# GLOBAL WARMING AND COASTAL EROSION

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**Abstract.** One of the most certain consequences of global warming is an increase of global (eustatic) sea level. The resulting inundation from rising seas will heavily impact low-lying areas; at least 100 million persons live within one meter of mean sea level and are at increased risk in the coming decades. The very existence of some island states and deltaic coasts is threatened by sea level rise. An additional threat affecting some of the most heavily developed and economically valuable real estate will come from an exacerbation of sandy beach erosion. As the beach is lost, fixed structures nearby are increasingly exposed to the direct impact of storm waves, and will ultimately be damaged or destroyed unless expensive protective measures are taken. It has long been speculated that the underlying rate of long-term sandy beach erosion is *two orders of magnitude greater* than the rate of rise of sea level, so that any significant increase of sea level has dire consequences for coastal inhabitants. We present in this paper an analytical treatment that indicates there is a highly multiplicative association between long-term sandy beach erosion and sea level rise, and use a large and consistent data base of shoreline position field data to show that there is reasonable quantitative agreement with observations of 19th and 20th century sea levels and coastal erosion. This result means that the already-severe coastal erosion problems witnessed in the 20th century will be exacerbated in the 21st century under plausible global warming scenarios.

## 1. Introduction

Coastal erosion is a global problem; at least 70% of sandy beaches around the world are recessional (Bird, 1985). Domestically, approximately 86% of U.S. East Coast barrier beaches (excluding evolving spit areas) have experienced erosion during the past 100 years (Galgano et al., 2004). Widespread erosion is also well documented in California (Moore et al., 1999) and in the Gulf of Mexico (Morton and McKenna, 1999). There must be a worldwide cause for such ubiquitous beach erosion. The three possible candidates are sea level rise (SLR), change of storm climate, and human interference. But there is no indication of a significant increase in storminess in this century (Zhang et al., 1997; WASA Group, 1998; Zhang et al., 2000), and human interference is neither worldwide in extent nor uniform regionally. Therefore, SLR remains as the plausible candidate (Leatherman, 1991), and determining whether or not the rate of global SLR is increasing is of the utmost importance. However, the rate of 20th century global sea level (GSL) rise is the subject of much controversy; the Third Assessment Report of the Intergovernmen-

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tal Panel on Climate Change (IPCC; see www.ipcc.ch) was unable to provide more than a broad range (about 1–2 mm per year) for 20th century GSL rise, and the extreme bounds given for the total 21st century rise are 10–90 cm. If the lower bound is correct, little effect will be felt. If the upper bound occurs, the results will be calamitous, since more than 100 million persons today live within one meter of mean sea level. The economic scale involved is equally vast.

When discussing impacts of sea level rise, it is very important to distinguish inundation from erosion. Concerning the former, as sea level rises, the high water line will migrate landward in proportion to the slope of the coastal area. In some areas the slope is very gradual, and the impact from sea level rise can be severe. For example, for low-lying regions such as salt marshes, an increase in the rate of sea level rise much beyond a few mm per year can result in marsh destruction because the plants there cannot respond rapidly enough to the increasing water level and drown.

Erosion of sandy beaches is an entirely different physical process from inundation. It involves a redistribution of sand from the beach face to offshore. It is most commonly realized during coastal storms. These storms are accompanied by a temporary increase of local sea level (the storm-generated surge above the normal astronomical tide) so that energetic storm waves are able to attack higher elevations of the beach and dune. Sediment there is extracted and put into suspension by the waves and carried offshore. Much of the sand is returned to the beach after the storm by long-period swell waves during normal water level. This phenomenon suggests that water level plays an important role in beach erosion; a quantitative demonstration of the relationship of storm erosion magnitude on the U.S. East Coast from nor'easters and their accompanying storm tide amplitude and duration has been given by Zhang et al. (2001). The issue for global warming scenarios concerning erosion is related, but takes this form – what is the effect on long-term erosion if water levels are *secularly increasing*, rather than only temporarily as is the case of coastal storms? The crucial role in erosion played by elevated water level during coastal storms clearly makes it plausible that long-term enduring increases of sea level will monotonically increase long-term erosion rates.

## 2. Beach Erosion and Relative Sea Level Rise (RSL)

### 2.1. THE 2-DIMENSIONAL SANDY BEACH EROSION MODEL

Bruun (1954, 1962) first constructed a simple 2-dimensional (cross-shore) model based on the equilibrium beach profile concept to estimate the erosion of sandy beaches in response to rising sea level. His model is based on the following assumptions:

1. The active beach profile perpendicular to the shoreline tends toward an equilibrium form for a given wave regime, and extends out to the so-called depth

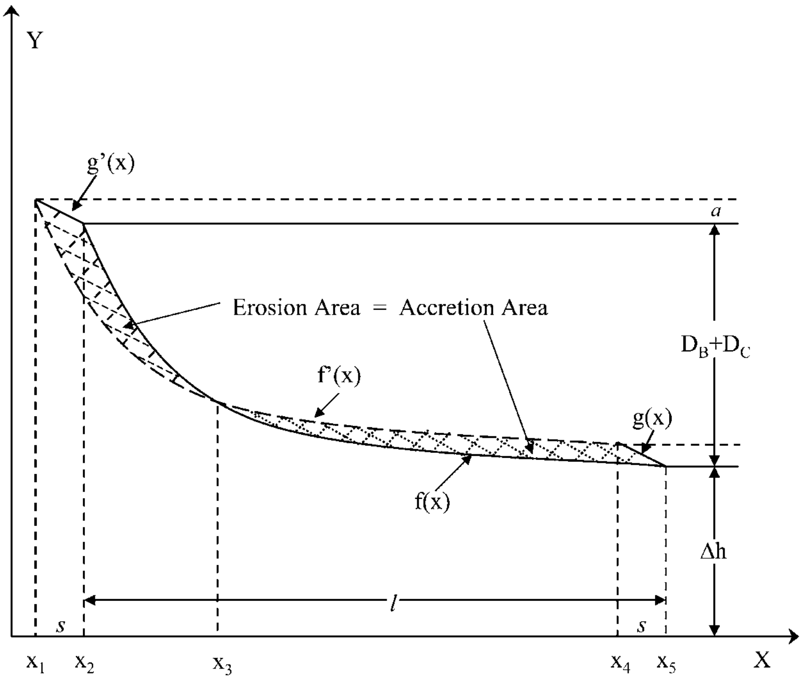


*Figure 1.* Active cross-shore beach profile geometry for derivation of the two-dimensional Bruun rule of beach erosion.

of closure (DOC). The DOC is the water depth (typically 10 m) at which ocean surface waves no longer significantly transport bottom sediments. The equilibrium active beach profile is thus defined as an idealized statistical average profile over seasonal and storm-induced fluctuations, and includes an underwater part that makes up most of the profile.

2. If other conditions remain unchanged and sea level rises, the active beach profile will achieve equilibrium with the new sea level by shifting landward and upward. This will result in erosion of the upper shoreface, with sediment deposition on the lower (mostly underwater) part of the profile (Figure 1).
3. Sediment eroded from the upper beach is equal to that sediment deposited on the nearshore bottom. In addition, there is no net sediment exchange between the active beach profile and the outer shoreface (i.e., beyond the DOC).
4. The increase in elevation of the nearshore bottom resulting from deposition of sediments from the beach face and dune is equal to the rise of sea level.

Given these conditions, a two-dimensional formula for shoreline movement due to a rise of sea level is given by inspection of Figure 1:

$$s(D_B + D_C) = al \text{ or } a = \frac{(D_B + D_C)}{l} s = (\text{active profile slope}) \cdot s\,, \qquad (1)$$

where $s$ is shoreline recession, $D_B$ is the elevation of the shore above sea level, $D_C$ is the depth of closure, $a$ is the rise of sea level, and $l$ is distance from the shore to the 'closure point'. The active profile slope, $(D_B + D_C)/l$, of the total beach profile (which includes the active portion that is underwater) is about 0.01–0.02 at most sandy coasts. The Bruun equation thus produces $s/a = 50$ to 100 in terms of the range of average slopes. This ratio range of $s/a$ is commonly used as a 'rule of thumb' to estimate shoreline retreat due to sea level rise (SCOR, 1991).

Bruun did not present a rigorous mathematical derivation of Equation (1) in his papers (Bruun, 1962, 1983), which has caused some confusion in the coastal research community. For example, Rosen (1978) argued that $l$ in Equation (1) should be replaced by the distance from the cross point ($x_3$ in Figure 1) to the closure depth. Allison and Schwartz (1981) gave another analysis of the Bruun model, and argued that it only holds if beach profiles follow certain curves. Dean and Maurmeyer (1983) derived the Bruun model by balancing the volume of sand eroded by shoreline retreat to that deposited by elevating the active profile. We present here an alternative mathematical derivation of Equation (1), and show that even though very simple, the Bruun model has considerable generality.

Assuming the initial and subsequent beach profiles in response to sea level rise are $f(x)$ and $f'(x)$ (see Figure 1), an equation can be written according to statement (3), above:

$$\int_{x_1}^{x_2} [g'(x) - f'(x)dx + \int_{x_2}^{x_3} [f(x) - f'(x)]dx = \\ = \int_{x_3}^{x_4} [f'(x) - f(x)]dx + \int_{x_4}^{x_5} [g(x) - f(x)]dx \,. \tag{2}$$

In terms of statement 1, 2 and 4, we have

$$f'(x) = f(x+s) + a \,. \tag{3}$$

Assuming that $g(x)$ and $g'(x)$ follow the same function, it follows that

$$g'(x) = g(x+l) + (D_B + D_C). \tag{4}$$

Substituting Equations (3) and (4) into Equation (2), we have

$$\int_{x_1}^{x_2} g(x+l)dx + \int_{x_2}^{x_5} f(x)dx + (D_B + D_C)(x_2 - x_1) = \\ = \int_{x_1}^{x_4} f(x+s)dx + \int_{x_4}^{x_5} g(x)dx + a(x_4 - x_1). \tag{5}$$

Considering $x_4 - x_1 = x_5 - x_2 = l$ and $x_1 - x_1 = x_5 - x_4 = s$, finally we obtain a result identical to that given in Equation (1) from very simple arguments:

$$(D_B + D_C) = al \,. \tag{6}$$

This derivation shows that the conjecture by Bruun is not dependent on the shape of the profile, nor the point of intersection of the new and old profile, nor the position of or seaward slope angle of the offshore bar.

There is one assumption in the derivation of Equation (6) that does not come from the statements 1–4 of the Bruun rule. We assumed that $g(x)$ and $g'(x)$ follow the same function, but this assumption might not be true. However, even in the extreme condition

$$\begin{cases} g(x) &= \Delta h + a \\ g'(x) &= \Delta h + (D_B + D_C) \end{cases} \tag{7}$$

(i.e., the ramps are vertical, a highly unlikely outcome), the maximum error due to the difference of $g'(x)$ and $g(x)$ is equal to $sa$. This area is insignificant compared to $(D_B + D_C)s$ when $a/(D_B + D_C) \ll 1$. For example, sea level rose 20–40 cm (Douglas, 1991) in the past century on the U.S. East Coast, and the value there of $(D_B + D_C)$ is normally 8–12 m (Bruun, 1983), giving $sa/(D_B + D_C)s \approx$ 1/20–1/60. Therefore, it is appropriate mathematically to use the Bruun model to compute the underlying long-term beach response to sea level rise when the rise is small compared to the active beach profile height $(D_B + D_C)$.

### 2.2. METHODS TO EXAMINE BEACH CHANGES IN RESPONSE TO SEA LEVEL RISE

There are two basic ways to test the Bruun rule: (1) comparing beach profiles before and after water level rise (Hands, 1983; Schwartz, 1965, 1967; Mimura and Nobuoka, 1995) and (2) comparing long-term shoreline change rates with sea level rise rates spatially to test whether sea level rise is correlated with beach erosion (Rosen, 1978). In the first case, it is required that there is no net lateral (longshore) sediment transport because the Bruun formula is for two-dimensional cross-shore beach profile change in response to sea level rise. Schwartz (1965, 1967) verified Bruun's hypothesis under controlled conditions in a small wave tank, and Hands (1980, 1983) further substantiated the potential of the Bruun model using Lake Michigan as a full-scale natural laboratory using the first method. It is not surprising that the Bruun formula is applicable in wave tanks and the U.S. Great Lakes because the model is a reasonable first approximation to the actual physical situation in which no significant longshore sediment transport exits. Bruun's result came to be called the *Bruun rule* later in the literature, and has been used extensively to predict the impact of sea level rise on beaches (Leatherman, 1991; Nicholls et al., 1995).

Results of the application of the Bruun rule to open-ocean coasts are conflicting. Some work seems to verify it (Mimura and Nobuoka, 1995), while others allege that the Bruun rule does not work (Pilkey and Davis, 1987). A review of the Bruun rule and other extended models concerning the response of beaches to sea level rise has been presented by SCOR (1991). There is considerable controversy and debate in the literature about the Bruun rule (SCOR, 1991; Leatherman et al., 2000a,b; Pilkey et al., 2000). This is not surprising because much more complicated conditions exist in open-ocean coasts than those in wave tanks and the Great Lakes.

Open ocean beaches at *specific sites* exhibit complex behavior (for example, rapid erosion downdrift of tidal inlets, or from antecedent geological factors) that departs from a simple linear relation of shoreline position to sea level. Thus the model cannot be used to predict future shoreline position for an arbitrarily selected beach location. Nevertheless, the model does reveal many interesting facets of the larger question, which is how large regions of coastline comprised of sandy beaches can be expected *on average* to respond to increases of sea level that will result from global warming. In essence, we will examine whether the Bruun rule is useful to investigate what will happen in an average sense to sandy beaches, rather than to predict the behavior at any particular beachfront property. This approach is very much in the spirit of using approximate climate models to determine the *sensitivity* of the overall climate system to variations of one parameter or another. The main objective of this study is to test if the Bruun rule shows a relation to the rates of sea level rise and sandy beach erosion along the U.S. East Coast using long-term historical shoreline position and sea level data.

There are several possible problems when historical shoreline data are used to test the Bruun rule, which involve: (1) using poor quality data (Dean, 1990); (2) using short-term data (Galvin, 1983); and (3) failing to remove or minimize the influence of inlets and human interference on sediment supply (Pilkey and Davis, 1987). For example, Dean (1990) utilized available data on a state-wide basis to compare shoreline change rates to average sea level rise rates. His results showed considerable scatter and no apparent relationship to sea level rise. In fact, New York and Delaware beaches were mistakenly thought to be accretional on average because a poor quality data set from May et al. (1983) was utilized; these areas are clearly erosional on average (Zhang, 1998). There are two problems with the May et al. (1983) historical shoreline change database. The data were collected from various sources, and there was no quality control nor error estimation for these heterogeneous data. The other problem involves employing a low accuracy technique of using uncorrected aerial photography to determine shoreline changes (Leatherman, 1983). These problems can be addressed by selecting study sites where long-term and high quality historical shoreline position data exist.

The U.S. East Coast is a nearly ideal location for testing the Bruun rule since both shoreline position and sea level histories are available there for the last 100+ years. Sea level rose by varying amounts ($\approx$20–40 cm) along the U.S. East Coast during the 20th century. The variation observed is due primarily to on-going glacial isostatic adjustment (GIA) (Peltier, 2001). With the disappearance of the great ice sheets that advanced as far south as Long Island about 21,000 years ago, the elevated forebulge region *adjacent* to the ice load adjusted by sinking while the formerly ice covered region rose. GIA occurs on a very large scale, and continues today even though the ice was gone by 5000–6000 years BP. This can

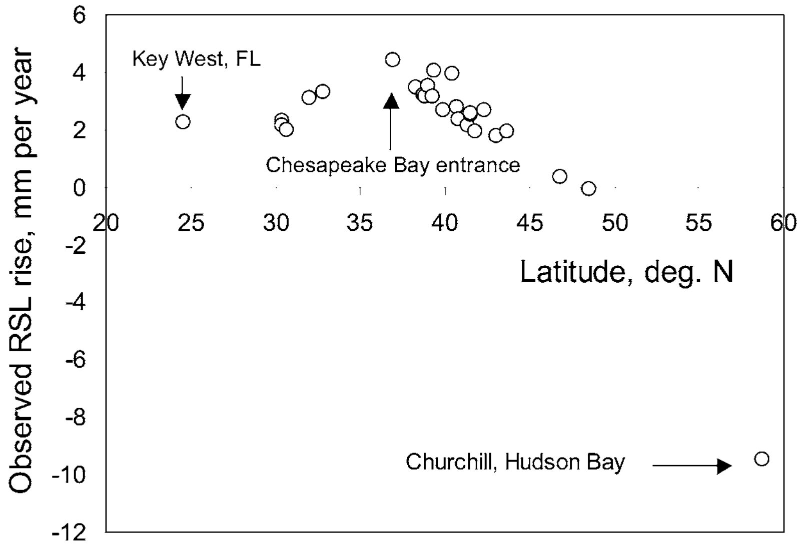


*Figure 2.* Relative sea level rise rates from Hudson Bay, Canada to Key West, Florida.

clearly be seen in Figure 2. What is shown are 20th century trends of sea level (see www.pol.ac.uk/psmsl) from long tide gauge records approximately (±10 deg) along a meridian from Hudson Bay (the center of the great Laurentide ice sheet load 21,000 yrs BP) to Key West, Florida. Note that sea level is still *falling* today about 10 mm per year at the Churchill tide gauge site on Hudson Bay due to the ongoing viscoelastic rebound. Coming south, sea level rise increases to a maximum of about 4 mm per year in the mid-Atlantic, and then recedes to near a background value of about 2 mm per year at Key West, Florida. This large geographic scale of sea level variation and the excellent coverage of the U.S. East Coast by long tide gauge records means that it is possible to compute by interpolation accurate values of relative sea level rise for beaches whose erosion rates are known.

### 2.3. SHORELINE POSITION DATA SOURCES

Existing shoreline position data available for this investigation consist of National Ocean Survey (NOS) T-sheets, aerial photographs, and kinematic GPS surveys. The earliest data in this collection reaches back to the mid-19th century. The high water line (HWL) is used as the shoreline indicator in this study because it can be identified in the field as a dry/wet boundary, interpreted on aerial photographs, and is the shoreline indicator used in historical NOS T-sheets.

Reliable vertical aerial photography only dates back to the early 1940s, but NOS T-sheets extend the record to the mid 1800s. The available digitized shoreline position data covers the open-ocean coasts from Long Island, New York to South Carolina except for the southern part of North Carolina. GPS-surveyed shoreline positions in 1993 and 1997 along the south shore of Long Island, New York, Delaware, and North Carolina are also incorporated into the existing data set. This data set of field and aerial photography measurements has been extensively evaluated for suitability for long-term shoreline position analysis by Crowell et al. (1991), Galgano (1998), Zhang (1998), Galgano et al. (1998), Douglas and Crowell (2000) and others, and the data quality has been found to be accurate enough to be useful for investigating the underlying trend of shoreline position.

### 2.4. THE OBSERVED RELATIONSHIP BETWEEN SEA LEVEL RISE AND BEACH EROSION

The Bruun rule, as noted earlier, has been verified experimentally by comparing beach profile positions to water levels in wave tanks and lakes. However, for open-ocean beaches, conclusive tests are much more difficult because the model is two dimensional, which describes beach erosion due to sea level rise only if other factors hold constant. Unfortunately, other influencing factors are spatially and temporally variable in most natural conditions. Further, shoreline changes induced by variability of sediment supply can be much larger than those resulting from sea level rise on some coasts. Thus the real oceanic beach situation can range widely from the ideal situation of wave tanks or lakes.

The key to testing the Bruun rule along open-ocean coasts is to remove or minimize regions of shoreline change induced by gradients in longshore sediment transport and variations in the active beach profile slope. To do so, we should seek shoreline sections where no longshore sediment transport occurs, or more realistically, where longshore sediment transport is in equilibrium (i.e., there is no gradient). However, it is difficult to find many such beaches. The solution is to compare sea level rise rates with shoreline change rates for geomorphic units influenced by similar factors *except* for the rate of sea level rise. These units are the coastal compartments recognized by Fisher (1967). He divided the U.S. mid-Atlantic coast into four coastal compartments displaying similar geomorphic behavior. The sediment exchange between these compartments is negligible because they are separated from each other by deep river entrances and bays. The four compartments include Long Island, New York, New Jersey, Delmarva (Delaware, Maryland, and Virginia), and North Carolina (Figure 3). South Carolina exhibits similar behavior, and therefore was included in our study as a fifth coastal compartment.

Each coastal compartment consists of four distinct units: (1) terminal north spit, (2) low, eroding headland, (3) long barrier islands with only a few inlets backed by open lagoons, and (4) short-stubby barrier islands with marsh-filled embayments separated by many inlets (Stauble, 1989; Leatherman, 1993). For example, Cape Henlopen is the north spit of the Delmarva coastal compartment. The shore section between Rehoboth Beach and Fenwick Island constitutes the eroding headland which provides the sediment source for the barrier islands to the south. The long barrier unit is composed of Fenwick Island (actually a sand spit) to Ocean City Inlet and Assateague Island. Finally, a barrier island chain with more than ten short

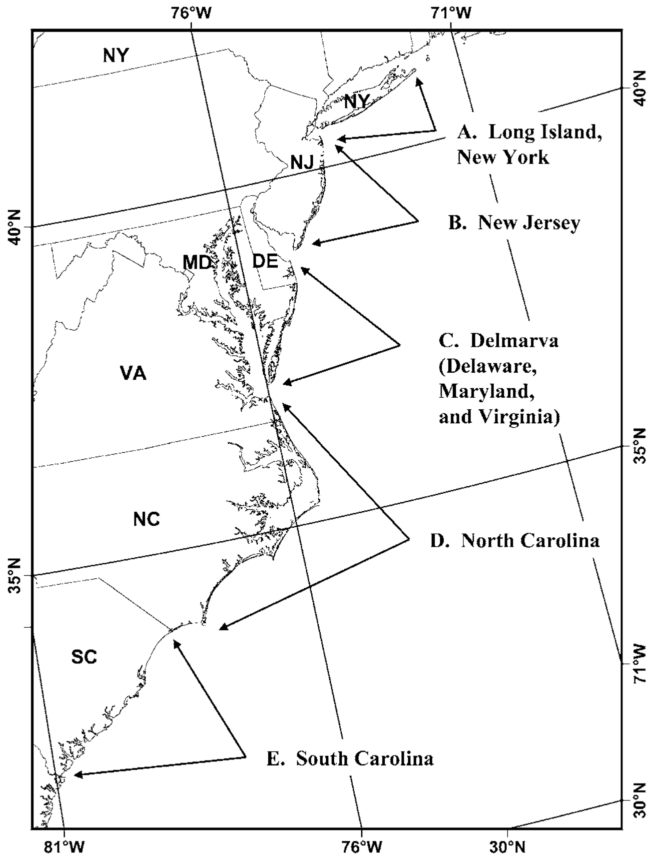


*Figure 3.* Location of coastal compartments, mid-Atlantic bight, U.S.A. The South Carolina unit is not a defined coastal compartment, but the long arcuate shore spanning the northern part served our purpose for this analysis.

members (the Virginia barrier islands) forms the southern unit of the Delmarva compartment (Figure 4). The southernmost portions of a compartment, with their large number of inlets, are not usable to study the beach response to sea level rise because the influence on sand supply of the multitude of inlets obscures the underlying erosion rates.

We have seen (Figure 2) that relative sea level trends change along the U.S. East Coast on a large geographic scale because of glacial isostatic adjustment ongoing since the last deglaciation that began about 21,000 years ago. Sea level rise is thus consistent on a scale of several hundred kilometers, and the value of sea level rise at a location on the East Coast can be interpolated accurately from Figure 2. This enables us to compare observed beach erosion rates to the local rate of SLR continuously along the barrier beaches and determine if there is a relationship. But the effects of longshore sediment transport, active profile slopes (see Equation (1)), and other local factors within a coastal compartment can result in shoreline changes

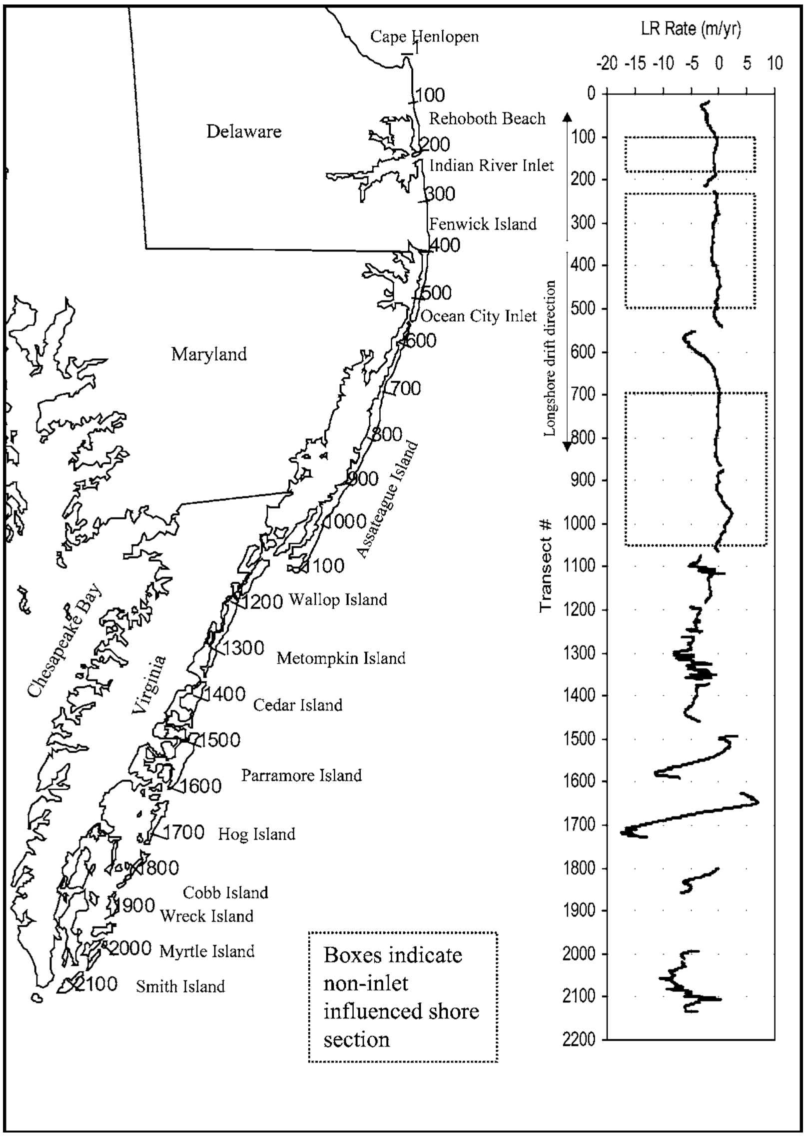


*Figure 4.* Long-term shoreline change rates at Delmarva. Shoreline change rate at each transect at 100 m interval is determined by linear regression (excluding storm-influenced shoreline positions). Note that large shoreline change rates occur near inlet-influenced areas, which therefore cannot be used to examine the relationship between sea level rise and beach erosion.

larger or smaller than the underlying ratio between sea level rise and beach erosion predicted by the Bruun rule. Shoreline segments influenced by tidal inlets and coastal engineering projects (such as seawalls or beach replenishment) obscure the relation of sea level rise to beach erosion because such segments depart radically from the assumptions of the model. Inlets play the dominant role in determining shoreline changes wherever these breaks in the littoral drift system are present. Opening, closing, and migration of inlets can affect many kilometers of updrift and downdrift beaches by changing longshore sediment supply. More than 65% of the shoreline along the U.S. East Coast is influenced by inlets (Galgano et al., 2004).

As an example of an inlet-influenced shoreline section, Figure 5 shows the downdrift arc of erosion and updrift accretion fillet at the Indian River Inlet on the Atlantic coast of Delaware. The arc of erosion is obviously much longer than the accretionary fillet. This situation is true for most inlets because ebb and flood tidal deltas trap a large volume of sediment. Far more sediment than that deposited at the updrift side is eroded downdrift of an inlet in order to satisfy the longshore current. It is clear that shoreline change (erosion and accretion) does not average out at inlet areas, although the volume of deposited sediment at the updrift side in combination with the sediment held in flood and ebb tidal deltas may still be equal to the volume of sediment lost at the downdrift side. Thus, the greater length of the erosion arc compared to the accretion zone biases the average shoreline change rate in a compartment toward erosion, and renders meaningless a comparison of sea level rise to a compartment-wide average erosion rate if inlet-influenced shorelines are included. Therefore, the erosion and accretion zones generated by inlets have to be excluded from the calculation of average shoreline change rates. The prior study which relied on state-wide shoreline change data failed to find any correlation with sea level rise (Dean, 1990).

Lateral growth of spits and coastal engineering projects can also alter shoreline change processes. These alterations, whose effect is highly variable, create discontinuities in the historical shoreline position record that mask underlying long-term behavior. To eliminate the bias induced by inlets, spits, and coastal engineering projects, only the shoreline segments not influenced by these factors in each coastal compartment are used in this paper to estimate the average long-term erosion rates.

Shoreline segments influenced by inlets were identified and removed by comparing spatial variations of shoreline trends before and after inlet opening or stabilization (Galgano et al., 2004). This method is very straightforward: 'Shorelines altered by inlets will deviate from previous long-term trends, but will return to their long-term trend at a point beyond the influence of the inlet' (Galgano, 1998). The shoreline segments influenced by coastal engineering projects and lateral spits can also be identified using a similar methodology.

The shoreline change rates used for this study were computed at a spatial interval of 100 meters in ArcView using linear regression (Zhang, 1998). The detailed procedure to compute shoreline change rates can be found in Leatherman and Clow (1983). Crowell et al. (1997) and Douglas and Crowell (2000) have demonstrated

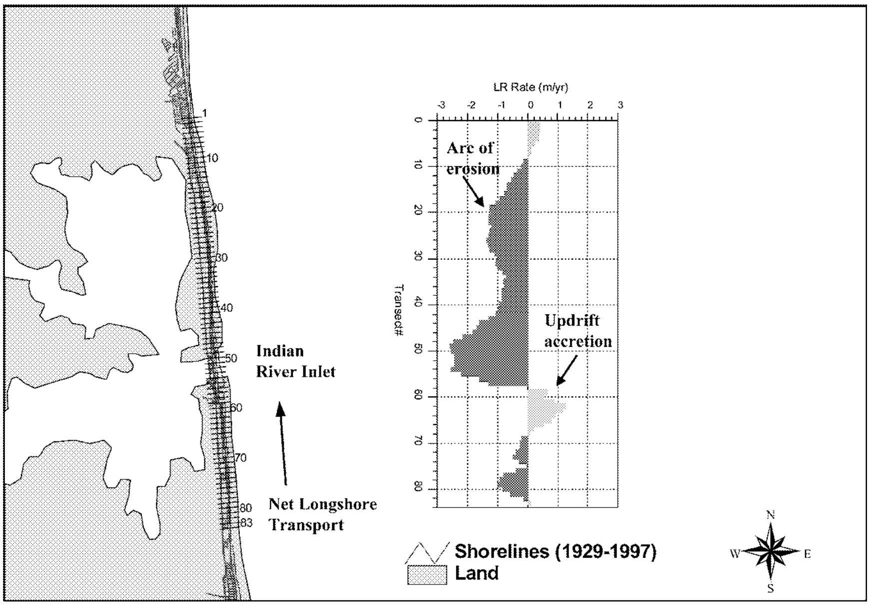


*Figure 5.* Shoreline change rates near Indian River Inlet on the Delaware coast. Shoreline change rates are computed every 200 m using the linear regression (LR) method. Note the length of erosion zone on downdrift side is about five times that of updrift shoreline accretion. Therefore, shoreline changes induced by inlet activities always bias average shoreline change rates greatly toward erosion.

that linear regression is the best estimator of long-term shoreline change rates which we utilized herein. However, arriving at the best estimate of the long-term shoreline change rate is complicated by the existence of seasonal and interannual variations of shoreline position caused by storms that are not modeled by linear regression. Storms can result in severe beach erosion with subsequent recovery lasting in some cases several years to as much as a decade (Thom and Hall, 1991; Morton et al., 1994; Douglas and Crowell, 2000). Thus post-storm shorelines deviate considerably from the long-term shoreline trend. Including these storm-influenced positions in the shoreline change data set distorts the estimate of the long-term trend, especially when shoreline position records are less than about 80 years long (Galgano et al., 1998). For this reason all shoreline positions influenced by large storms were excluded from linear regression analyses performed in this study.

In addition to eliminating shoreline change rates for areas influenced by inlets and coastal engineering projects, the well-known erosion ‘hot spot’ at Sandbridge, Virginia was removed in the computation of average shoreline change rate because large quantities of sand are lost offshore there (Kimball and Wright, 1989) due to focusing of wave energy.

The percentage of shoreline sections not influenced by inlet and coastal engineering projects are presented in Table I. These shoreline sections constitute about

Table I
Percentage of shore sections not influenced by inlets and coastal engineering projects

| Location | Length (km) | (Length of sections not influenced by inlets and coastal engineering projects)/(length of entire compartment) | (Length of erosional areas not influenced by inlets and coastal engineering projects)/(length of entire compartment) |
|---|---|---|---|
| Long Island, NY | 134 | 53% | 34% |
| New Jersey | 177 | 18% | 13% |
| Delmarva | 176 | 39% | 29% |
| North Carolina | 145 | 30% | 24% |
| South Carolina | 265 | 29% | 25% |
| All Areas | 898 | 32% | 24% |

32% of the entire study area, of which 75% and 25% are erosional and accretional, respectively. The local effects of accretion and erosion caused by longshore sediment transport are averaged out by using tens of kilometers of shoreline in rate computations because there are no sediment sinks, such as flood and ebb deltas. The local geological effects are also minimized by rate averaging at spatially large scales. Therefore, average change rates of shoreline sections not influenced by inlets and coastal engineering projects on a compartment basis are used to test the Bruun rule.

The rates of sea level rise for each shoreline sector were interpolated based on the trends from tide gauges along the coast (Figure 2). The final results were insensitive to the interpolation method employed. We chose to use the most accurate method, which was to determine the latitude for each shoreline transect and obtain an estimate of sea level trend for it from trends determined by tide gauges. An interpolating quadratic polynomial was obtained from a least squares fit to the sea level trends from the coastal tide gauges along the compartments having a record length of $\geq$60 years. Finally, the erosion rate for each transect was divided by its rate of sea level rise, and the average rate of erosion divided by rate of sea level rise was computed for each compartment. We find that the ratio of shoreline change rate, $\mathbf{r}$, to the rate of SLR, $\mathbf{s}$, varies from about 50 to 120, with an average value of 78 for the five coastal compartments (Table II). This rate is in good agreement to the 'rule of thumb' for the Bruun rule. Thus the rate of shore erosion is approximately two orders of magnitude greater than the rate of sea level rise, and Bruun rule is validated. But the variability of the results between compartments is large and needs consideration.

We first note that the ratio of erosion to SLR rates for Long Island, New York and Delmarva (e.g., Delaware, Maryland, and Virginia) are relatively low at 50

Table II

Ratios of shoreline change rates, **r**, to rates of SLR, **s**, for each coastal compartment. Compartment averages are shown, but the rate of RSL rise for each transect was computed by interpolation from Figure 2 for the actual latitude of the transect. Negative sign of shoreline change rate indicates that beaches have experienced erosion

| Compartment | Long Island, New York | New Jersey | Delmarva | North Carolina | South Carolina |
|---|---|---|---|---|---|
| Average latitude (degrees) | 40.86 | 39.92 | 38.30 | 35.85 | 33.76 |
| Average RSL rise rate (a, mm/yr) | 2.62 | 3.17 | 3.83 | 4.16 | 3.81 |
| Average shoreline change rate (s, m/yr) | –0.13 | –0.38 | –0.20 | –0.32 | –0.34 |
| s/a | 50 | 120 | 52 | 77 | 90 |
| Average s/a, all compartments | 78 | | | | |

and 52, respectively, compared to the other compartment results. There is evidence in both cases that beach replenishment is occurring naturally. On-going erosion of the Montauk bluffs at the eastern end of Long Island is providing sediments to downdrift (westward) areas. Also, there is strong scientific evidence that relict glacial shoreface sand is being fed onto the beach (Schwab et al., 2000). In the case of Delmarva, there is a relict Pleistocene barrier in Delaware that supplies sand to the littoral system (Kraft, 1971).

Leatherman et al. (2000b) demonstrated that the shoreline change rate is about 150 times that of the sea level change rate. That result was obtained by removing the acretional sections from shorelines not influenced by inlets and coastal engineering projects. Such accretion can result from local variations in longshore sediment transport, sand feed from offshore, or the influence of local geological factors. Therefore, localized erosion effects caused by longshore sediment transport are not averaged out by removing all accretional sections, and the ratio can be viewed as the upper bound of the ratio of shoreline change rate versus the rate of sea level rise. The average ratio of 78 derived herein can be viewed as the lower bound of the ratio because some shoreline sections may receive a sand feed from offshore (Kraft, 1971; Schwab et al., 2000).

## 3. Discussion and Conclusions

The agreement between the simple Bruun rule and observed erosion trends along the U.S. East Coast suggests that sea level rise induces beach erosion, and further that the rate of erosion is about two orders of magnitude greater than the rate of sea level rise. Of course, this does not mean that sea level rise causes long-term erosion directly; there is too little energy associated with it. In our view, rising sea levels act as an enabler of erosion because higher water levels allow waves to act further up the beach profile and move sediment seaward. The Bruun rule describes how beach profiles respond to sea level rise if other conditions (e.g., sediment supply) remain unchanged, and this process will occur as long as there is a rise in sea level.

Some may find it surprising that we have not considered in this analysis the possibility of storm activity as an alternative to sea level rise as a determiner of barrier beach erosion rates. But there is substantial evidence that the effect of storms on shoreline position is episodic, rather than secular. Morton (1994) in his study of beach erosion and recovery at Galveston Island, Texas due to Hurricane Alicia found that recovery after the storm was proportional to the long-term rate of erosion, and approached 100% after about 10 years for those areas that were stable before the storm. Galgano (1998) and Douglas and Crowell (2000) also found that in Long Island, New York and Delaware that beach width appeared to recover to the long-term trend after severe nor'easters.

Zhang et al. (2002) analyzed a more extensive set of shorelines that verified the earlier studies on beach recovery. The fact that barrier beaches along the U.S. East Coast recover to their long-term trend positions after storms *regardless of storm severity* strongly suggests that storms are not responsible for long-term beach erosion. In other words, if long-term erosion were event-driven, one would expect that larger storms would result in more net shoreline retreat than smaller ones, which is not supported by the available data. Finally, there is a critical and fundamental fact that cannot be overlooked; the U.S. East Coast barrier islands have existed in more or less their present state (albeit in more seaward positions) for at least the last few thousand years, indicating that they exist in a state of dynamic equilibrium. If this were not true, great storms would have destroyed the barrier islands long ago by overwash processes and cutting of inlets. But if left alone, microtidal inlets eventually close and the shoreline straightens, and dunes are rebuilt by aeolian processes. At any given time (such as now) we have a 'snapshot' of the long-term situation blurred by inlet activity. From this perspective, sea level rise is ultimately responsible for long-term beach erosion on the U.S. East Coast barrier beaches, and probably for sandy beaches everywhere.

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