AN ANALYSIS OF COASTAL RECESSION MODELS: NORTH CAROLINA COAST

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ABSTRACT: Using the North Carolina barrier island shoreline as the test area, a variety of simple geometric recession models has been applied to predict shoreline erosion rates for various sea-level rise scenarios. All sea-level rise scenarios assume no acceleration in rate of rise. South of Cape Lookout, the Bruun Rule, Generalized Bruun Rule and the slope of the migration surface all lead to similar recession predictions. North of Cape Lookout, the slope of the migration surface predicts a much greater recession than Bruun-related models. This suggests the possibility that the islands are in an "out-of-equilibrium position" with respect to present sea level. If this is the case, the possibility exists that very rapid migration of the northern islands will soon occur.

The assumptions used in the present mathematical models depicting shoreline retreat are generally weak. Better models are needed, especially for shorelines where recession is part of the barrier island migration process. The large number of types of islands in a wide variety of geologic and oceanographic settings makes a universally applicable model difficult, if not impossible, to formulate.

INTRODUCTION

The response of the open-ocean sandy shoreline to a rising sea level is one of the most important applied problems facing coastal geologists today. Predictions of greenhouse-related sea-level rise vary considerably, but all agree that acceleration is likely. The Environmental Protection Agency projects that future sea-level rise on a world-wide basis will range from 0.52 to 3.45 m by 2100 A.D. (Hoffman and others, 1983). The Committee of the National Research Council on Carbon Dioxide Assessment suggests a rate of 0.70 m/century by the year 2100 (Revelle, 1983). Discussions of sea-level rise and related phenomena are presented by several authors in this volume (e.g., Braatz and Aubrey, Gornitz and Lebedeff, and Komar and Enfield) and will not be addressed here.

The purpose of this paper is to test several shoreline recession models by applying them to the entire open-ocean North Carolina barrier island coast. The models applied include the Bruun Rule (Bruun, 1962), the Edelman rule (Edelman, 1968, 1970) and the Generalized Bruun Rule (Dean and Maurmeyer, 1983). In addition, rates of shoreline movement due to a sea-level rise are predicted on the basis of slope of the ravinement surface or barrier island migration surface (Swift, 1976a,b). Finally, present erosion rates (Kochel and others, 1983; Benton, 1983) are extrapolated.

The Bruun, Edelman and Modified Bruun rules are briefly outlined below. For more detailed discussions of these models, the reader is referred to the original papers and to Dean and Maurmeyer (1983).

The Bruun Rule (Bruun, 1962) is the basis for all other erosion models that are presently used. It is still the most widely used and recognized method of calculating shoreline change. Bruun maintained that the shoreface profile reacts to a sea-level rise by simply retreating landward and upward such that the profile remains constant relative to sea level down to the depth of effective wave motion. This depth is assumed to be 10 m for the purposes of this study. The active profile in Bruun's equation essentially corresponds to the shoreface. The Bruun Rule is stated as:

$$R = \frac{L}{(B + h)} S = \frac{1}{\tan \theta} S \qquad (1)$$

where R = recession due to sea-level rise; S = sea-level rise; B = berm height; θ = active profile slope; h = depth of active profile base; and L = width of active profile.

It is assumed that there is no net loss of sediment due to longshore transport, and that the amount of sand eroded from the subaerial portion of the profile will roughly equal the volume deposited on the lower shoreface. From the equation, it can be seen that R is directly proportional to S, and the amount of recession is larger than the amount of sea-level rise by an amount proportional to the tan θ term. Therefore, according to the Bruun Rule, gentle beaches will recede faster than steep beaches for a given sea-level rise.

Rosen (1978) applied the Bruun Rule to eroding shorelines of Chesapeake Bay. He concluded that, in the particular circumstances of the bay shorelines, the Bruun Rule accurately characterized and predicted shoreline recession rates for known rates of sea-level rise.

In 1968 Edelman developed a model for quantifying shoreline response, based on profiles of the Dutch coast, and concluded that the equilibrium profile approximates a constant at any one instant and is of uniform slope. In addition, Edelman concluded that for a given storm surge, higher dunes will recede less than lower dunes.

Edelman's second model is much more innovative than his first and actually provides a numerical answer to the dune erosion question (Edelman, 1970). The assumption that changes of profile keep pace with rising sea level makes this model more realistic than the first. The Edelman II model is as follows:

$$R = L \ln\left(\frac{hb_o + hd_o}{hb_o + hd_o - S}\right) \qquad (2)$$

where R = recession due to sea-level rise; L = width of active profile; S = sea-level rise; hb_o = depth of active profile base; and hd_o = height of dunes.

The two main assumptions behind equation 2 are the constancy of wave conditions throughout the time period analyzed, and the direct relationship between sea-level rise and the speed of profile migration, resulting in proportional rates of movements for the two processes. The sole difference between the Edelman and Bruun models is the allowance for a reduction in dune height through time when using the Edelman II model. This allowance causes the Edelman II model to yield slightly greater recession values than those found by using the Bruun Rule.

Dean and Maurmeyer (1983) have modified the Bruun Rule, adopting it for usage in predicting the recession/migration of a retreating beach which is part of a larger barrier island system. Their model, which they call the Generalized Bruun Rule, is as follows:

$$R = \frac{S(L_o + W + L_l)}{(B_o + hb_o) - (B_l + hb_l)} \quad (3)$$

where R = recession due to sea-level rise; S = sea-level rise; L_o = width of oceanside active profile; L_l = width of lagoon-side active profile; hb_o = depth of base of active zone; hb_l = depth of base of active zone of lagoon side; B_o = open-ocean berm height; B_l = lagoon berm height; and W = width of the barrier island.

The main assumptions associated with the use of this model are the constancy of island width W through time by the overwash of sand, and the vertical growth of the entire island at the same rate as sea level rises. This diversion of island sand from the shoreface causes the Generalized Bruun Rule to predict a higher recession value than the Bruun Rule does for the same setting. As will be discussed more fully subsequently, this is a logical outgrowth of the different rates of shoreline movement for migrating barrier islands compared to islands which are merely experiencing shoreline recession without significant overwash.

Recently, Everts (1984 and this volume) developed a model for shoreline recession differing from Bruun's work in several important ways. As Everts states (p. 998), his model "is not constrained to the singular movement of sediment in an offshore direction; it accounts for changes in sand volume within a shoreline reach, including that caused by alongshore and cross-shore transport, transport into inlets, overwash, beach nourishment, sand mining, and others; it allows for barrier island preservation during a rising sea level; and it treats sediment movement in a more analytical way." These developments are very important because they address many, if not all, of the weaker aspects of the Bruun Rule. Conversely, Everts' model is similar to Bruun's in other ways, namely, that the shoreface is assumed to be in equilibrium with sea level and will thus translate vertically an amount equal to the rise in sea level. This means that, as in any model, sand redistribution is needed to maintain the equilibrium profile.

Unfortunately, the Everts' model could not be applied to the coast in this study because of the lack of the requisite accurate nearshore and shoreface profiles. (See Everts, this volume, for application of his model to other coastal areas.)

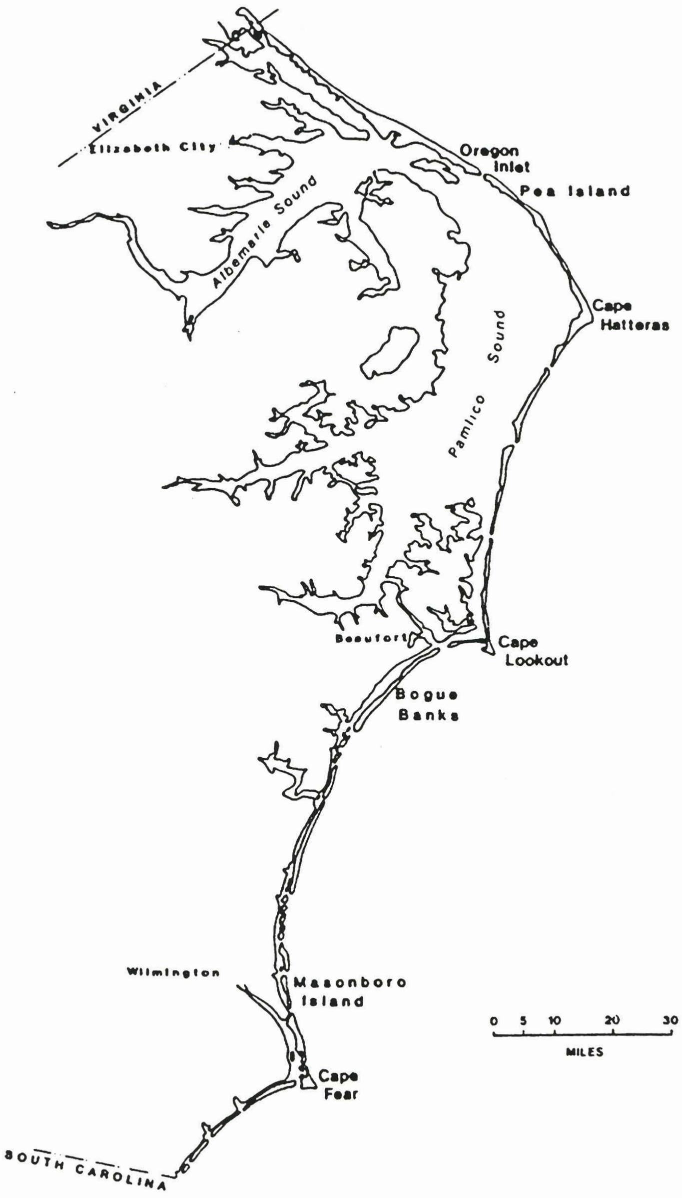

FIG. 1.—Index map of the North Carolina study area.

MODEL-CALCULATED RECESSION

The Bruun Rule, Generalized Bruun Rule and Edelman II models were applied as shoreline recession predictors for the entire North Carolina coast (Fig. 1). Most of the data used in this study are measurements obtained from the U.S. Geological Survey topographic quadrangle maps and National Ocean Service charts available along the 92 transects shown in Figure 2. A number of assumptions were used in the models where profile data were incomplete or not sufficiently detailed.

Sea level, unless stated otherwise, is assumed to be rising at the rate of 23 cm/century. No acceleration of sea-level rise is assumed. The depth of the base of the active profile, equivalent to the shoreface, is assumed to be 10 m for all of the North Carolina coast. For Bruun Rule calculations, berm height, B, is assumed to be 1 m above mean sea level. For the Generalized Bruun Rule the open-ocean berm height is assumed to be 1 m, the lagoonal berm height 0.5 m, the depth of significant sediment movement on the lagoon side 1 m, and the width of the zone of active sediment movement in the lagoon 20 m. Dune height for use in the Edelman II model calculation is either 1 m, 3 m or 5 m, depending upon the dune height classification of Kochel and others (1983).

Edelman II model results are not plotted in Figure 3, because the results are essentially the same as Bruun Rule

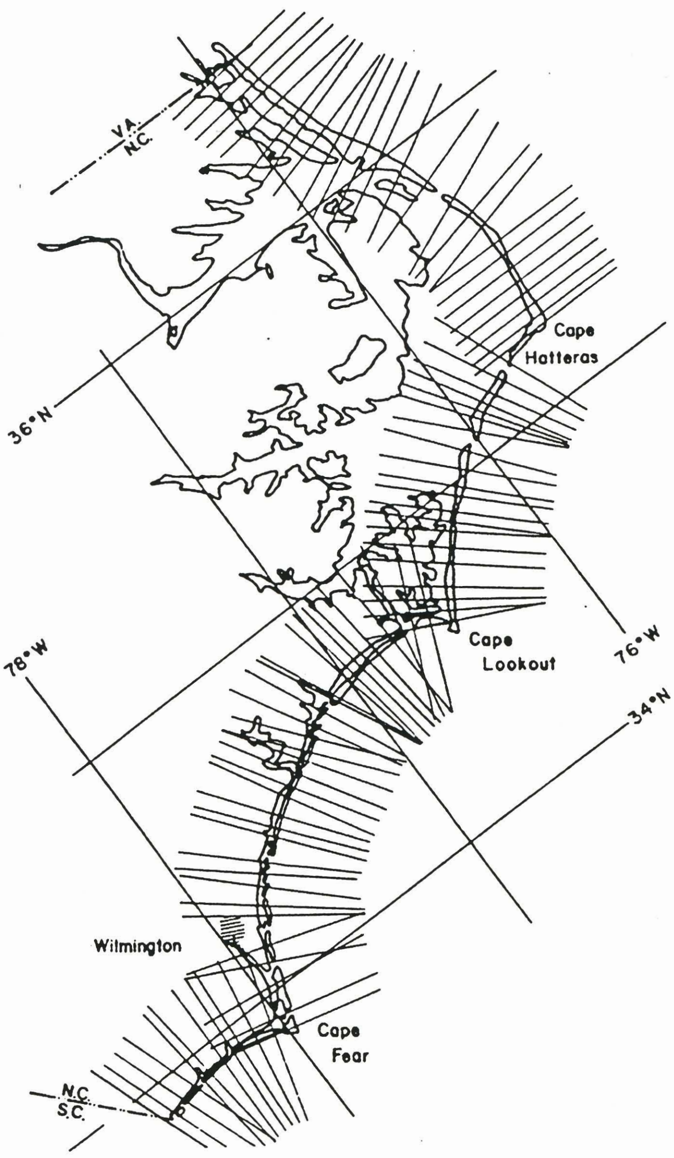

FIG. 2.—Map of the study area showing transect lines along which model calculations were made.

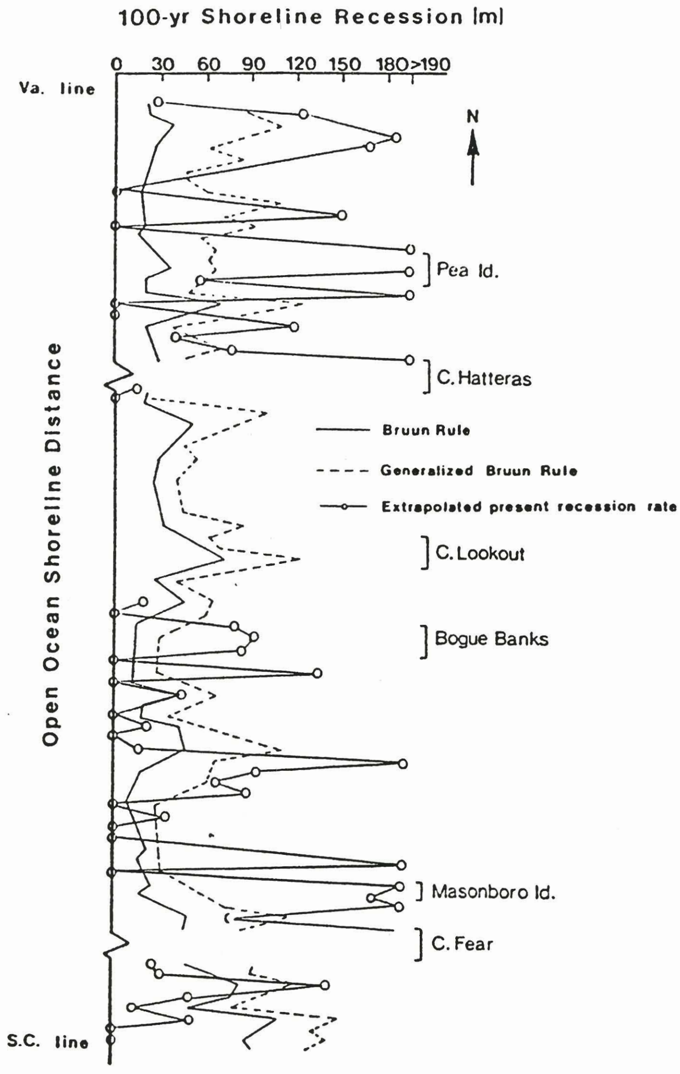

FIG. 3.—Comparison of expected 100-yr shoreline recession rates in meters calculated using the Bruun Rule and the Generalized Bruun Rule. Shown also is the extrapolated present rate of erosion. Calculations are based on an assumed sea-level rise of 23 cm/100 yrs.

calculations. The circles shown on Figure 3 are 100-yr extrapolations of present erosion rates which average 0.631 m/yr (May and others, 1982).

The trends of Bruun Rule- and Generalized Bruun Rule-calculated erosion rates are more or less parallel throughout the study area (Fig. 3). Some of the variability in predicted rates of shoreline movement is due to shoreface-connected ridges and other features which locally affect calculation of the slope of the shoreface. The average erosion rates for the coast predicted by these two models is typically between 40 to 60 m per 100 yrs. Rates predicted by both models for the cape regions are anomalously high due to the effect of the offshore sand shoals on apparent shoreface slopes. Only Cape Lookout recession values are plotted on Figure 3.

The Generalized Bruun Rule consistently predicts more recession than the Bruun Rule. This is because the Generalized Bruun Rule requires the entire island profile, from the base of the shoreface to the landward limit of the lagoon's active profile, to remain constant throughout time, whereas the Bruun Rule requires profile maintenance only from the base of the shoreface to the top of the first dune (or berm). The need for more sand to maintain the entire island profile results in larger recession rates.

In should be noted that the Bruun and Generalized Bruun predictions (Fig. 3) are both conservative in that they assume that only sand is being bypassed through the shoreface. It is possible to use a "sediment compatibility factor" (Dean and Maurmeyer, 1983) to take into account that mud may also be bypassed. The basic assumption is that island and shoreline recession rates are directly proportional to the percentage of mud in shoreface-bypassed material. The "sediment compatibility factor" was not applied in this study because more studies, such as that of Hine and Snyder (1985) are needed to determine the grain size of barrier island shorefaces of North Carolina islands.

Extrapolation of present rates of erosion (not available on national seashores) produced highly variable recession rates for the next 100 yrs (Fig. 3). Zero recession rates shown on Figure 3 usually represent shoreline areas presently experiencing accretion. Most often such areas are near inlets, and accretion rates cannot be considered good indications of future shoreline movement. Overall, the extrapolated recession values have no clear relation to the rates of model-calculated recession. Furthermore, in most cases, extrapolations of present recession rates are higher than those predicted by the models, assuming a 23 cm/century sea-level rise rate.

Why the difference between extrapolated and predicted rates of erosion? At this point, one can only list possibilities, which include the fact that: (1) many factors other than sea-level rise, including a regional sand deficit, may cause shoreline retreat, (2) extrapolation of short-term data is meaningless and does not lead to meaningful long-term values of shore retreat, (3) the predictive models are unrealistic, or (4) some combination of all of the above.

It is useful to emphasize again that all of the model-predicted values shown in Figure 3 are based on the assumption that there will be no acceleration in the rate of sea-level rise. Since this is a poor assumption, all shoreline recession values shown in Figure 3 are minimum values.

RECESSION PREDICTED BY MIGRATION SURFACE SLOPE

If the sea level were to rise 10 m in the next decade, the shoreline would be inland at the 10-m contour line. The scenario which would correctly predict shoreline position of this highly unlikely event is the migration surface slope model, which is based on the assumption that the extent of shoreline retreat is a function of the slope of the lower coastal plain.

There is no question that this is a valid model for large and rapid sea-level rises. For example, the slope of the barrier island migration surface must have been the major control of shoreline position during the times represented by the steeper portions of the Holocene sea-level curve (e.g., Blackwelder and others, 1979). The more difficult question is, what role does migration surface slope play in determining shoreline position in a shorter term sea-level rise of 0.2 or 1 m?

TABLE 1.—DEFINITION OF THE VARIOUS MIGRATION SURFACE SLOPES USED TO CALCULATE RECESSION RATES. LOCATION OF THE VARIOUS SLOPES ON A TYPICAL LOWER COASTAL PLAIN CROSS SECTION IS SHOWN IN FIGURE 4

Slope *A* =	Difference in elevation of a point 2 km inland from the lagoon shoreline and base of shoreface ÷ horizontal distance between above points.
Slope *B* =	Difference in elevation of points 30 km landward and 30 km seaward from shoreline ÷ horizontal distance between above points (60 km).
Slope *C* =	Difference in elevation of shoreline and base of shoreface (10 m) ÷ horizontal distance between above points.
Slope *D* =	Difference in elevation of a point 20 km landward from lagoon shoreline and base of shoreface ÷ horizontal distance between above points.
Slope *E* =	Elevation of a point 2 km landward of the lagoon shoreline ÷ 2 km.

A wide variety of migration surface slopes can be chosen, each resulting in different "rise to run" ratios and consequently a wide variety of retreat rates. The five slopes chosen for this study are shown in Figure 4 and Table 1. The slope-calculated rates of shoreline recession, assuming a 1-m rise in sea level, are shown in Figure 5 for five representative coastal localities.

The extreme recession of more than 5,000 m predicted for a 1-m sea-level rise for slopes *A* and *D* at Cape Hatteras are due to Diamond Shoals. This large sand body, extending more than 20 km seaward at the cape, produces an apparent, very gentle migration surface and consequently very large recession predictions. Since the shoal is a body of sand restricted to the continental shelf or a shoal retreat massif (Swift, 1976b), it is not part of the regional barrier

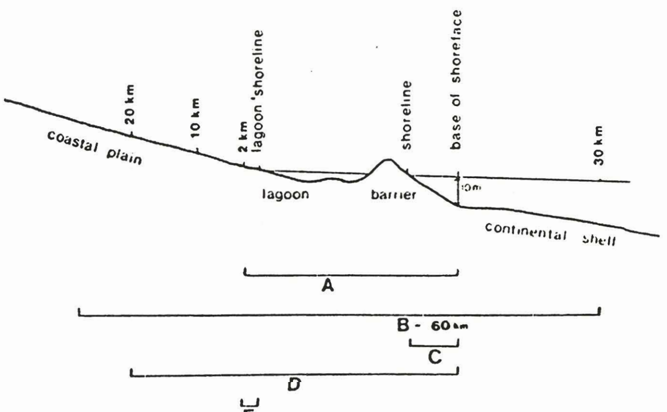

FIG. 4.—A diagrammatic cross section of the lower coastal plain and barrier island system showing the reaches over which the various migration surface slopes used in Table 1 are defined.

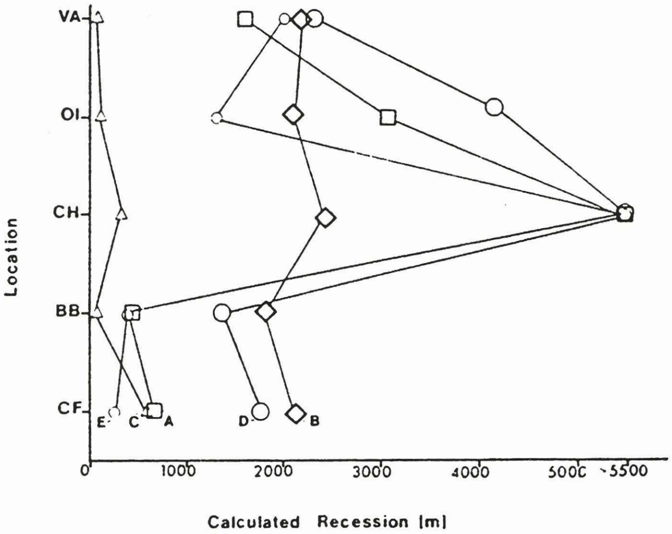

FIG. 5.—*Expected shoreline recession as a result of a 1-m sea-level* rise, assuming that recession is controlleld only by migration surface slopes. The various slopes used are shown in Figure 4 and Table 1. Key to localities is as follows: Va = Virginia line, OI = Oregon Inlet, CH = Cape Hatteras, BB = Bogue Banks, CF = Cape Fear. Localities are shown in Figure 1.

island migration surface, and the predicted Cape Hatteras retreat is meaningless.

Slopes *B* and *C* are unaffected by the presence of Diamond Shoals. Slope *C* extends from the barrier island shoreline to a depth of 10 m (Fig. 4). Basically, this is the shoreface slope. Using slope *C* nearly always produces the least amount of predicted recession, reflecting the fact that the shoreface is the steepest portion of the lower coastal plain of North Carolina. It is also not a reasonable approximation of the barrier island migration surface slope, because the shoreface is, in itself, a migrating feature.

Slope *B* usually covers the greatest horizontal distance of any of the alternative slopes chosen. It extends 30 km seaward and landward of the barrier island shoreline. The distance on which this slope is based is so large that it effectively minimizes the size of the barrier island perched on it and also is unaffected by the cape-associated shoal. Recession rates obtained using this slope are typically among the highest. Most often a 1-m sea-level rise will cause a shoreline retreat in excess of 2,000 m, if slope *B* is assumed to be the best predictor (Fig. 5). The uniformity of predicted recession values is due to the fact that this regional slope averages out numerous coastal morphologic irregularities, such as shoals and estuaries. Slope *B*, because of its regional nature and the consequent smoothing out or elimination of local topographic variations, may be the best migration surface slope to predict average regional shoreline recession rates.

Slopes *A*, *D* and *E* predict much more variable rates of shoreline recession than do slopes *C* and *B*. In Figure 5 it can be seen that slopes *A* and *D* predict relatively high shoreline recession rates, especially for the northern half of the state, and that slope *A*, which extends 2 km onto the mainland, consistently predicts less recession (by 500 to 1,000 m) than slope *D*.

Figure 6 depicts the amount of shoreline recession which can be expected from 1-m and 6-m sea-level rises calculated for slopes *A* and *B*. The amount of recession ranges from 1 km to nearly 18 km with a 6-m sea-level rise. The greatest amounts of recession are predicted at the capes, but these are likely to be unrealistically high for the reasons just discussed.

North of Cape Hatteras, slopes *A* and *B* predict roughly comparable recessions of 1 km for a 1-m sea-level rise and 6 km for a 6-m sea-level rise. South of Cape Hatteras, slope *B* again yields about a 1 km recession for a 1-m rise and a 6-km shoreline retreat for a 6-m sea-level rise. The use of slope *A* for the same rise, however, predicts only a 1-km recession for a 6-m rise.

The more regional slope *B* generally predicts significantly greater recession than slope *A* for a given sea-level rise. A few notable exceptions to this are north of Cape Hatteras, where extensive coastal zone swamps cause slope *A* to be more gentle than slope *B*.

COMPARISON OF MODEL AND SLOPE PREDICTIONS

Figure 7 presents a comparison of the 100-yr recession of the North Carolina shoreline based on slope *A* and on the Generalized Bruun Rule, assuming a sea-level rise of 23 cm/100 yrs. Results of extrapolation of present rates for 100 yrs are also shown as unconnected circles.

North of Cape Lookout, slope *A* predicts a much greater recession rate than the Generalized Bruun Rule. We believe this is a result of the very gentle migration surface produced by wide back-barrier lagoons. South of Cape Lookout, the difference between the two models is slight. The two produce impressively similar recession rates.

It is suggested that the close correspondence between slope- and model-predicted recession rates for the southern part of the study area (which exhibits a relatively steep migration surface) indicates that a sort of equilibrium has been achieved. That is, the shoreline is more or less in its equilibrium position with relation to the level of the sea. From another viewpoint, if the Bruun model has any natural basis, model-predicted retreat cannot be greatly different from that predicted by the slope of the land.

On the other hand, the great difference in predicted rates of shoreline retreat north of Cape Hatteras may indicate that the present islands are in an out-of-equilibrium position with the level of the sea. If this is the case, the possibility exists that very rapid migration of the northern islands will soon occur. Possibly, this out-of-equilibrium situation could lead to overstepping of the island chain.

TOWARD BETTER MODELS?

The results of applying models and migration slope data to projections of shoreline recession for a rising sea level are difficult to evaluate. We know (as did the authors of the models) that the models do not include many of the fundamental evolutionary concepts that are well established by coastal recession/island migration studies. The number of environmental parameters is large, and the relative importance of the various parameters is highly variable for different shoreline locations. Perhaps the situation is so complex that a generally applicable and accurate model for shoreline recession in a rising sea level is an impossibility. One hopes this is not the case, because accurate prediction of short-range recession rates in a rising sea level has important societal and geological ramifications. Problems include the following. (1) The number of variables affecting shoreline recession is very large. Probably all such variables have not yet been recognized. (2) The variables are often difficult, if not impossible, to quantify in any meaningful way. (3) The relative importance of these variables varies widely over short distances. (4) The relative importance of these variables varies through time as, for example, the slope of the shoreface changes or the position of a shore-connected ridge changes during a storm. (5) Even if all variables are known and quantified, our understanding of shoreline processes is as yet too meager to know precisely how they act and interact in the shore environment.

If one takes the broad view and considers the response of shorelines to a rising sea level to be a problem in barrier island migration, a whole new set of variables and assumptions comes into play. (See the discussion by Everts, this volume.) Some of them are listed and briefly discussed here.

(1) The more gentle the migration surface (lower coastal

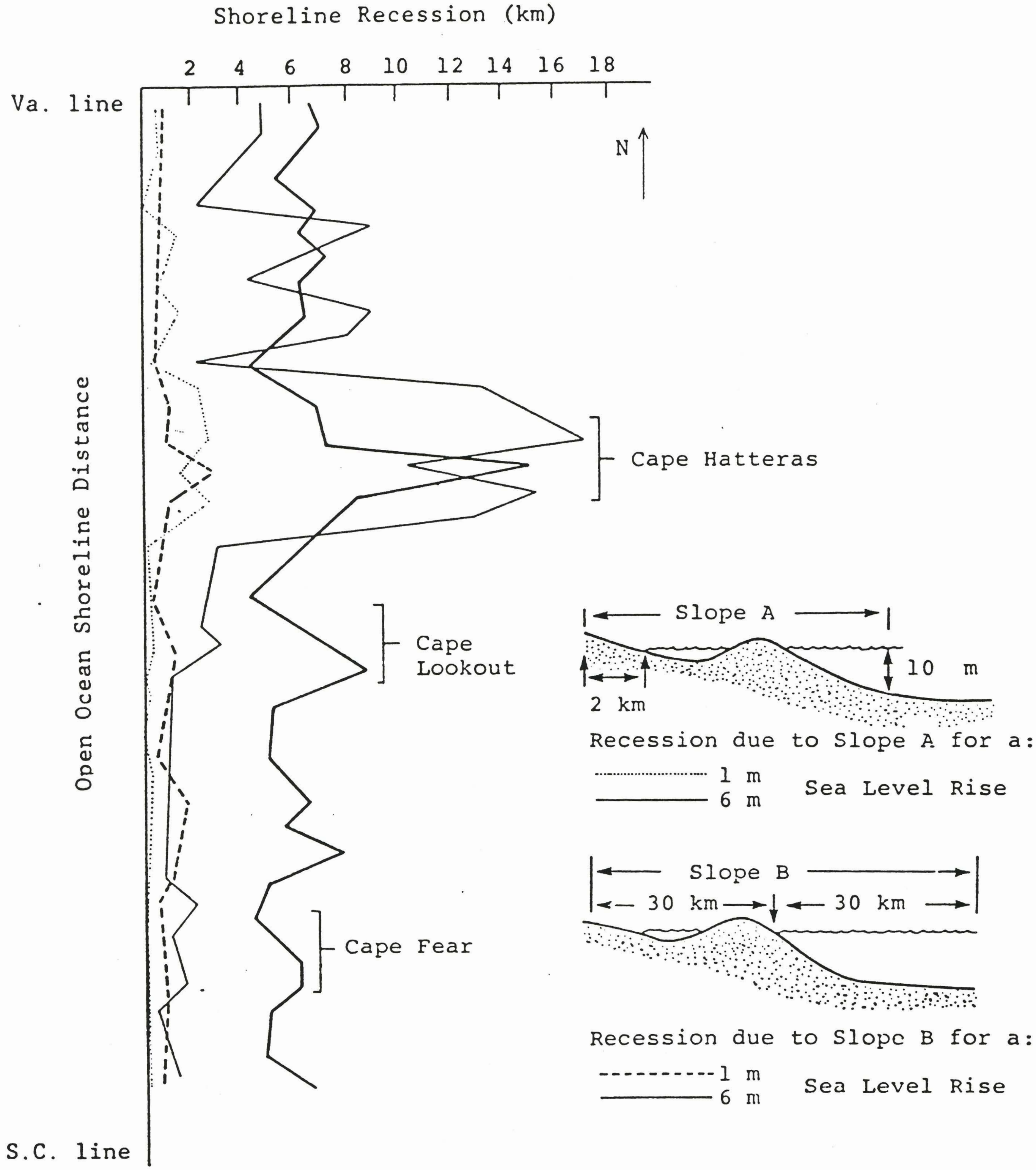

FIG. 6.—Graph showing the amount of shoreline retreat in kilometers due to 1-m and 6-m sea-level rises and assuming that migration surface slope is the only factor in control of recession. *Slopes A and B are defined* in Table 1.

plain slope), the greater the amount of recession from a given rate of sea-level rise.

(2) Prior to island migration, large amounts of sediment may be moved through existing tidal inlets and deposited in lagoons (Everts and others, 1983). Deposition in tidal deltas may represent a major sand sink during periods of extended sea-level stillstand. During island migration in response to a sea-level rise, the flood-tidal delta may be a

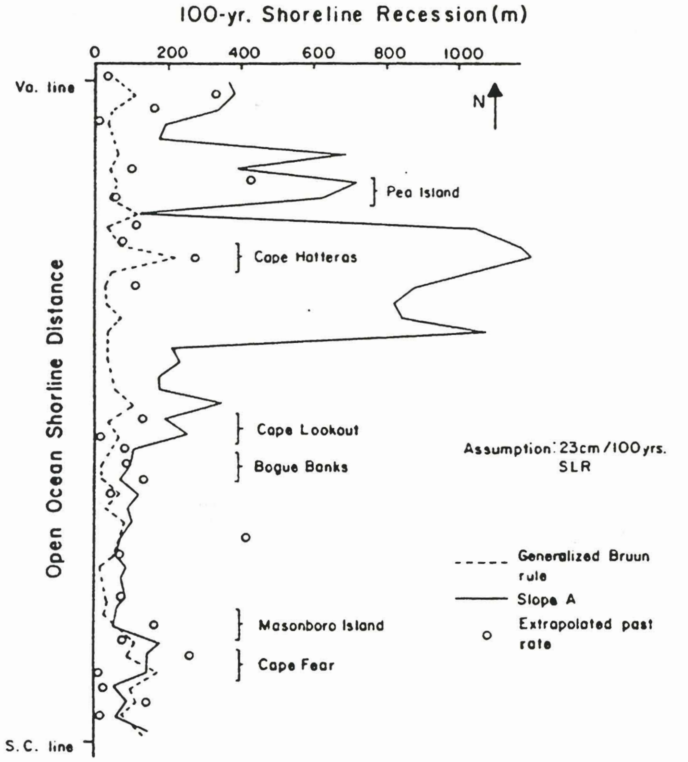

FIG. 7.—Comparison of shoreline recession (in meters) in the next 100 yrs predicted by the Generalized Bruun Rule and by the slope of the migration surface (slope *A*). The dots show recession rates extrapolated over the next 100 yrs from present erosion rates.

major sand source briefly slowing down shoreline recession.

(3) The latest stillstand, lasting possibly as long as 5,000 yrs, has allowed some barrier islands to prograde (Everts, 1984; Heron and others, 1984) and also to increase the volume of their dunes, thereby increasing the supply of sediment potentially available for incorporation into the early stages of the migration process.

(4) Most barrier islands in North Carolina will continue to lose land mass in a rising sea level, through shoreline recession on both sides until efficient overwash begins, allowing island migration to commence. The critical width of an island necessary for efficient overwash to proceed may vary significantly depending upon wave climate.

(5) Accompanying the transition from island thinning to island migration by storm overwash will be a reduction in shoreface slope (Swift, 1976a). Everts (1984) estimates that once the critical width is reached, the rate of shore movement will increase from four to eight times the rate for a thinning island, since essentially all available sand will move through overwash and inlet transport processes, reducing the amount available for shoreface maintenance.

(6) Other things being equal, the steeper the shoreface, the greater the initial rate of migration/recession. Once a more gentle shoreface profile has been reached as a result of the rapid recession of the upper shoreface, there will be a relative increase in the sediment supply, since fair weather-wave onshore transport will be more effective. This, in turn, will reduce the shoreline recession rate, beginning the process of steepening the shoreface again (Moody, 1964).

(7) Finally, barrier island migration models must be able to account for the variations in shoreline erosion caused by the incorporation of shoreface-bypassed sediment, which is not compatible with that needed for preservation of the shoreface slope. Mud is of no value in maintaining a shoreface in all but the gentlest of wave regimes, so a shoreface which is backed by fine-grained sediment can become sand-starved, receding at a much faster rate than when sand is available (Swift, 1976a; Dean and Maurmeyer, 1983; Everts, 1984).

NORTH CAROLINA ISLAND SCENARIOS (100–200 YRS)

The following are four possible short-range scenarios of barrier island response to sea-level rise (Fig. 8). These are additional illustrations of the fact that different types of islands respond at different rates and by different mechanisms. They are also indications of the fact that the various recession models applied in this paper are very simple approximations at best. The scenarios are based on a number of assumptions, most of which have been discussed in the preceding section and are discussed also by other authors in this volume.

Scenario #1: regressive barrier island without back-barrier marsh.—

Bogue Banks, North Carolina, is a 19-km-long, east-west trending barrier island. Except for its central portion, it is a wide beach-ridge island. It is also a regressive island (Heron and others, 1984) and contains a larger volume of sand than any other North Carolina island. The back-barrier lagoon is open, i.e., it is not filled with salt marsh, and fringing marshes are narrow to non-existent. At the present time, both open-ocean and lagoonal shorelines are actively retreating where not stabilized by man.

With continued and accelerating rise in sea level, the island can be expected to continue to thin until the critical width is achieved that will allow overwash-deposited fans to extend into the back-barrier lagoon. At that point, true island migration will commence (Fig. 8A). Shoreline retreat on both sides of the island prior to overwash dominance will be relatively slow because of the large volume of sand stored in the high beach-ridge system of this island. The island-thinning process will also be slowed, because of the lack of mud and the preponderance of sand-size material being supplied to the eroding system by shoreface bypassing.

Once migration begins, it will occur at a slow rate because sand-size material will continue to be furnished through shoreface bypassing. The dominance of coarse material is assumed by the lack of salt marsh on the lagoon side of this island. Island migration and the accompanying initial loss of large volumes of sand across the island can be expected to cause the shoreface to become more gentle. This, in turn, should cause a slight reduction in island migration rates with time (Fig. 8).

Scenario #2: narrow transgressive island with marsh filled lagoon.—

Masonboro Island, North Carolina, is an example of a transgressive island backed by a salt marsh-filled lagoon.

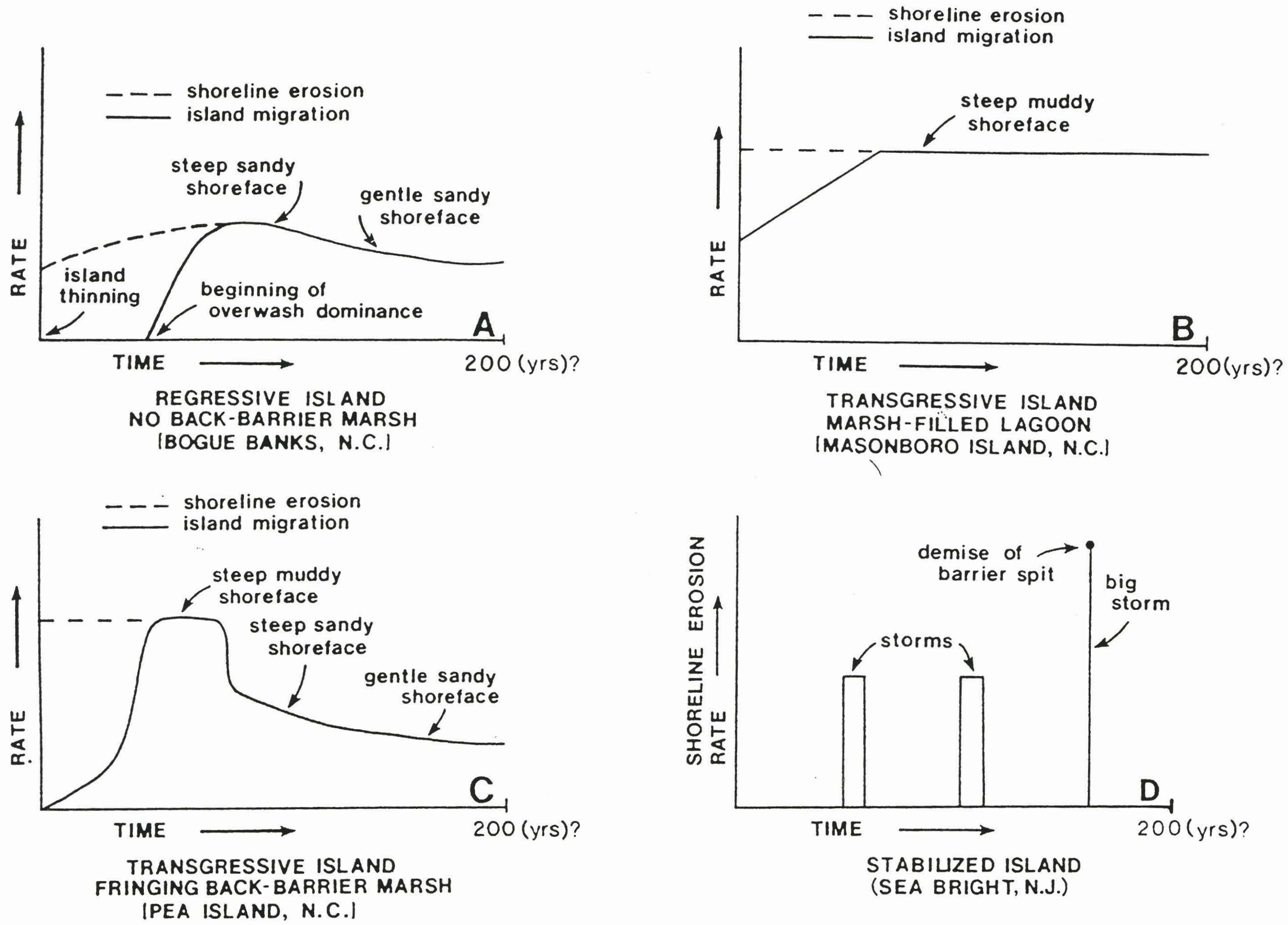

FIG. 8.—Four possible scenarios showing 100- to 200-yr(?) histories of the response to a rising sea level of four different barrier islands.

At present, this 8-mi-long (13 km), narrow, undeveloped low island is subject to frequent overwash, some of which crosses the entire island. In recent years, the island's sand supply has been strongly reduced by the Masonboro Inlet jetties at the north end of the island. In 1986, 800,000 cu yds (611,680 cu m) of sand were pumped onto the island to prevent shoreline retreat from flanking the jetties and exposing adjacent Wrightsville Beach to storm waves approaching from the southeast.

A possible scenario of island migration in a rising sea level is shown in Figure 8B. This scenario assumes that there will be no sand replenishment in the future. Initially, the rate of island migration is moderate because, at present, most overwash remains on the island. At the point of island narrowing, with cross-island overwash becoming a frequent event, rapid and steady migration will ensue. The rate of migration will be enhanced by the large mud component in the sediment arriving via shoreface bypassing.

Scenario #3: narrow island with fringing marsh.—

Pea Island, North Carolina, is a relatively narrow island which is presently thinning by erosion on both front and back sides (Jarrett, 1983). In most locations, the island is backed by a substantial fringing salt marsh. At present, overwash seldom crosses the entire island, even in locations where an artificial dune line, constructed by the National Park Service in the 1930s and 1940s, has been breached.

After initial thinning, rapid island migration should ensue due to the bypassing of muddy sediment on the shoreface. It is assumed (in Fig. 8C) that migration will be sufficiently rapid to prevent re-establishment of the fringing marsh. If this is the case, the rate of migration should abruptly decrease as fine but sandy floor sediments in Pamlico Sound replace the muddier, fringing marsh-lagoon sediments at the bypassing interface on the shoreface.

Scenario #4: the stabilized island.—

A digression from the general scope of this paper, but of considerable practical interest, is the response of a stabilized island to sea-level rise. A good example of such an island is Sea Bright, New Jersey.

Sea Bright is a north-south trending barrier spit, long subjected to heavy development pressure. Both open-ocean and back-barrier shorelines are totally stabilized. Little visible recreational beach remains and the shoreface has steepened considerably. Offshore bar formation or beach flattening can no longer occur in response to storm waves. The future scenario of Sea Bright evolution in an accelerating rise in sea level depends on natural processes as much as on governmental decisions regarding the priority of the funding of future sea wall maintenance and repair.

A possible scenario is shown in Figure 8D. The spit will thin slightly in step-like fashion as the result of sea wall failure in future storms, followed by wall reconstruction. By this time, the barrier spit will resemble a fortress atop a narrow sand ridge with a non-existent system for sand transfer in any direction except offshore. A "very large" storm can be expected to destroy much of the sea wall. After such an event, flattening of the oversteepened shoreface could result in total loss of the barrier spit, since shoreline retreat would be too rapid for island migration to occur.

BARRIER ISLAND SCENARIOS, 1,000–2,000 YRS

Figure 9 shows two scenarios of barrier island response viewed in a longer term sense, perhaps on the order of 1,000–2,000 yrs. In the case of a very rapid rise in sea level of the sort that typifies the steep part of the Holocene sea-level curve, the migration rate of islands, and the recession rate of shorelines, would be identical and both would be a direct function of coastal plain slope (Fig. 9A).

In the case of an accelerating sea level, island migration and shoreline recession both accelerate together. At some point, if acceleration continues, either mainland welding or island overstepping will occur (Fig. 9B). In any event, the island disappears, at least temporarily.

DISCUSSION AND SUMMARY

The generalizations discussed in this paper apply specifically to the North Carolina barrier island shoreline. To some extent the principles developed have application to all barrier islands, but it is important to emphasize that all discussion and data have been concerned with open-ocean unconsolidated shorelines. Little relevance is assumed or expected for non-barrier and especially for rocky shorelines.

Clearly, a very large number of process and product variables is involved in the response of barrier island shorelines to a rising sea level. This fact alone makes the formulation of a universally applicable model for predicting shoreline retreat highly unlikely. What makes the possibility of an accurate model a virtual impossibility is that even if we could measure shoreline process variables in any meaningful way, we could not analyze the data accurately because how the processes interact is not fully understood.

On unconsolidated shorelines, one obvious factor that complicates predictions of shoreline response is the ease by which the shape of the sea floor can change. Typically, the most rapid changes in the shape of the shoreface occur as a result of emplacement of structures such as jetties. Such stabilization structures cause a readjustment of sources and sinks of shoreface sediment which, in turn, profoundly affect nearshore wave patterns and sediment transport. The changes on natural shorelines are perhaps less spectacular and more gradual, but it is clear that a single event such as

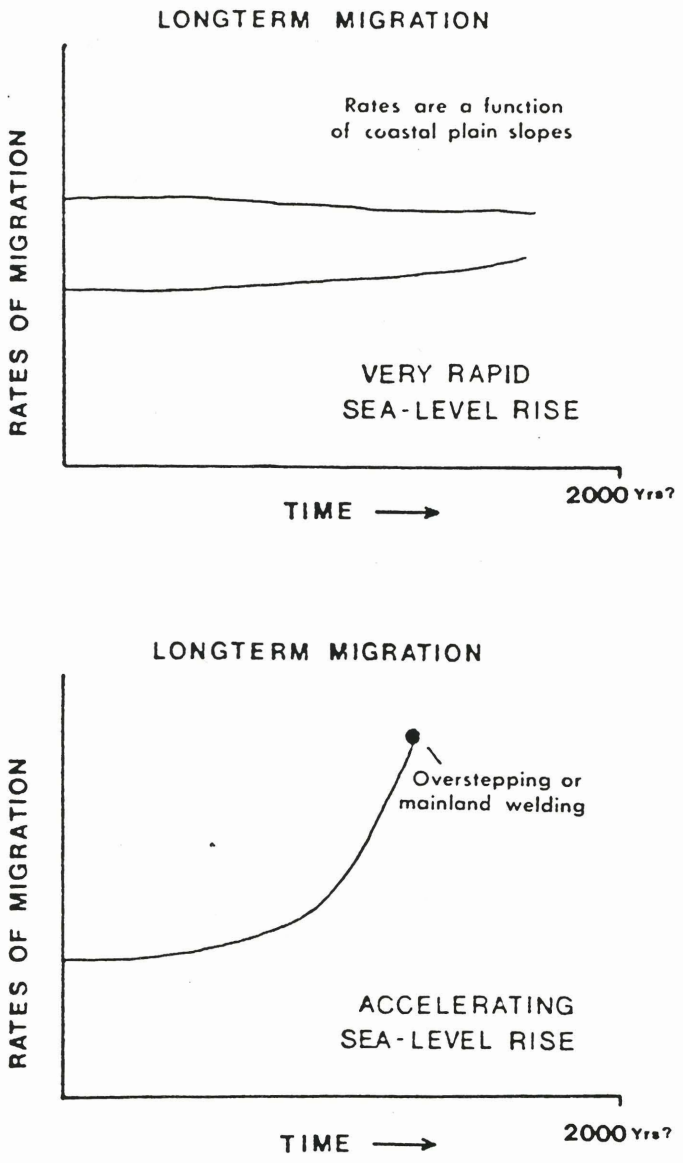

FIG. 9.—Two possible scenarios showing 1,000- to 2,000-yr(?) responses to a rapid sea-level rise and an accelerating sea level.

a storm can cause important and lasting changes (e.g., Moody, 1964).

If the perfect answer is not available, then we should attempt to look for predictive tools that come closest to the truth. If all variables that affect shoreline retreat cannot be measured, we should learn to estimate the most important ones.

How meaningful or accurate are the results of this study, particularly the plots of model-predicted recession and slope-predicted recession? Are the predicted recession rates realistic? First of all, long-range shoreline recession predictions by models cannot be drastically different from slope-predicted rates. There is no question that, if shorelines are retreating up a slope, the geometry of the slope will be a factor in determining rate and distance of translation. Slope is a "real world" factor.

The fact that from Cape Lookout south, the Generalized

Bruun Rule and slope *A* predicted similar recession rates (Fig. 6) affords some degree of mutual credibility for both approaches. Comparison of Generalized Bruun Rule and Slope *A* recession rates with the extrapolation of present rates of erosion, again for the stretch south of Cape Lookout, also shows some similarities. That is, 100-yr extrapolated erosion rates, although highly variable, are mostly within 100 m of the other predictors and sometimes much closer. The numerous factors other than sea-level rise which are involved in control of local erosion rates are undoubtedly responsible for the high variability of extrapolated rates of erosion.

North of Cape Lookout, a different situation prevails. A very large difference in shoreline recession is predicted by migration slope and by the Generalized Bruun model. The principal reason for the high slope-predicted recession value can be construed to be the anomalously large lagoons (Pamlico and Albemarle sounds) behind the Outer Bank barrier chain. Swift (1976a, p. 276) suggests that the Outer Banks are a "near stillstand coastal sector with effect of rising sea level compensated by sand surplus associated with coastwise sand flux." There is no field evidence, as yet, to support or deny Swift's contention, but if it is true, the stillstand of the shoreline is certainly a temporary one. The presumed surplus of sand absorbed by the shoreface has held the Outer Bank's shoreline in place sufficiently long for this shoreline position to be out of equilibrium with the present level of the sea. As discussed earlier, the difference in predicted recession rates may also be a measure of shoreline stability or vulnerability to future sea-level changes.

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