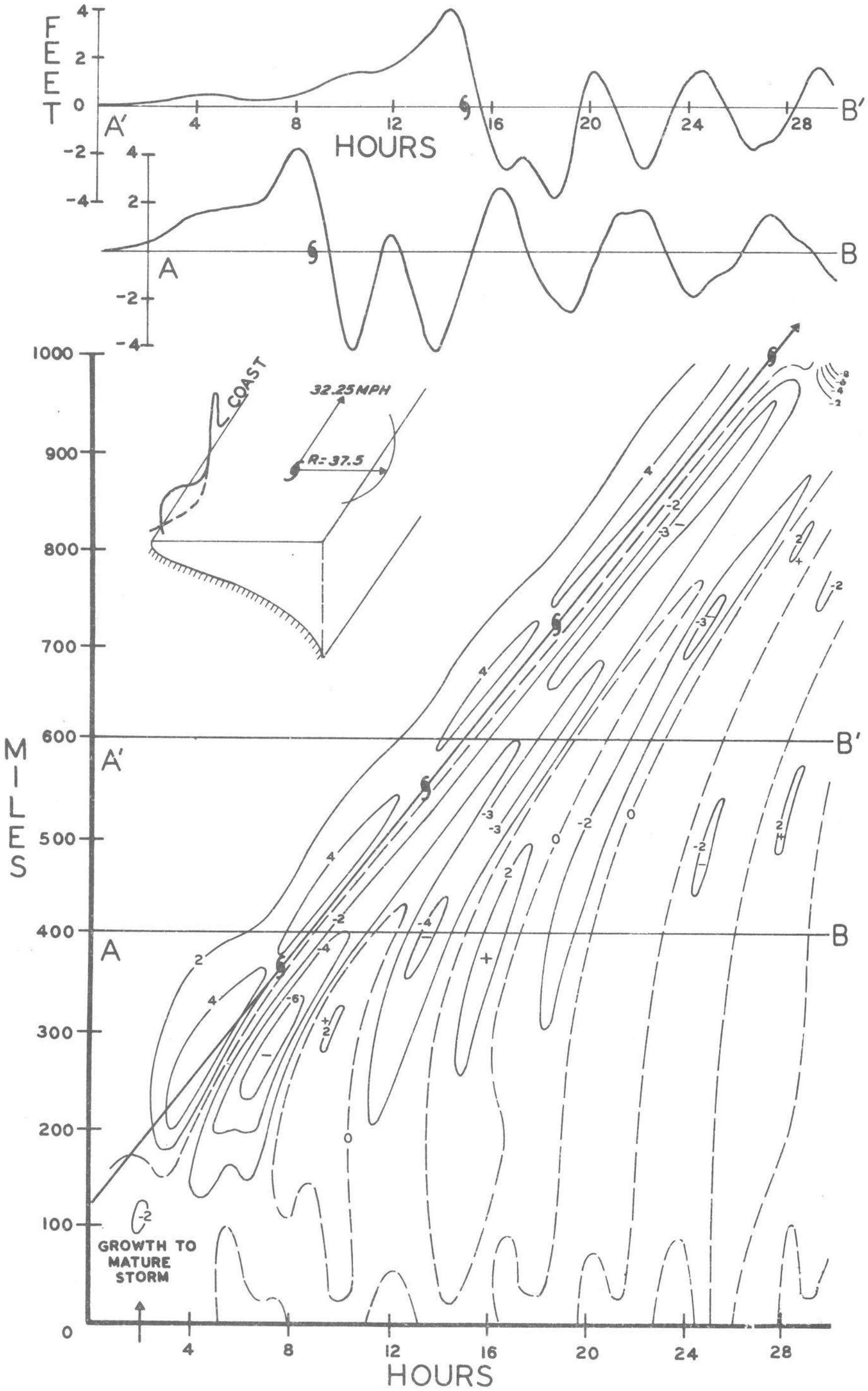

Figure 15.--Same as figure 12 except this is for a much larger storm generating a nonresonant situation. A transient wave packet lies behind the storm. The packet cannot overtake the storm because its group velocity is approximately the speed of the storm.

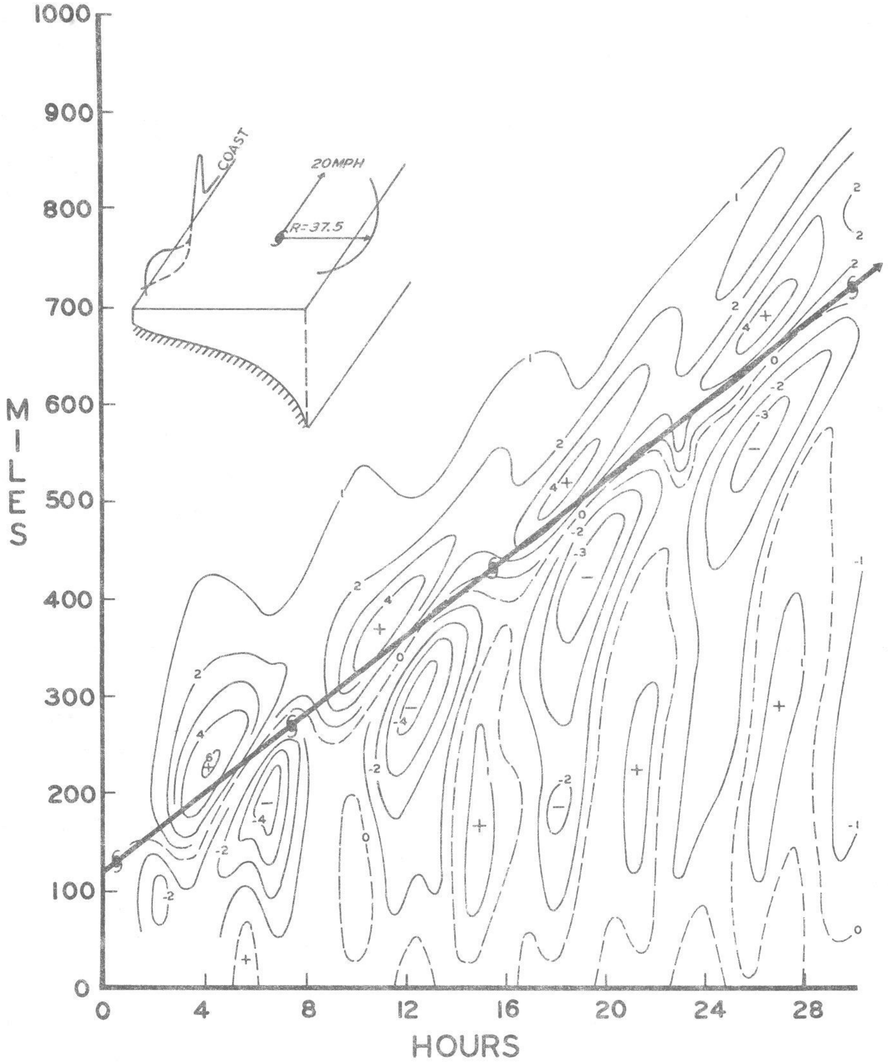

Figure 16.--Same as figure 15 except this is for a storm moving slower than the packet's group velocity. The packet overtakes the storm.

directly generated surge; as the storm moves up the coast, the packet lags behind, spreads, and flattens with time. On the coast, waves exiting the packet superimpose on the directly generated surge (the directly generated surge pulsates as waves pass through). On the upper panel of the figure, we plot time-history surges for points A and A' on the coast. The resurgences, in general, are not resonant waves; instead, they are waves inside the packet. Notice how they decrease in amplitude with time, which is to be expected since the packet flattens and elongates with time.

Suppose the storm speed is reduced so that it is smaller than the speed of the wave packet. What happens? Figure 16 illustrates this situation with time-history surge contours for the entire coast. None of the contours parallel the storm's speed line (i.e., the directly generated surge is obscured). The packet passes through the directly generated surge; but the phase speed of waves within the packet is greater than the packet speed and hence greater than the storm speed. This gives a significant pulsating effect on the surge directly under and following the storm. Note that if figure 16 is set on top of figure 15 and the directly generated surge is subtracted out, then the crests and troughs of the wave packet for both figures are in phase.

The significant time-history surge at any coastal point, with a moving wave packet, is most complicated. If the driving forces are invariant after initialization, then for ideal steady state there remains only a forced wave (the directly generated surge) moving up the coast with storm speed (i.e., coastal points experience the passage of only one wave).[33] The resurgences are not invariant on the sea; in their transition state, they can pass, follow, remain on top of, or lag the directly generated surge. The duration of resurgences at a coastal point depends on the character and age of the wave packet, and--unlike resonance--does not depend solely on the time spent by the storm on the shelf before passing a coastal point.

In real life, we should not ignore coriolis and bottom stress. Coriolis affects the period of the waves and their initial and relative spacing on the coast with time. Bottom stress does not greatly affect the amplitude of the directly generated surge, but it can have a significant damping effect on resurgences; also, the periods of the resurgences are slightly altered. In operational SPLASH runs, we use a smaller basin length than that in figures 15 and 16, and we limit our computations to 18 hr of real time. This means that if resurgences exist, then (usually) at least one will pass the basin center before computations are terminated. Illustrations of the SPLASH output for actual, nonresonant cases are shown in previous and subsequent topics.

B. Stationary-Invariant Storm on the Shelf

Conceivably, storms can enter a shelf area and then stagnate or meander slowly about the coast. How do we handle this situation? A simple way--not necessarily the best--is to assume a stationary-invariant storm[34] and compute the steady-state directly generated surge; this might, however, require computations for an extraordinary length of time before the surge becomes fully developed. Such a procedure is undesirable for several technical reasons; instead, we consider surge generation with time and attendant transients.

In our surge model, we assume an initial quiescent sea.[35] If we impose surface driving forces from a stationary storm located on the shelf, then with time the coastal surge ap-

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[33] We are assuming that the sea has accommodated itself to the storm-driving forces and no energy travels to surrounding volumes of the sea; this, however, is rarely (if ever) true.

[34] The track of a stationary storm telescopes into a point; or else, a point on the track has a finite time duration during storm passage.

[35] We could assume other initial states, but we would still be faced with transients.

proaches an equilibrium state; however, the sea temporarily reacts with transients while adjusting and accommodating itself to the imposed driving forces. These transients are most pronounced along the coast--the shallower the shelf slope, the more noticeable they become. The transients occur because, until the sea heights and currents adjust from their quiescent state to one that balances the driving forces, the unbalanced driving forces introduce an excess of momentum into the sea.

If we suddenly impose a stationary mature storm in shallow water, then the transients can be extremely large. However, we can control them by beginning with a zero strength storm that grows to maturity; a large growth time would not generate transients, for the sea has time to adjust to the driving forces. In the real world, transients do exist with very slow moving storms; hence, it is not wise to totally ignore them.

As an illustration, consider time-history surge contours on the open coast, computed by SPLASH, for a stationary storm located distance R seaward from the coastal center (fig. 17). The storm grew to maturity in 4 hr and was invariant thereafter. Notice the seiche-type oscillations (standing waves) on the coast and also the spreading of surges away from the coastal center with time.

The term "seiche" is used in a descriptive rather than a classical sense; we do not mean simply to imply that there is a linear node line in the basin. The period of the oscillations vary with storm size, basin slope, and distance of the storm center from the coast; the time occurrence of the first peak depends, in part, on the growth time of the storm. These special oscillations--and their formative period--have not been studied empirically or otherwise; this is an interesting future research project.

In figure 17, the insert on the upper right gives a time-history curve[36] of computed surges on coastal point A where peak surge occurs; notice how the oscillations dampen with time as the sea tends to an equilibrium state. Below AB, there is a similar situation for the negative surge; notice how the absolute depth value of the troughs gets larger with time and how it contrasts with the peaks on AB.

The driving forces of a stationary storm can be viewed as waves of all lengths, some with predominant amplitude, and directed in all directions. They will tend to excite water waves of corresponding directed wavelengths. However, water waves with crests perpendicular to the shore are not readily excited because the stationary forces are not moving with the phase speed of these waves (note that the amount of excitation for transient waves can be influenced by the growth time to maturity of the storm; a shorter growth time would produce more energetic waves). This leaves water waves (for the steady-state limit) and secondary or transient waves that are directed with crests and troughs at and near parallel to the shore. Note especially that ocean depth contours of the Continental Shelf are nearly parallel to the

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[36] A tide gage placed at point A would give this time-history curve.

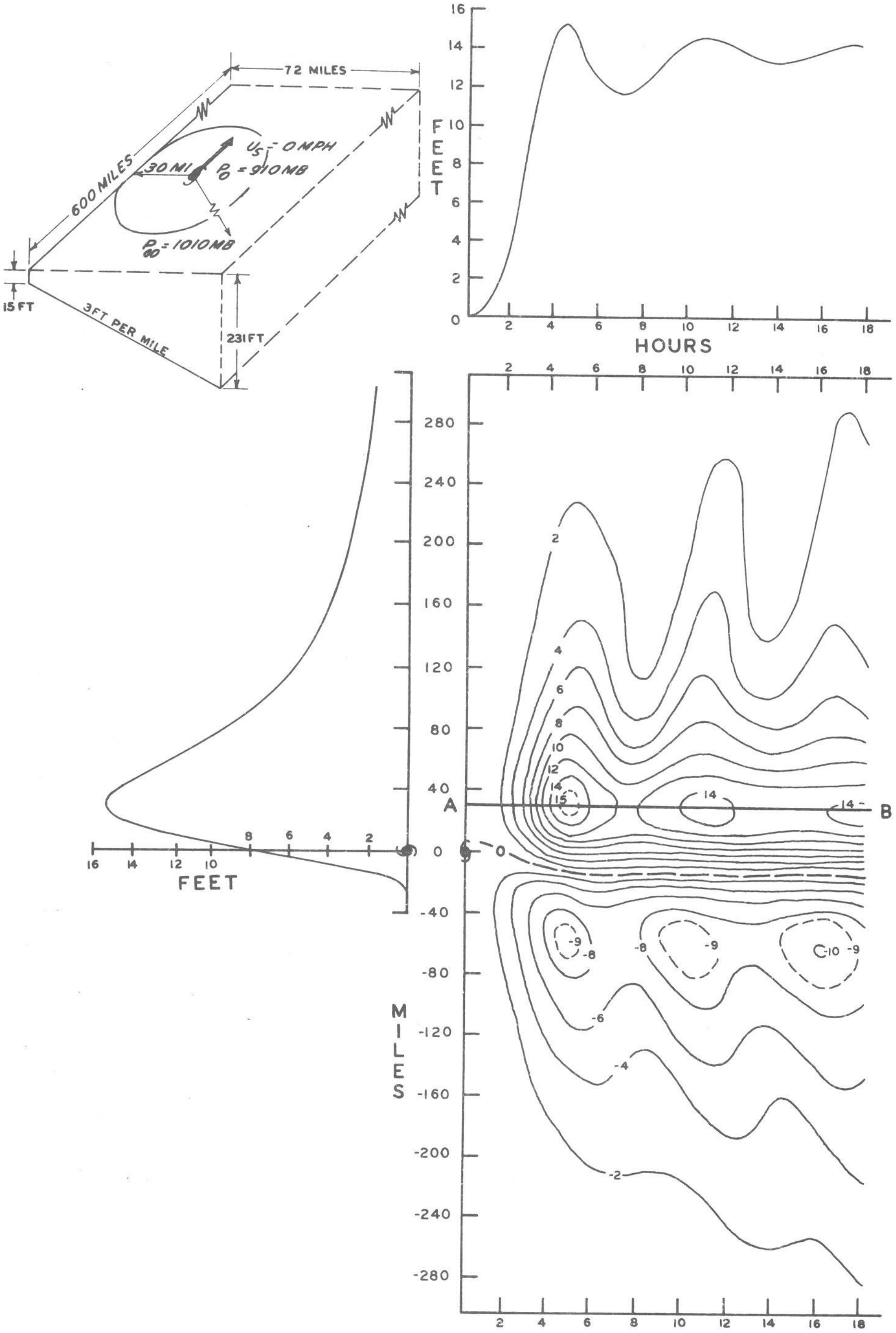

Figure 17.--Same as figure 13 except this is for a stationary storm (a nonresonant situation). The upper panel gives time-history surges for a point on the coast.

shore but vary perpendicular to the shore; this means that the action of waves with crests parallel to the shore is entirely different than that perpendicular to the shore.

The waves with crests nearly parallel to the shore form a packet consisting of generally low wave numbers (long waves) in the alongshore direction (crests perpendicular to the shore). A group velocity, however, cannot be assigned to the packet as a whole, for the dispersion relation is neither smooth or single valued for the wavelengths and frequencies in the packet. As a result, the packet tends to spread out rather than move as a whole, with the longer waves spreading out more rapidly. These longer waves also have longer periods; as a result, we obtain a pattern in which the water along the shore moves up and down almost in unison, with the portions farthest from the shore oscillating with slightly longer periods as in figure 10. Note; the double train of highs and lows are the result of superposing transients on the steady-state surge.

The amplitudes of the oscillations in figure 12--not the periods--vary inversely with storm growth time; but growth time is an idealized concept, difficult to relate with the real world. For a wide range of growth time, however, the height of the second peak along line AB is almost invariant (although its time position varies); hence, for a working criterion, we say that this second peak is representative for a stationary storm.

The insert on the lower left gives the envelope of highest surges on the open coast, regardless of time. The peak surge on this curve is the first peak on line AB; its value is strongly influenced by storm growth time and thus is inadequate for our purposes. For stationary storms, we should ignore the envelope and use the second peak surge on the open coast for our surge forecast.

In figure 17, the storm was placed at distance R from the coast. What if the distance changes? Well, we do have complications; if the storm is at a distance that is large compared to R or if it is off the Continental Shelf in deep water, then the highest surge is not necessarily the first peak on line AB. What we must remember is that it takes time for surges to reach the shore, sometimes a lot of time. However, for a wide range of growth time, the height of the second peak is almost constant (although its time of occurrence varies); this is so even if the second peak is the largest of all peaks. We suggest that the second peak on line AB be used for forecasting.

C. Storms Traveling Normal to the Coast

An invariant storm traveling normal to the coast of a sloping basin[37] does not form an equilibrium surge on the shelf. The storm, moving from sea to land or land to sea, tra-

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[37] The track of the storm parallels the maximum gradient of ocean depth contours; the depth is not constant under the track as that with alongshore-moving storms.

verses ocean depth contours that change with time relative to the storm.[38] The surge under the storm is continuously forming; if the storm travels rapidly, there are no transient oscillations. The peak surge on the coast is insensitive to initial placement of the storm--providing such placement is in deep water or far inland. This is a most excellent property, for only a segment of the total track is sufficient for computing the coastal storm surge.

The storm is mature before entering the shelf, and shelf waters as yet are little affected by the storm's driving forces. However, when the storm enters the shallow shelf, a new situation presents itself. The sea on the shelf continuously battles and tries to adjust itself to the moving storm, but there is no way it can accommodate both the storm and changing depth patterns along the storm's track;[39] it cannot form a steady-state directly generated surge. A dominating factor for storms traveling normal to the coast is the continuously changing depth patterns of the basin relative to the moving storm. In a gross way, one can view this case as a pure transient surge that completely dominates surge generation. It is difficult for the sea to form resonance or a distinct wave packet with a landfall storm. Resurgences have wave fronts that are perpendicular to the coast; but it takes an alongshore storm track to generate them, whereas a track normal to the coast is 90° out of phase. There is only a forced wave (directly generated surge) that follows the storm, and it continuously changes its form while the storm moves across variable ocean depths.

A landfall storm forms a circulating mound of water under the storm that eventually impinges on the coast. After landfall, the driving forces on the sea gradually disappear, and the sea no longer battles the storm; the forced wave is now free; it is partially reflected at the coast, transfers its energy to neighboring volumes, and eventually disappears. For an exiting storm (storm track from land to sea), a similar situation takes place; however, there is only a limited time to form a circulating mound of water in the vicinity of the coast and hence a lower potential to develop significant surges at the coast. Landfall (exiting) storms are discussed in SPLASH I.

D. General Comments on Transients

By no means have we exhaustively discussed transients in the preceding sections. There are many other wave forms that can be excited by storm-driving forces on continental shelves. Our purpose was to acquaint the surge forecaster with particularly simple transient surge phenomena and how they affect coastal storm surges; in real life situations, transients will not always be so simple.

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[38] A constant depth basin, unbounded in the horizontal, allows an equilibrium surge to form regardless of the storm's vector motion; this is why sloping depths and a coastline on the Continental Shelf are so important.

[39] One can postulate that a storm, which harmoniously or properly varies in speed and size as it traverses the shelf, could set up a special kind of resonance phenomena. This would be an interesting future research project.

For more than one type of transient to occur simultaneously is possible. Moreover, there are secondary transients--which we have not discussed--due to changes in basin depths alongshore (i.e., two-dimensional bathymetry). Similarly, secondary transients can be excited if the storm's path, its size, or strength varies dramatically with time on the Continental Shelf. Also, there are localized transients of small wavelength, which do not show up with SPLASH computations.[40]

Up to now, we tacitly have assumed that transients are free systems that do not accept energy from the storm. This of course is not true, for energy continuously pours into the sea to form a hierarchy of waves with time. In fact, with passage of time, the original transients may no longer be evident, and new transients take their place. This is important, for it means that the local storm surge is insensitive to storm initialization, providing initialization is <u>distant in space and time</u> (i.e., we compute the same surge at a coastal point regardless of the exact initialization procedure). However, the term "distant in space and time" is very loose, and we cannot always satisfy it with the SPLASH surge model. This creates serious problems such as:

1. The present SPLASH model uses a straight line (base line) to represent the coast and a cartesian grid for computations; the natural coast, storm track, and driving forces are shifted nonconformally according to the base line. This means that transient phenomena may not be properly represented if the coast significantly curves in space.

2. A storm moving <u>rapidly</u> along the shore and on the shelf will cross a false lateral boundary in our model basin; this will set off spurious waves.[41] Also, the initial transients (generated by highly suspect initialization procedures) may be unrepresentative because they are generated so closely to the time of storm passage at the coastal point of interest. The remedy for this situation is a larger basin so that initialization occurs inside the basin, long before the storm passes a coastal point of interest; but this involves computer storage problems and the problem of curvilinear coastlines.

3. A storm moving <u>slowly</u> along the shore and with a long track on the shelf cannot satisfy the initialization criteria "distant in space and time" for the surge model. Our model initializes computations 12 hr before storm passage at the coastal point of interest; the track distance for this 12-hr period is small--sometimes smaller than the storm size. The slow storm motion causes initial transients, which are highly suspect, that immediately affect the coastal point of interest. The remedy for this type of situation is to compute for exceptionally long real-time runs; but this creates problems, for example, in numerical stability, economics, and curvilinear coasts.

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[40] Our grid size in numerical computations with the SPLASH model is 4 mi; hence, small wavelengths on the sea cannot be seen with our model.

[41] Not so if the storm is initialized in deep water (or on land) and if the track crosses a conceptual extension of the lateral boundary

Storm tracks are not linear and orient themselves in diverse ways relative to coastlines; also, storm speeds along the track are variable--similarly, for storm size and strength. This means that the possibilities for transients are numerous. For operational use, significant transients fortunately occur only with storm tracks near parallel to the coast and with stationary or exceptionally slow moving storms on the shelf.

The surge forecaster should be aware and suspicious of computed transients; he should not accept such computations blindly but rather should give due consideration to possible errors from initialization procedures. A particular example is a stationary or slow-moving storm; the first peak transient on the coast may be too large for useful forecasting. There are critical situations where one form of transient gives way to another. Similarly, the storm track angle-of-attack to the coastline greatly influences the generation of transients; thus, there are critical angles with which to contend. In general, if the storm is initialized in deep water or on land both distant from the coast and if we have confidence in the forecast or given track, then any transients computed by the model are representative for the open coast surge.

APPENDIX III. STORM TRACK CURVATURE AND TIMES OF HIGH WATERS ON THE SURGE ENVELOPE

Some important aspects of a storm track, from a meteorological point of view, are:

1. Recurvature away from the coast.
   a. Distance of the storm from the coast at the point of maximum curvature.

2. Recurvature toward the coast.
   a. Landfall (exit) point on the coast.

Generally, the exact form of the curve (track) is not considered important if these aspects are known. Such information, however, is unacceptable for storm surge computations; we need to know the disposition of the <u>total</u> track. The surge forecaster must understand that his choice of storm track--<u>relative to the coast</u>--has considerable influence on the generation of surges in space and time; he must not choose tracks[42] with a debonair spirit, but rather with a healthy respect for such aspects as how they generate surges on the coast, the surge arrival time with respect to astrononomical tide, the ever-present possibility of generating critical situations, and transients. Note that the storm surge is an oceanographic phenomenon, and blind reliance on standard or ordinary meteorological predictions of storm track can be dangerous.

A storm traveling near normal to the coast generates significant coastal high waters at/<u>about landfall time</u>; however, the ends of the coastal surge envelope can occur several hours

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[42] A typical example would be to connect a straight line between initial and final points of a forecast track interval, even though the track has significant curvature.

after landfall; but in most cases, the surges there are insignificant compared to the core of high waters. For practical purposes then, the high waters are appended to astronomical tide at landfall time for a coastal surge forecast, SPLASH I.

For alongshore/curvilinear storm tracks, we can no longer be so cavalier on time of high waters. This is so because the component of storm track on the coast, as well as high waters, can last for many hours. Consequently, to aid the surge forecaster (in the SPLASH II computations), we append the times of high waters on the computer display of the coastal surge envelope (to the nearest hour); he then can add the astronomical tide (plus the sea-level anomalies) for a total tide forecast at selected points along the coast. It would be good to be so direct, but our computations use only a segment of the total track (12 hr before and 6 hr after the nearest approach of the storm to the basin's center); *we do not want to print out the times with unaccountable track segments*. However, if an end or ends of the segment are in deep water or somewhat inland, then this is sufficient to represent the continuation to total track; we then extend the printout of times even though we cannot account for the total track. Our purpose for printing times of high waters along *selected* coastal intervals is to aid the surge forecaster to discriminate those surges that are generated by the segmented track and representative of the total track. To acquaint the surge forecaster with decision processes for printout of times of high waters on the coast, we illustrate several storm tracks in figure 18.

The panel on the left of figure 18 (alongshore-moving storm) has a *monotonic* track with respect to the ordinate but not necessarily so with respect to the abscissa; also, the storm remains inside the basin. Our computations here are approximately valid between MATR STM and

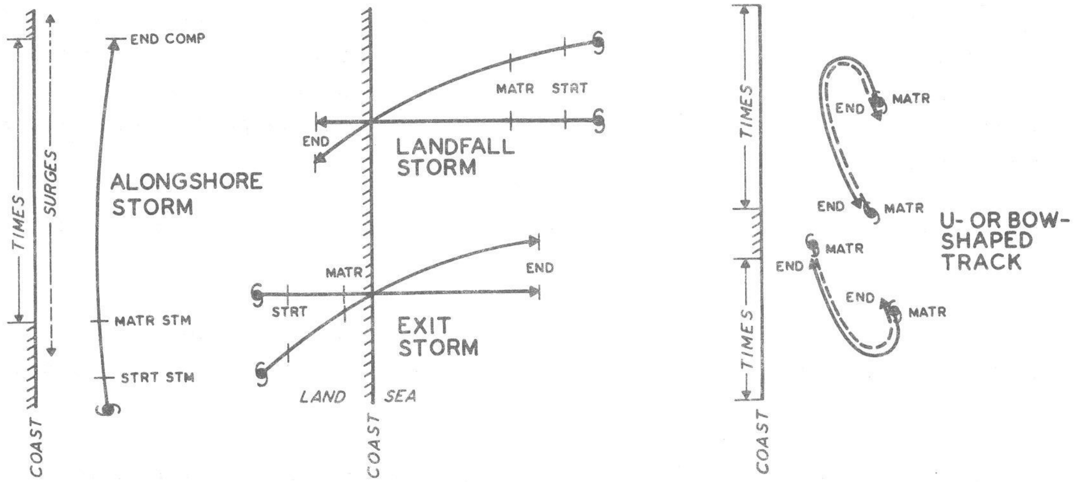

Figure 18.--Possible storm tracks relative to a coastline. Only a portion of the coast has representative surges for a given track segment. "Times" means occurrence of high waters along the coast, valid for a given track segment.

END COMP; hence, we print out times along the coastal component for this segment. For this special case, however, note:

1. The surge about MATR STM may be too high because of initialization phenomena.

2. The surges about END COMP are valid because the high waters lead the storm; note also that if the storm is moving down the coast, then the surges about END COMP may be too small because the high waters now lag the storm. The alongshore track, however, can have strong curvature, or the vector storm motion can be abnormal. In some of these special cases, the segment--or one end of the segment--may sufficiently represent the entire or remaining track. For a storm moving up the coast, we adopt the following procedures to print out times of high waters on the coastal surge envelope display:

1. If MATR STM is in deep water or one storm radius inland, then the printed times are extended downward to the end of the coast.

2. If END COMP is in deep water or one storm radius inland, then the printed times are extended upward to the end of the coast.

3. If the storm travels rapidly (MATR STM and END COMP are off the basin), then the times are printed along the entire coast.

4. If the storm travels slowly or is stationary--and remains inside the basin--during computations, then (at most) only a few times will be printed out;[43] this serves to warn that the coastal surge envelope can be polluted with transients. The surge forecaster now must subjectively consider the time-history plot of coastal surges. For a stationary storm, the arrivel time of the second peak on the coast with the attendant surge profile may give an acceptable surge forecast.

5. If a stationary storm is in deep water or more than one storm radius inland, then it will print out times along the entire coast.

Note also that if the storm travels down the coast (as opposed to traveling up the coast), then there is a mirror image printout of the five procedures for the times of high waters.

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[43] Warning; if you insist on using a very slowly moving storm (say, average speed <3 mi/hr), then take pains to assure that the center of your 24-hr track segment is close to the nearest approach of the storm to the basin center or station.

Suppose we now have a landfall/exit storm (middle panel of fig. 18). The storm can have any angle of attack to the coast; also, it can be curvilinear, but we consider--at this time--only a monotonic track with respect to the ordinate. For these special cases, we adopt the following procedures to print out times of high waters on the surge envelope displays:

1. If the storm track has MATR/END in deep water and END/MATR at least one storm radius inland, then times of high waters are printed out along the entire coast.

2. If the storm track has only one end of the track segment in deep water or one storm radius inland, then:

   a. The printout of times is between the track points MATR and END on the coast.

   b. One end of times is extended upward/downward for the remainder of the coast; the extension is that end of the track segment in deep water or one storm radius inland.

3. If procedures 1 and 2 do not apply, then times of high waters are printed out along that component of track between MATR and END on the coast; for this case, we subjectively must determine whether we have (want) to consider a stationary storm as in procedure 4 in the preceding paragraph.

It would be good if we could stop here and restrict all tracks to be monotonic with respect to the ordinate (i.e., the coast), but this at times is unacceptable for real life situations. A glance at climatological storm tracks (Cry 1965) shows several types of curves in space that are (1) quasi-linear shaped, (2) U- or bow-shaped, (3) S-shaped, (4) looped, or (5) cusped. So far, we have considered only type 1. We do not consider types 3 through 5 because it takes more than five points (fig. 1) to portray such tracks. We specifically want to consider type 2; for such tracks, it is assumed that there is a maximum/minimum stationary point on the track--but not both--with respect to the ordinate (i.e., the track is not a loop).[44] Because of computational restrictions (and subtle numerical/dynamic constraints), our model computes for only a segment of the total track. Consequently, we have to be very careful on how this segment is chosen. We suggest that the tracks have the gentlest possible curvature; the surge forecaster should straighten out the tracks with strong curvature--consistent with meteorological accuracy.

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[44] If you are determined to use a loop in the track, there will be a strange printout of times of high waters on the envelope display. If you feel there is a loop, try to consider instead a near--but not--stationary storm during the looping interval.

Suppose we now have a U- or bow-shaped track with one stationary point (right panel of fig. 18); note that there are four possibilities--a max (min) point, with the storm traveling toward (away) from the coast. The feature here is that the track is no longer monotonic with respect to the ordinate. We adopt the following procedures to print out times on the surge envelope:

1. If the storm track has MATR and END points in deep water or one storm radius inland, then times are printed on the entire coast.

2. If the storm track has a <u>maximum</u> (not minimum) point and there travels <u>toward</u> the coast and if END does not satisfy procedure 1, then times are printed from END upward to the end of the coast.

   a. We do not print times below END because we have not accounted for that portion of track in the computations.

   b. Although MATR on the storm track is inside the basin, we treat it as though it were in deep water or one storm radius inland.

3. If the storm track has a maximum point and there travels <u>away</u> from the coast and if MATR does not satisfy procedure 1, then times are printed from MATR upward to the end of the coast.

   a. We do not print out times below MATR because we have not accounted for that portion of track in the computations.

   b. We treat END as though it were in deep water or one storm radius inland.

4. If the storm track has a minimum (not maximum) point and there travels <u>toward</u> the coast and if END does not satisfy procedure 1, then times are printed from END downward to the end of the coast.

   a. We do not print out times above END because we have not accounted for that portion of track in the computations.

   b. We treat MATR as though it were in deep water or one radius inland.

5. If the storm track has a minimum point and there travels <u>away</u> from the coast and if MATR does not satisfy procedure 1, then times are printed from MATR downward to the end of the coast.

   a. We do not print times above MATR because we have not accounted for that portion of track in the computations.

   b. We treat END as though it were in deep water or one radius inland.

SPLASH II is designed to accept quasi-general segmented storm tracks--relative to the coastal center (station) of a chosen basin. If proper care is not exerted to center the track segment relative to station, then the program will not perform the computations and will terminate with messages to this effect. Examples of some unacceptably positioned segmented tracks[45] are shown on figure 19; these segments have one end at closest approach to station, but the program insists that closest approach be near the middle of the track segment. The remedy here, of course, is to properly choose a relevant track segment so that closest approach is near the center of the segment. Note that it is a very luring prospect to set the center of the segment at the point of maximum curvature because this point is important for meteorological forecasting; we must overcome this temptation and focus instead on that portion of track which is important to oceanographic aspects in surge generation.

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[45] The tracks are acceptable, but segments of the track--relative to station--are unacceptable.

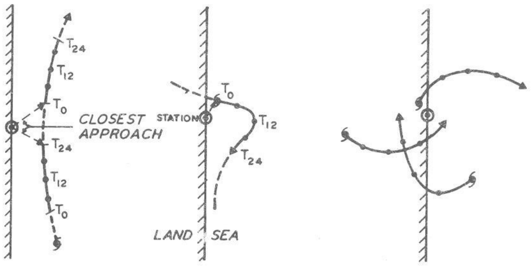

Figure 19.--Improperly chosen track segments relative to station on the coast. In the SPLASH II model, it is necessary that the track segment be chosen so that "nearest approach" occurs neat T_{12}.

(Continued from inside front cover)

WBTM TDL 25 Charts Giving Station Precipitation in the Plateau States From 850- and 500-Millibar Lows During Winter. August F. Korte, Donald L. Jorgensen, and William H. Klein, September 1969. (PB-187-476)

WBTM TDL 26 Computer Forecasts of Maximum and Minimum Surface Temperatures. William H. Klein, Frank Lewis, and George P. Casely, October 1969. (PB-189-105)

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WBTM TDL 28 Techniques for Forecasting Low Water Occurrences at Baltimore and Norfolk. James M. McClelland, March 1970. (PB-191-744)

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