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A PRELIMINARY VIEW OF STORM SURGES BEFORE AND AFTER STORM MODIFICATIONS FOR ALONGSHORE-MOVING STORMS

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Silver Spring, Md.
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ABSTRACT. Numerical means are used to compute storm surges (meteorological tides) in a standard basin of constant slope, bounded by a straightline coast. All storm tracks in this study are constrained to lie parallel to the coast; the storm can lie at any distance from the coast and travel with any speed, but once set, the distance and speed are invariant with time. Two driving forces, wind stress and atmospheric pressure gradient, are used to generate surges; they are derived from an analytic wind profile. The model storm is described with two invariant parameters, storm size and difference between ambient and central pressure of the storm.

To illustrate peak surges on the coast, two nomograms are constructed; one considers a continuum of storms (size and pressure) with a fixed track (speed and distance from coast), the other a continuum of tracks with a fixed storm. Simple correction factors are developed to consider a continuum of storms and tracks in a standard basin.

The peak surge on the coast is not always monotonically related to the parameter, maximum wind speed of a storm. In fact, it is found that the peak surge may increase or decrease according to the manner in which other storm parameters are affected by a change in maximum wind. In particular, any change in storm size is important because the coastal storm surge varies as the abeam distance of the storm from the coast relative to the storm size.

1. INTRODUCTION

Previously, we discussed storm surges--before and after storm modifications--for storms traveling from sea to land and with tracks perpendicular to the coast (Jelesnianski and Taylor 1973). We now do the same for storms traveling parallel to a coast, i.e. alongshore.

The generation of surges along coasts is most pronounced when a storm traverses the continental shelf. The traverse length is minimum for a landfall storm with track normal to the coast, but for an alongshore-moving storm or a track at an acute angle to the coast, the traverse length is orders of magnitude longer. The ocean depth patterns relative to the storm tracks are constantly changing with time if the storm moves across the basin whereas for an alongshore moving storm, the depth patterns are almost constant with time. All this means an alongshore-moving storm, compared to a landfalling storm, can generate complicated surges abounding on a long stretch of coast.

All natural storm tracks and coasts are curvilinear to some extent. Tracks are rarely parallel to a coast. In almost all cases the track of an alongshore moving storm has a small oblique angle to the coastline. It is the nature of the storm surge to be sensitive to the small oblique angle, and small changes in the angle can be just as significant for surge generation as small modifications of a storm.

At this time we want to avoid discussing surge generation due to curvilinear coasts and tracks, complicated ocean depth patterns, tracks with small oblique angles to the coast, variable storm dynamics with time, accelerating storm motions, explosive filling or deepening, etc. We do this by conveniently restricting our basins, storm tracks, and storms. By this we mean the basins will be simple, with a fixed straight-line coast and a constant one-dimensional slope depth profile; the storm track will always be parallel to the coast and the storm speed, intensity, size, etc., will be invariant with time. In spite of these simple constraints, there are a host of complicated surge phenomena to deal with.

We do not consider every possible situation, and we do not give a simple yes or no answer to the question "Do surges decrease with storm modification?" However, we do point out situations that may be crucial for surge changes due to storm modifications.

Our results point out that if the scale size of a storm changes with storm modification, there is no monotonic relation between peak surge and maximum wind. The abeam distance of the storm from the coast relative to storm size is an important factor for peak surge. This means any change in storm size--apart from changes in maximum wind--is also important for generation of storm surges.

2. SOME CONSTRAINTS, DEFINITIONS, AND DYNAMICS PERTINENT TO THIS REPORT

To discuss some important surge phenomena, we form several strong constraints in our oceanographic-meteorologic system. We avoid secondary-surge phenomena that can occur with complicated basin configurations or with storm or track variations with time. These phenomena should not be dismissed lightly, for in special situations they can be important when dealing with surge modifications due to storm modifications.

To compute surges in this study, a storm is modified ideally,* and we are concerned only with surge modifications in a simple basin. If the basin were not simple, i.e., if dramatic changes in two-dimensional depth patterns or strong coastal curvature relative to storm size were permitted, then secondary surge modifications would swamp the ordinary surge modifications reported in this study.

To avoid surge phenomena generated with ocean depth patterns that vary in two-dimensions, a standard basin is used in our computations (fig. 1). The coast is a straight line and the ocean bottom has a constant slope. We set the coastal boundary of the basin as a vertical wall with finite depth. The natural slope of the continental shelf is orders of magnitude smaller than the slopes over distances ℓ_0 and ℓ_1. These distances are orders of magnitude smaller than any horizontal scale length of the surge and storm size. The storm surge--a long gravity wave--does not "see" the rapidly changing depths within the small distances ℓ_0 and ℓ_1. If these distances are small compared to storm size, then it is permissible to use a vertical wall at the coast. Note, we cannot use small-sized storms such as a tornado.

We assume a constant coriolis parameter for latitude 30° North. The parameter does not change significantly across scale lengths of the storm surge wave.

We also want to avoid surge phenomena due to complicated and tortuous storm tracks. All vector storm motions will be linear, exactly parallel to a straightline coast, and invariant with time. This is shown in figure 1, where $\pm r$ is the abeam distance (seaward or landward) of the storm from the coast, and $\pm U_s$ is the storm speed (up or down) along the coast. The ratio $\pm r/R$ is an important measure in surge generation, where R is the radius of maximum wind for a stationary storm (i.e., R is storm size). As a further constraint, all storm parameters in our storm model (Jelesnianski and Taylor 1973), will be invariant with time. A storm and its motion are fixed for the entire storm duration.

In spite of our simplified oceanographic-meteorologic system, the surge dynamics generate a large assortment of surface waves on the sea. Some of these waves are:

Directly Generated Surge: This is a forced wave, directly under and following the storm as it proceeds up or down the coast. The wave moves with storm speed.

Resurgences: These are external or free waves generated by the storm, of at least two general types:

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*We mean computing surges first with one storm, and then re-computing with a second but slightly different storm. Each storm is invariant with time, and the storm tracks are identical.

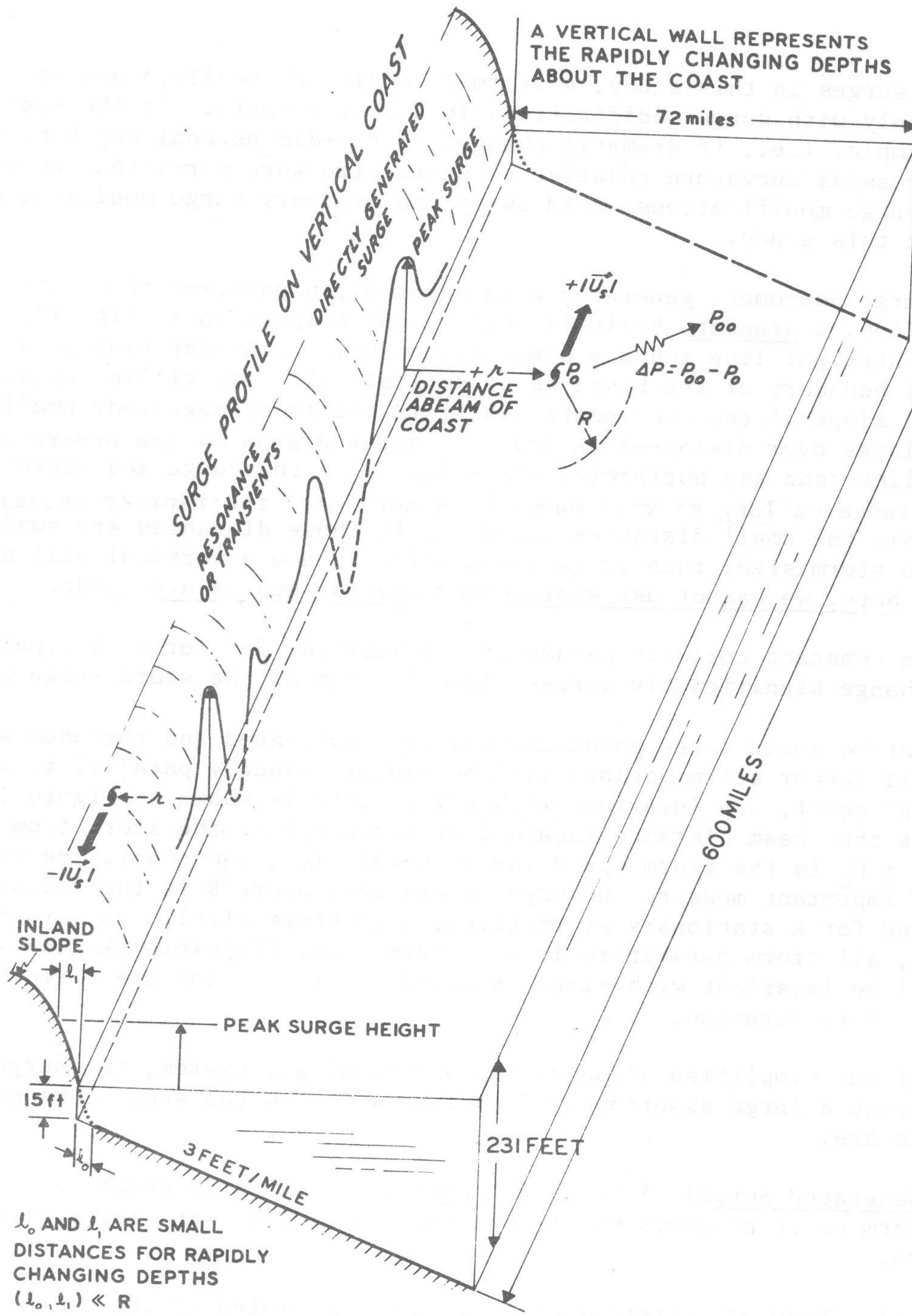

Figure 1.--For surge computations in this study, an idealized, standard basin is used; the bottom has a constant slope of 3 feet per mile and the coast is a straight-line. The immediate coastal slope is represented by a nearly vertical wall. An idealized storm track for an alongshore-moving storm is represented by the distance r and storm speed U_S. The character of the idealized storm is described by storm size R and pressure drop ΔP. A snapshot picture of a coastal surge profile is shown along the coast.

1. resonance from an orderly transfer of energy into the sea by the storm with time. A train of waves forms behind the storm and the wave speed is equal to storm speed.

2. transients of a temporary nature due to initialization procedures, quasi-orderly transfer of energy, etc. The wave speeds can be greater, equal to, or smaller than storm speed.

The assemblage of surges on the coast for any given time is called a coastal storm surge profile. The assemblage of highest water at each point on the coast for the duration of the storm is called a coastal storm surge envelope. The highest surge on the envelope is called the peak surge; it usually comes from the directly generated surge. The directly generated surge is generally larger than external (resonant or transient) waves because of bottom stress. After sufficient time elapses, the directly generated surge is an equilibrium surge and thereafter the envelope of surges on the coast is a straight line. (Note, this envelope is completely different from the envelope generated by a landfalling storm.) The statement "sufficient time" is very loose; although the forced wave can develop quickly, it takes a lot of time to dissipate transients and the surges then go through an adjustment period. While these adjustments are taking place, especially if the storm is slow moving, the transients can overtake and pass through the directly generated surge. This composite of waves gives a complicated surge envelope until transients are dissipated. For the special case of resonance, the external waves along the coast travel with storm speed and cannot overtake the directly generated surge; the surge envelope is then a straight line.

The model storm (Jelesnianski and Taylor 1973) and its vector storm motion is chosen conveniently simple. However, if the storms change while moving along their tracks, or travel on curvilinear tracks or accelerate, then these digressions can give secondary surge modifications and transients which swamp primary surge modifications. By primary surge modifications we mean those generated by idealized* storm modifications in a standard basin.

3. DRIVING FORCES OF A MODEL STORM

For input driving forces in our surge computations, we use a model wind profile with resulting pressure and inflow angle profiles (Jelesnianski and Taylor 1973). In the following, we concentrate on coastal peak surges

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*See previous footnote. We assume modifications have taken place before the storm enters the continental shelf.

generated by our model storms; for particular illustrations of surge profiles and envelopes on the coast, with resonance and transient phenomena, we refer to SPLASH, part II (Jelesnianski 1974).

To compute surges in our standard basin with idealized meteorology, we need to fix two parameters for the storm track and two parameters for the storm. These are (see figure 1):

Track

1. distance of storm abeam of coast, $\pm r$,
2. speed of storm, $\pm U_s$

Storm

1. pressure drop of storm, $\Delta P = P_\infty - P_0$, where P_∞ and P_0 are respectively the outside ambient and central pressures of the storm,
2. distance of maximum wind from storm center (storm size), R.

In our storm model, the maximum wind is given implicitly by ΔP and R. It would be nice to have a nomogram of peak surges for a continuum of the above parameters, however, some of the above parameters must be fixed in any nomogram of peak surges.

For a bird's eye view of peak surges in a standard basin generated with idealized meteorology, we begin with a special case. Suppose we have a fixed track--say, storms are 30 miles abeam of the coast and traveling at 30 mph--and we now ask the question, "What are the peak surges for a continuum of storms?" To answer, we use the surge model SPLASH, Part II, (Jelesnianski 1974). The results are shown in figure 2. Some features of the nomogram are:

1. If R remains constant, then a decrease in wind always gives smaller surges (also, smaller pressure drops).
2. For a constant pressure drop, an upper or critical peak surge appears at about R = 35 miles. There is nothing special about this size, it occurs because of the specialized basin and particular track chosen to produce the nomogram.
3. If initially R < 35 mi and ΔP remains constant, then a decrease in wind gives larger surges; also, the surge varies almost linearly and directly with R.
4. If initially R > 35 mi and ΔP remains constant, then a decrease in wind gives smaller surges; also, the surge varies almost linearly and inversely with R.

Figure 2 is for a particular storm track. But the peak surge is also a function of the track. To show dependence of peak surge on track, let us consider another special case. Suppose we have a fixed storm, the pressure

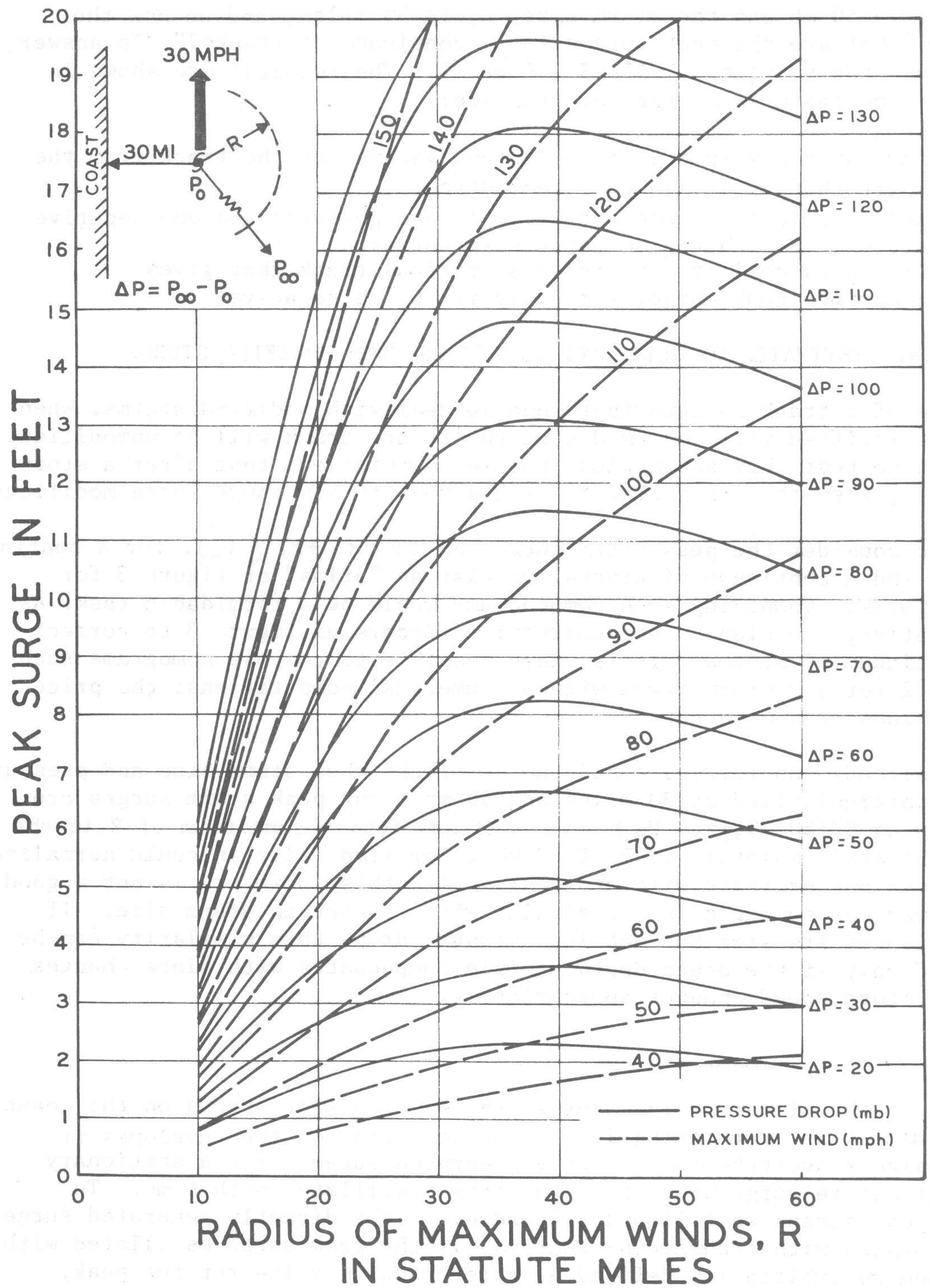

Figure 2.--The ordinate gives the peak surge on the coast of a standard basin generated by an idealized storm as a function of the maximum wind radius R, pressure drop ΔP, and maximum wind. The storm traverses the basin with a constant fixed track (r = 30 mi, U = 30 mph). The maximum wind for a stationary storm is implicitly defined by the storm (R,ΔP).

drop, ΔP, is 50 mb and the storm size, R, is 30 miles, and we ask the question, "What are the peak surges for a continuum of tracks?" To answer, we again use the surge model SPLASH, Part II. The results* are shown in figure 3. Some features of the nomogram are:

1. for any storm speed, there is one distance of the track from the coast that gives an upper peak surge.
2. near the coast, there are at least one positive and one negative storm speeds that give upper peak surges.
3. if U_s is positive, there is a critical track that gives a maximum peak surge; similarly if U_s is negative.

4. ESTIMATES OF SURGE MODIFICATIONS FROM MODIFIED STORMS

The nature of a track is important when we deal with modified storms. When a storm is modified it is assumed that the future track will be unmodified. We do not contest this assumption, but we do point out that after a storm is modified, then the particular track has much to say about surge modification.

We want to consider the peak storm surge, $SS(\Delta P, R, \pm r, \pm U_s)$, for a continuum of storms and a continuum of tracks, or else an "atlas" of figure 3 for various storms. Composing such compendiums would be a formidable task. As an alternative, we plan to use correction factors on figure 3 to correct for a continuum of storms. It is then possible to compose nomograms such as figure 2 for any storm track without numerical computations; the price paid is a loss of some accuracy.

Figure 3 already considers a continuum of tracks when storm size and pressure drop are particularized at 30 miles and 50 mb ; our peak storm surges are then given as $SS(50,30,\pm r,\pm U_s)$. We will now form a continuum of R in the figure, but still maintain a ΔP of 50 mb . For simplicity we could normalize the abscissa and ordinate with storm size R ; this, however, is not a good idea because the nomogram is not similar with respect to storm size. If a storm changes its size but not its pressure drop, then similarity can be maintained only if the ocean depth profile compensates with slope changes or if the storm speed changes appropriately.

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*For some of the slower moving storms, the envelopes of surges on the coast are polluted with transients; i.e., there are bumps on the envelopes if the transients overtake the directly generated surge. For a stationary storm the entire surge profile on the coast oscillates with time. To present peak surges we followed this rule: if the directly generated surge was influenced with transients--that is, if the peak surge oscillated with time--then we arbitrarily defined a representative value for the peak, namely the height of the second oscillation. It turns out that this value is insensitive to most initialization processes used with SPLASH, Part II (Jelesnianski 1974).

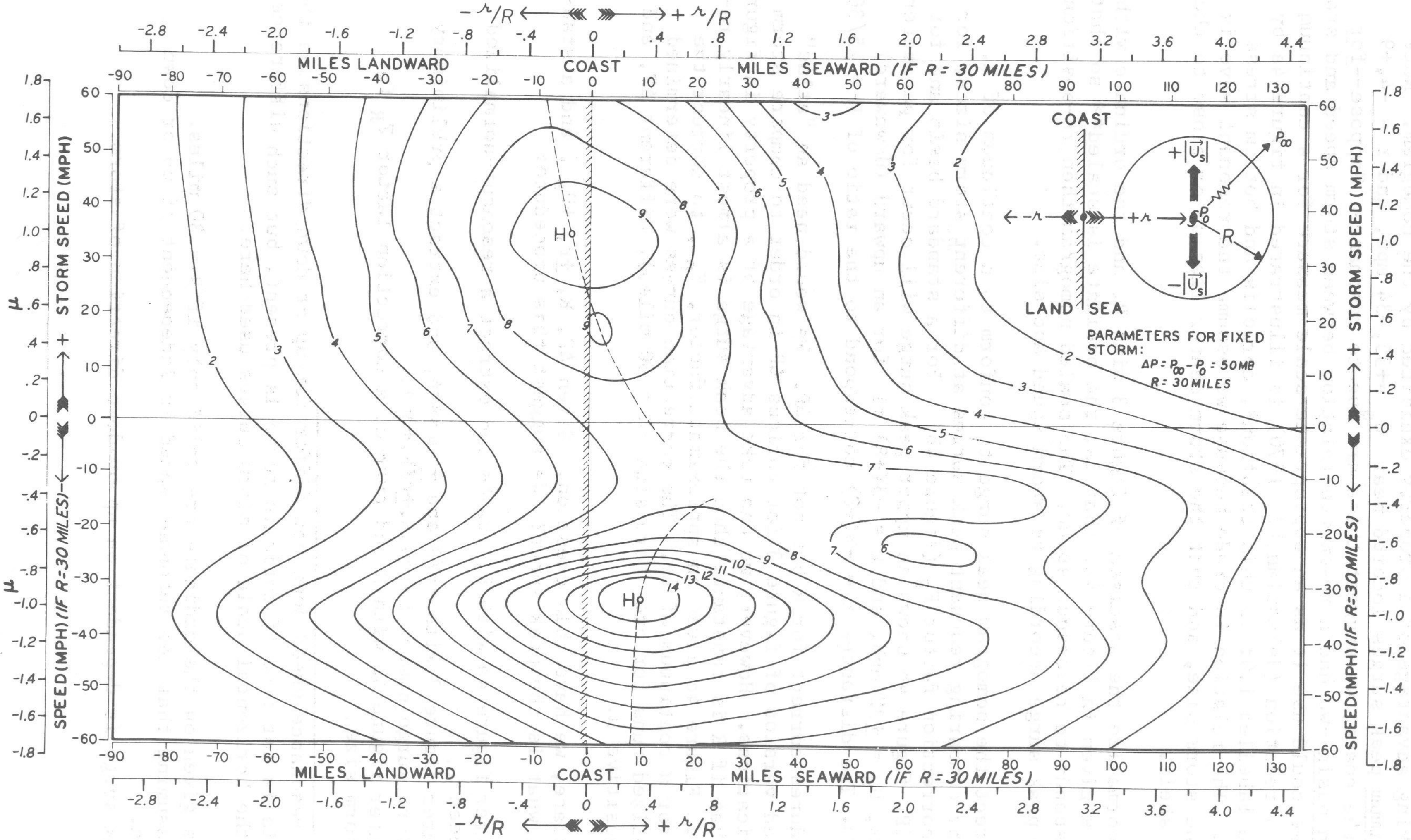

Figure 3.--Contours of peak surge SS on the coast of a standard basin as a function of the parameters of idealized tracks, $\pm r$, $\pm$ U. The storm maintains a constant ΔP = 50 mb and R = 30 miles. If R changes, then the abscissa may be normalized by $\pm$ r/R, and the ordinate by a μ scale (μ is defined in figure 4a).

Somehow, we need to revise the scales of figure 3 for a continuum of R. We do so by taking advantage of a property exhibited by the nomogram. Note the two maximum peak surges located near U_s =+35,-34 mph, and r = -4,+9 miles from the coast; we suggest these are due to resonance. Suppose--for our standard basin--we had a resonance relation between storm speed and storm size; then we could use it as an appropriate scale measure for a continuum of R. Such a relation (Jelesnianski 1970) is illustrated in figure 4a by the μ curve labelled 1.0; in this relation*, coriolis and bottom stress are ignored. The relation is crude because we assume the resonant wave is 4.0 times the storm size, and that the storm center lies on or close to the continental shelf.

Suppose we normalize the abscissa of figure 3 with R, and the ordinate with the relations given in figure 4a; that is, the ordinate is scaled** so that μ = 1.0 corresponds to resonance speed. The scaled nomogram then re-positions the maximum peak surge according to storm speed and size.

We must correct the nomogram peak surge to conform to a continuum of R. We do this by comparing resonant peak surges at different storm sizes, for a ratio or correction factor F_R (figure 4b). For a standard basin and for any fixed ΔP, figure 4b shows an upper peak surge will occur for parameters R = 25 miles, U_s = $\pm$32 mph, and r = -3(+8) mi for an upward (downward) moving storm. The distances r = -3(+8) correspond to the ratio of R = 25/30.

These procedures correct for R but not for ΔP. We would need an "atlas" of the scaled version of figure 3 for various ΔP in order to compare storm surge modifications. However, we can take advantage of a property in figure 2. Note, that if R is constant, then the peak surge is almost linearly related to ΔP. Figure 4c gives an approximate factor, F_p , to correct the peak surge for a continuum of ΔP. The correction curves were determined with specialized runs for one storm size (R = 30 miles), different ΔP, and different positive μ.

To recapitulate, we have this question. Given ΔP, R, $\pm$r, $+U_s$, and a standard basin, what is the peak surge? We suggest this procedure:

1. Enter figure 4a with R, U_s*** and extract a resonant-normalized speed μ.
2. Enter figure 3 with $\pm$r/R and $\pm$ μ****, and extract a preliminary storm surge number $\overline{SS}(50,R,\pm r/R,+\mu)$.
3. Enter figure 4b with R and extract a correction factor F_R for storm size.

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*We assume resonance speed does not differ for up or down directions on the coast. This is not true if coriolis force is present, but such difference is small for the horizontal scale of storm surges used here.

**The speeds given on the ordinate are valid only if R = 30 miles.

***We are assuming that the resonant speed is independent of up or down direction.

****The peak surge is dependent on up or down direction of storm.

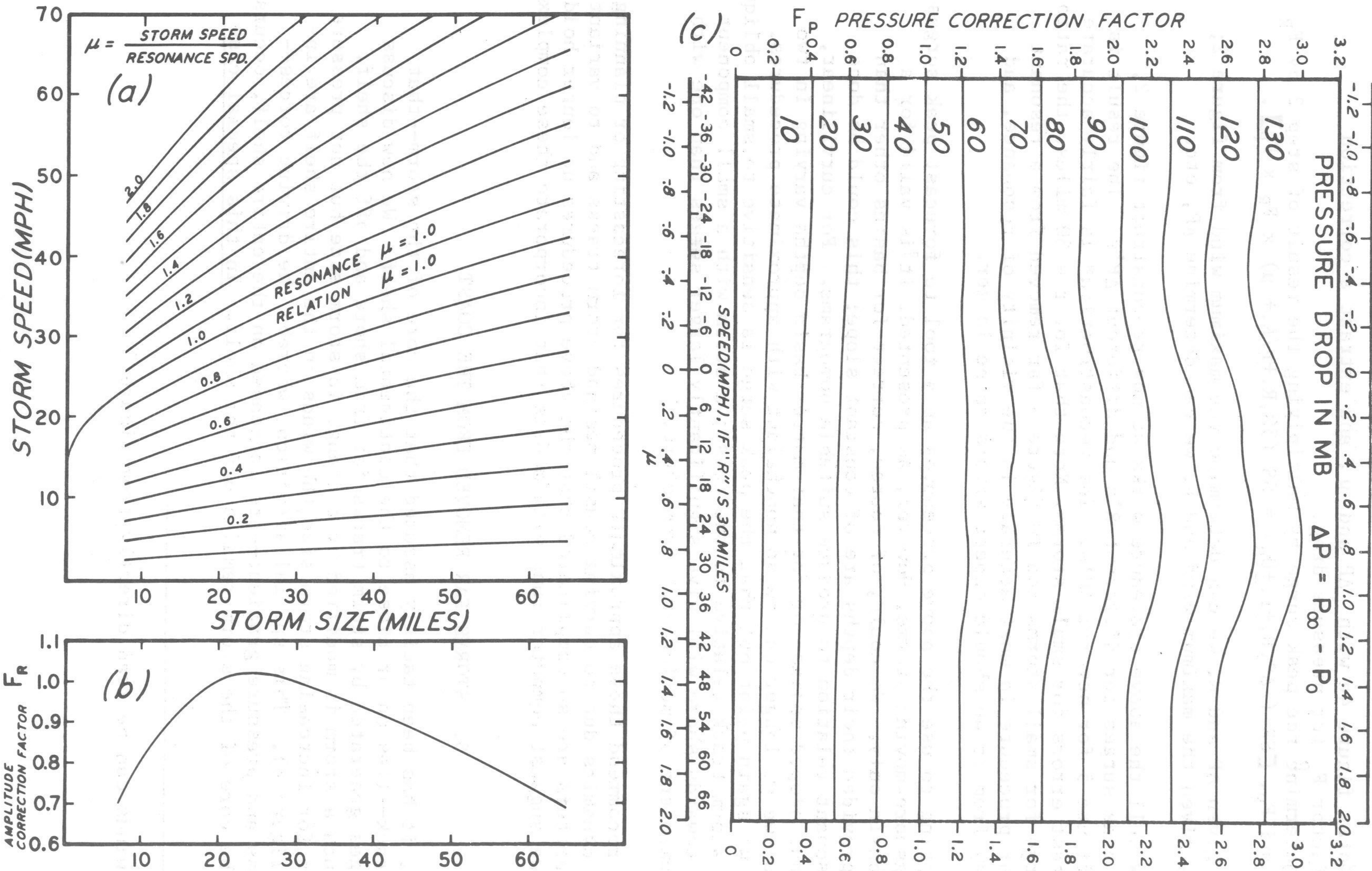

Figure 4.--Nomograms to correct figure 3, if a continuum of storms is to be considered. Figure 4a normalizes the storm speed with respect to resonance speed for a given storm size (valid for a standard basin only); figure 4b corrects for resonant amplitude change if R is other than 30 miles; figure 4c corrects for amplitude change if ΔP is other than 50 mb .

4. Enter figure 4c with ΔP and μ, and extract a correction factor F_p for pressure drop.
5. Determine the peak surge by multiplying the result of step 2 by F_R and F_P, [$SS(\Delta P, R, \pm r, \pm U_s) = SS(50, R, \pm r/R, \pm \mu) \times F_R \times F_P$].

Note that given ΔP and R, we can determine the maximum wind from figure 2; similarly, given the maximum wind and R, we can determine ΔP, etc.

To see how well the above procedure works we now re-construct figure 2, computing peak surges for different R's and different ΔP's. The result is shown in figure 5 for several ΔP's. The reconstruction* is fairly accurate with greatest errors for small storms. Note that for r = 30 miles, the ratio r/R is large for small storms and in figure 3 far removed from a resonant point. Our procedure is most accurate in the vicinity of resonance, and moving away from it we should expect errors to be larger.

It is tempting to use the above procedures as a tool to forecast peak surges with alongshore-moving storms. However, as presented, it is valid for a standard basin only. We could, of course, correct for basins other than standard provided their depths are of constant slope; this could be done with a resonant relation to produce suitable nomograms. For curvilinear, non-constant sloped basins--or for that matter basin depths varying in two dimensions--we no longer can be so nonchalant with approximate procedures. Moreover, we again point out that the peak surge is sensitive to small oblique angles of storm track relative to the coast; a storm with a small component of motion towards shore will give significantly larger surges than one with a small component of motion away from shore.

We do not recommend these approximate procedures for forecasting or planning. The surge dynamics due to curving coastlines and storm tracks and to variant storm parameters are so complicated that the above procedures no longer hold. Instead, we suggest computer runs with models that incorporate these complexities.

5. STORMS FAR REMOVED FROM THE COAST

Up to now, it has been tacitly assumed that the core of the storm--that is, the track--lies on or close to the continental shelf. We now discuss storm surges generated by storm tracks far from shore and off the shelf. Suppose such a storm is modified by a change in storm size but not pressure drop; then for increasing storm size, the winds on the entire shelf are increased (figure 6). This special situation, whereby the driving forces--wind stress and pressure gradient--are increased on the entire shelf, occurs only if the core of the storm remains off the shelf. In this special case

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*Maximum winds can be read directly from figure 2.

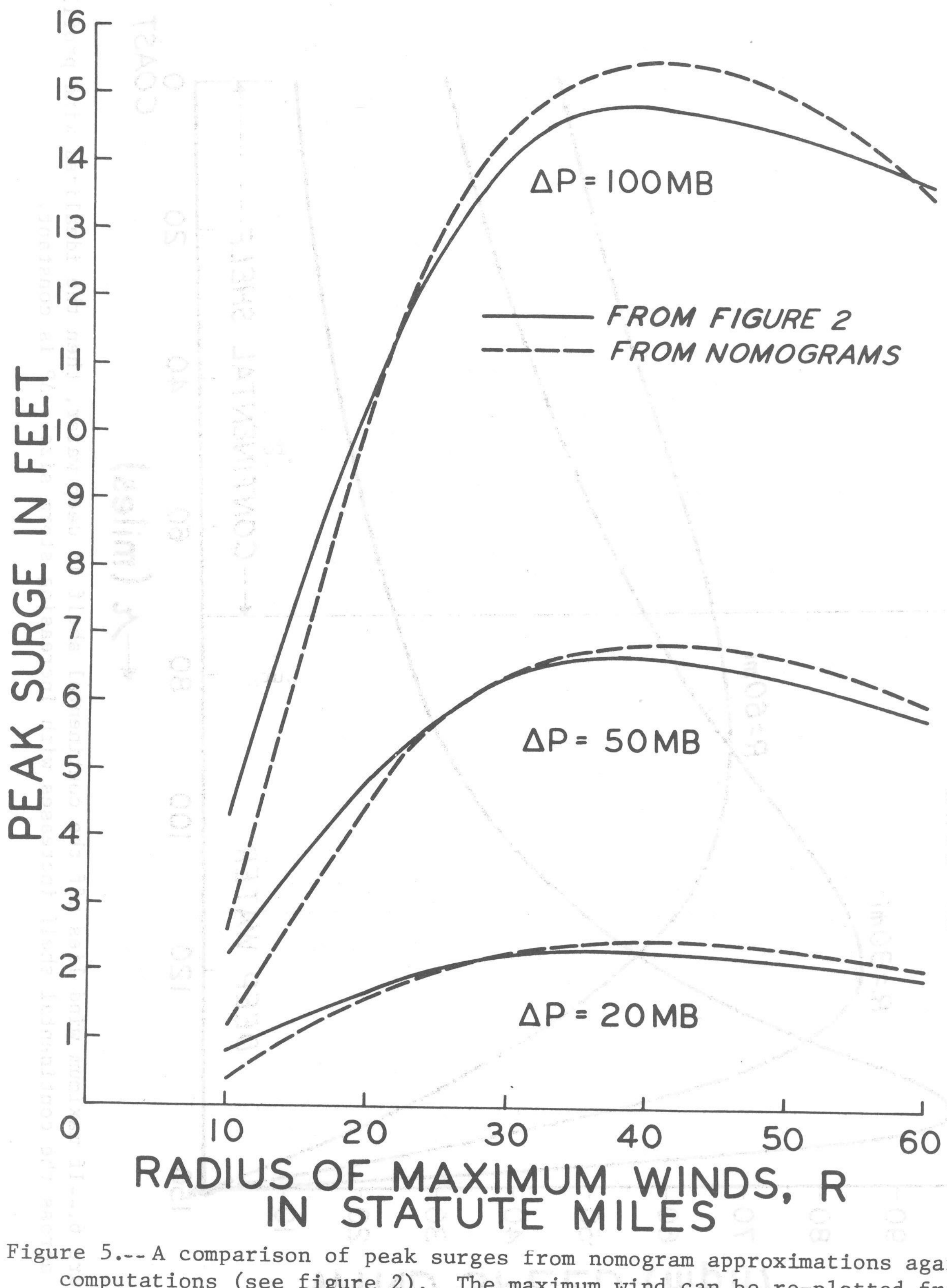

Figure 5.--A comparison of peak surges from nomogram approximations against computations (see figure 2). The maximum wind can be re-plotted from figure 2.

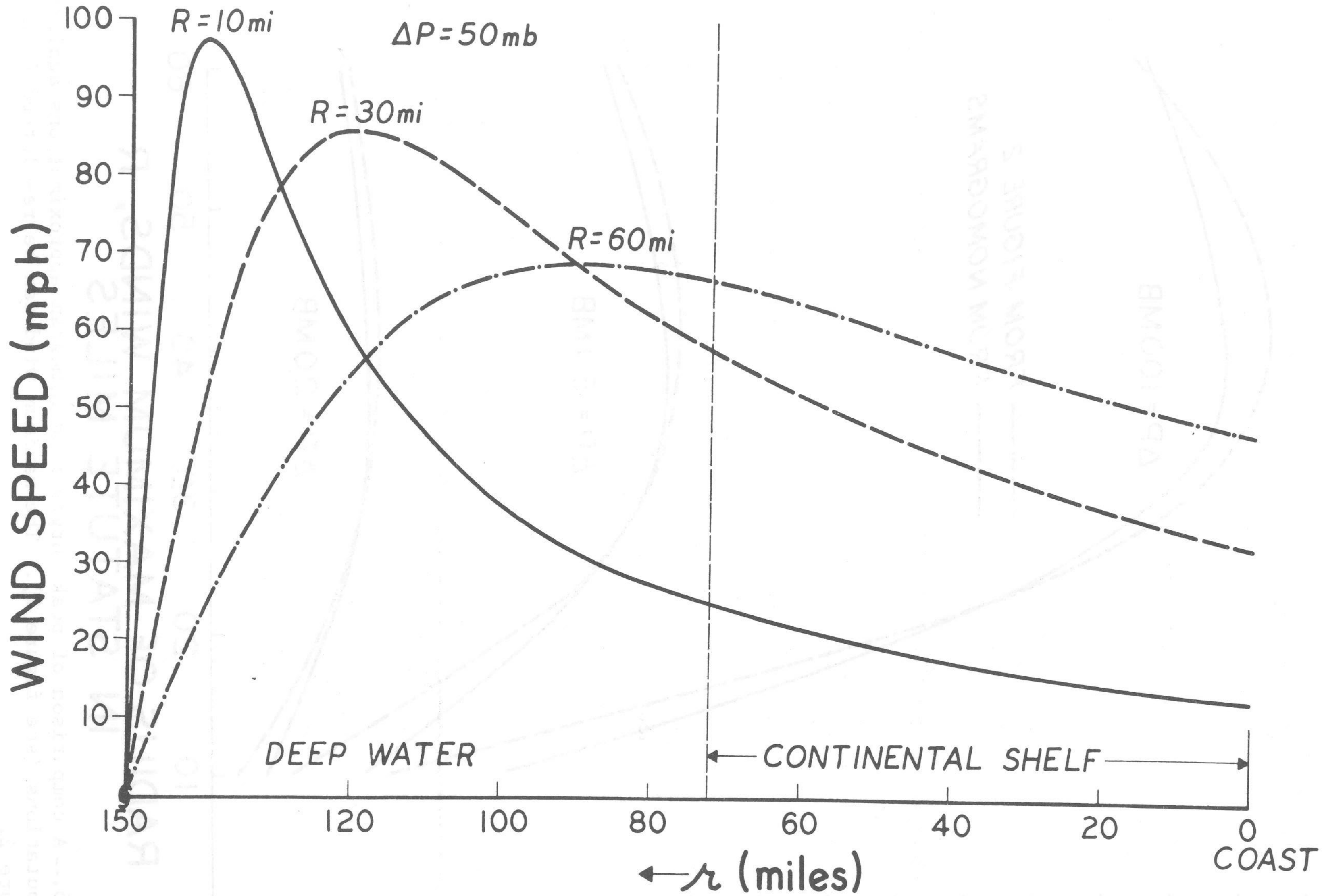

Figure 6.--If maximum wind lies off the continental shelf in deep water, then the idealized wind profile across the continental shelf increases with increasing storm size. ΔP is constant.

the coastal surge will increase* with increasing storm size, no matter what the change in maximum wind off the continental shelf is.

For this case, coastal surges are generally small, much smaller than those generated by a track on the shelf and close to shore. However, it is well to remember some communities have constructed buildings so close to shore that there is little tolerance for water rises higher than normal astronomical tide. For these communities, a small storm surge at high astronomical tide can be disastrous; hence, the size of the storm can easily be a decisive factor. An example is Hurricane Agnes, 1972. The track was about 180 miles abeam of Tampa, Florida where rises of water above five feet are intolerable. For this storm, the SPLASH II model produced a surge range of 1-3 feet with storm size ranging between 15-60 miles; in conjunction with astronomical tide plus seasonal and anomolous trends in sea level, this easily approaches or exceeds the critical level.

6. SUMMARY AND CONCLUSIONS

The peak coastal surge generated by a storm traveling parallel to a straight-line coast is sensitive to the distance of the storm from the coast relative to storm size. If a storm is modified so that its size changes, then storm size is an important parameter apart from maximum wind.

For a constant pressure and a fixed track parallel to the coast, the peak surge is not monotonic with respect to the maximum wind. If the maximum wind decreases concurrently with increasing storm size, then the surge increases to a critical value and thereafter decreases.

If a storm is modified at a great distance from the coast and the core of the storm remains off the continental shelf, then decreasing the wind concurrently with increasing storm size results in higher surges on the coast. Surges from such storms are very small, but in conjunction with high astronomical tide and sea level anomolies, the total tide can become damaging at some coastal regions.

Merely decreasing the maximum wind of a storm is insufficient information to determine coastal surge changes. Sometimes the surge will decrease, other times increase, depending on other parametric changes such as storm size, storm track, and storm speed.

Storm modifications may decrease surges in one basin, yet increase surges in another basin; similarly, for storm modifications in a basin with alternate tracks. Hence, surge versus storm modifications is a complex relation not amenable to simple rules.

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*We are assuming that transmission of energy from deep water onto the shelf gives much smaller coastal surges than those generated by driving forces on the continental shelf.

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