Sea Level Rise Shown to Drive Coastal Erosion

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Our research has shown that an important relationship exists between sea level rise and sandy beach erosion. The link is highly multiplicative, with the long-term shoreline retreat rate averaging about 150 times that of sea level rise. For example, a sustained rise of 10 cm in sea level could result in 15 m of shoreline erosion. Such an amount is more than an order of magnitude greater than would be expected from a simple response to sea level rise through inundation of the shoreline.

Sea level is certainly only one of many factors causing long-term beach change. Shoreline revisions from inlet dynamics and coastal engineering projects are more pronounced in most areas of the U.S. east coast and tend to mask the effect of a rise in sea level even over extended intervals. The implication is that sea level rise is a secondary but inexorable cause of beach erosion in such areas.

Despite this link between sea level and erosion, the exact mechanism requires more investigation. At the least, however, it is plausible that rising sea level enables high-energy waves to reach farther up the beach and redistribute sand offshore.

Global mean temperature has increased about 0.5°C in the 20th century. This rise could be responsible for up to about one half of the observed global sea level rise of nearly 20 cm during that period because of thermal expansion of the oceans and melting of small glaciers [*Intergovernmental Panel on Climate Change (IPCC)*, 1996]. An increasing concentration of greenhouse gases in the atmosphere is expected to raise global temperature 1.5 to 4.5°C in the 21st century and cause accelerated sea level rise [*IPCC*, 1996]. If it does, it will exacerbate already severe beach erosion problems along the highly developed U.S. east coast, and oceanic beaches everywhere else. This result has ominous implications for the ever-increasingly developed coastlines of the world.

Enormous Problems Loom

Global sea level will increase about 20 cm by 2050 according to best estimates [*IPCC*, 1996]. Combined with local subsidence caused by ongoing glacial isostatic adjustment, sea level along New Jersey, Delaware, and Maryland will rise up to 40 cm by the year 2050. This projected rise will result in as much as 60 m of erosion, about two times the average beach width, and cause enormous problems in these highly urbanized coastal areas.

Because of the global scale of the problem, the role of sea level rise in coastal erosion is of immense scientific and practical interest. About 70% of the world's sandy beaches experience erosion [*Bird*, 1985]. The rates are usually small (1 m/yr or less), but since sandy beaches are typically only a few tens of meters wide, fixed structures such as lighthouses or buildings will find the beach seaward of them substantially narrowed during their useful lifetime. The result is greatly increased exposure over time to wave damage and flooding from storms. In the case of U.S. east coast beaches, more than 80% have experienced an underlying secular trend of erosion during the past 150 years [*Galgano et al.*, 1998] as revealed by repeated geodetic surveys since the middle of the 19th century.

Excluded from the likely causes for the pervasive erosion phenomenon are storms, as there is no apparent overall increase in storminess this century [*Zhang et al.*, 1997], and human interference, which is neither worldwide in extent nor uniform regionally. But what nearly all of the Earth has experienced during the last century is an increase of relative sea level. Our evaluation of historical U.S. east coast sea level records and shoreline positions confirms laboratory and theoretical predictions that coastal erosion rates can be expected to be more than 100 times the rate of sea level rise for undisturbed sandy beaches.

Insight Difficult

Gaining insight into coastal erosion processes is difficult for a number of reasons. A particular problem comes from the transient impact of severe storms on shoreline position. Great storms can cause more erosion in a few hours or days than may have occurred in the previous half century, followed by a subsequent partial or full recovery process lasting a decade or even longer [*Morton et al.*, 1994; *Galgano et al.*, 1998]. In addition, shoreline position indicators, such as the high water line, are inherently somewhat imprecise. This means that determining the underlying trend of erosion requires very long histories of shoreline position. Galgano et al. have shown that 80 years or more are often required to determine whether a beach in its natural state can even be described as inherently eroding or accreting.

Another problem involves engineering modifications to the beach designed to alter erosion processes, such as sand replenishment, jetties, groins, and seawalls. These alterations, whose effectiveness is highly variable, create discontinuities in the historical shoreline position record that mask underlying long-term behavior. Fortunately, enough U.S. beaches are free of engineering changes and anomalous geomorphic characteristics, and have sufficiently long survey records, so that insight can be gained concerning why long-term beach erosion occurs.

Perhaps the most commonly proposed reason for long-term erosion is sea level rise. A simple two-dimensional (2-D) equilibrium model [*Bruun*, 1962] predicts that long-term shoreline retreat can be a large multiple (50-200 times) of the magnitude of sea level rise, far greater in magnitude than the inundation effect of sea level rise on oceanic beaches.

The Bruun model, or a modified form, has been widely used to estimate the impact of future sea level rise on beach erosion, even though many investigators reject it out of hand. They do so because it ignores along-shore sediment transport processes and wave climates. The model does work for some special cases of wave tanks and certain lake environments where the theory is a reasonable first approximation to the actual physical situation.

Historical Shoreline Positions

We examined whether the Bruun model can give a useful estimate for the long-term response of an open ocean coast to sea level rise. Because sea level has risen by varying amounts (20 to 40 cm) geographically along the U.S. east coast during this century, if there is a connection between sea level rise and coastal erosion, it should be apparent. To find out, we compared historical shoreline positions and sea level data along open oceanic beaches with their complex sediment transport processes and wave climates.

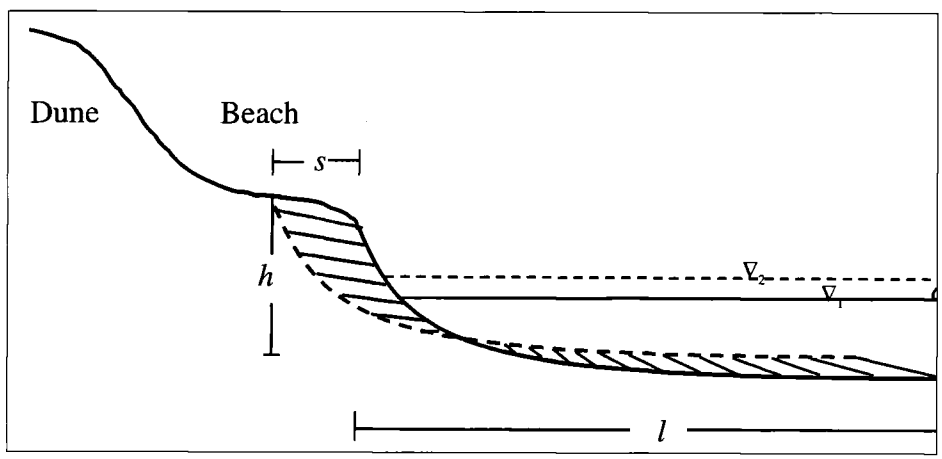

Fig. 1. Beach response to sea level rise based on the Bruun rule (not to scale). S = beach recession in response to sea level rise of a, where h = height of active profile and l = length of active beach profile.

Table 1. Long-term shoreline change rates (m/yr) ± one standard deviation along the U.S. Numbers in parentheses are the shoreline length used in the analyses in kilometers.

Location	Erosion rate for Entire Area, km	Erosion rate for all areas not influenced by inlets and coastal engineering	s/a*	Erosion rate for erosional Areas not influenced by inlets and coastal engineering	s/a
Long Island, N.Y.	-0.44 ± 0.89 (134)	-0.13 ± 0.25 (71)	53	-0.27 ± 0.17 (46)	110
New Jersey	-0.12 ± 1.50 (177)	-0.38 ± 0.58 (32)	101	-0.68 ± 0.36 (22)	181
Delmarva	-2.26 ± 3.39 (176)	-0.20 ± 0.74 (70)	56	-0.53 ± 0.35 (52)	150
North Carolina	-0.87 ± 1.79 (145)	-0.32 ± 0.41 (44)	88	-0.50 ± 0.25 (34)	139
South Carolina	-0.78 ± 2.73 (265)	-0.34 ± 0.38 (76)	109	-0.41 ± 0.35 (65)	132

*s/a is the ratio of shoreline erosion rate to sea level rise rate.

Past tests of the Bruun model on the open-ocean coast have been inconclusive. Some work seems to verify it, while others allege that the Bruun model does not work at all [e.g., *Pilkey et al.*, 1987]. The Bruun scheme is an idealization based on a 2-D model of shore response to sea level rise. The beach profile in this model achieves equilibrium with an increased sea level by shifting landward and upward, resulting in erosion of the beach and upper shoreface and deposition on the lower, much larger part of the active beach profile (Figure 1).

The Bruun model does not suggest that a low energy phenomenon like sea level rise actually causes erosion; rather, increased sea level enables high-energy, short-period storm waves to attack further up the beach and transport sand offshore. Sea level rise is an enabler of erosion in this view. Clearly also the model can only hope to apply where there is no gradient of alongshore sediment transport; the model must fail near barrier island inlets, evolving capes and spits, or areas where wave energy is focused on the shore by bathymetric features.

It is easy to understand why the simple Bruun model has been so controversial. Barrier islands are highly dynamic in their response to oceanographic and meteorological inputs. In addition to a storm-induced, erosion-recovery cycle, great storms can also open barrier island inlets causing severe local erosion. A barrier island can even be completely overwashed and the dunes obliterated.

Observing Subtle Erosion Effects

How can it be possible to discern a subtle erosion effect driven by sea level rise in the presence of these strong storm impacts? The answer is that high-energy processes are of relatively short duration (days to years) compared to the age of barrier islands (thousands of years). These geological entities can be substantially altered in the short term, but they recover to their pre-storm forms in varying degrees [*Morton et al.*, 1994; *Galgano et al.*, 1998] as long-period ocean waves return sand to the beach face and along-shore transport supplies new sand. Even tidal inlets opened by severe storms will ultimately close (if left alone), and the shoreline straighten. Indeed, if barrier islands did not have a long-term equilibrium configuration, they could not maintain their identities in the face of meteorological assaults and would have been battered away long ago.

It is essential when discussing shoreline position change to differentiate between seasonal-to-interannual variations and changes occurring on the scale of a century. No accurate statement about the underlying rate of erosion of a beach can be made from observations of shoreline position for a few decades. Relating sea level rise to shoreline position must rely on comparisons of the long-term (100-plus years) trend of position to the long-term trend of sea level. In this matter a certain similarity exists between a sea level time series and a series of shoreline positions; in both cases a meaningful trend can only be determined from a long time series.

Erosion from New York to South Carolina

Figure 2 illustrates the variability of erosion trends, showing shoreline position trends for the U.S. east coast from Long Island, New York, to South Carolina, for beach areas not influenced by inlets or engineering modifications. The trends, in meters per year, were derived from all possible differences of shoreline positions divided by the time interval between them. Open circles indicate trends computed from shoreline positions heavily influenced by storms; their larger scatter demonstrates that storm-influenced shorelines should not be used to calculate erosion trends, as discussed by Galgano et al. [1998]. The great scatter of the trends does occur partly because of the inherent uncertainty of the position measurements of up to about 10 m [*Crowell et al.*, 1991], but far more important than measurement error is the effect of erosion and subsequent extended recovery of shoreline position associated with severe storms.

The horizontal dashed line in Figure 2 is the average (0.5 m/yr) long-term erosion rate computed without storm-influenced shoreline positions. The obvious convergence of the trends computed from all possible shoreline position differences to the same value demonstrates that there is an underlying average rate of erosion for

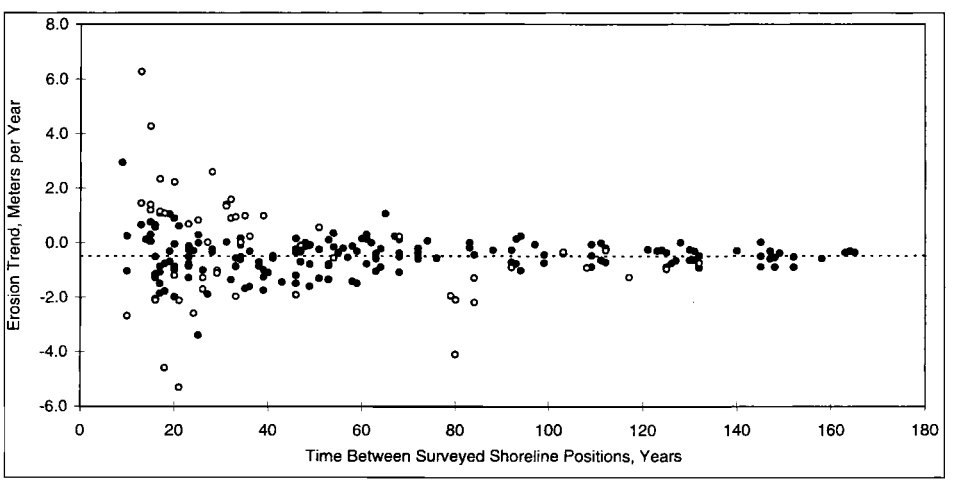

Fig. 2. Beach erosion/accretion trends for the U.S. east coast (New York-South Carolina) derived from all possible combinations of shoreline positions (in meters per year) divided by the time interval between them (after Galgano et al. *[1998]). Results are for barrier island beaches free from effects of inlets and engineering projects. Trends shown as open circles involved shoreline positions affected by severe storms and show a much larger scatter. The apparent trend is as likely to be erosional as accretional for shoreline positions less than about 80 years apart, and the values converge to an average of erosion rate of about 0.5 m/yr with increasing time span between observations.*

the U.S. east coast that is not zero, and that long records of shoreline position data are needed to determine erosion trends.

Is there a robust association of regional erosion to regional relative sea level rise? The necessary historical shoreline position data for comparison of erosion rates to sea level rise are obtainable from historical and modern National Ocean Survey T-sheets, vertical aerial photography, and kinematic Global Positioning System surveys. These data have the requisite high accuracy [*Crowell et al.*, 1991], length of record (>100 years), and spatial characteristics (entire U.S. mid-Atlantic coast) to satisfy the conditions to evaluate the Bruun concept.

In addition to the long-term shoreline change data, reliable estimates of sea level trend are also necessary. Rates of sea level rise were computed for the period 1930-1995 since many U.S. east coast tide gauge records cover this period, and 65 years is long enough to determine the trend.

Spatial variation of wave energy could also have an effect on long-term shoreline change. However, Zhang [1998] has shown that there is no relation between wave height and long-term erosion rate.

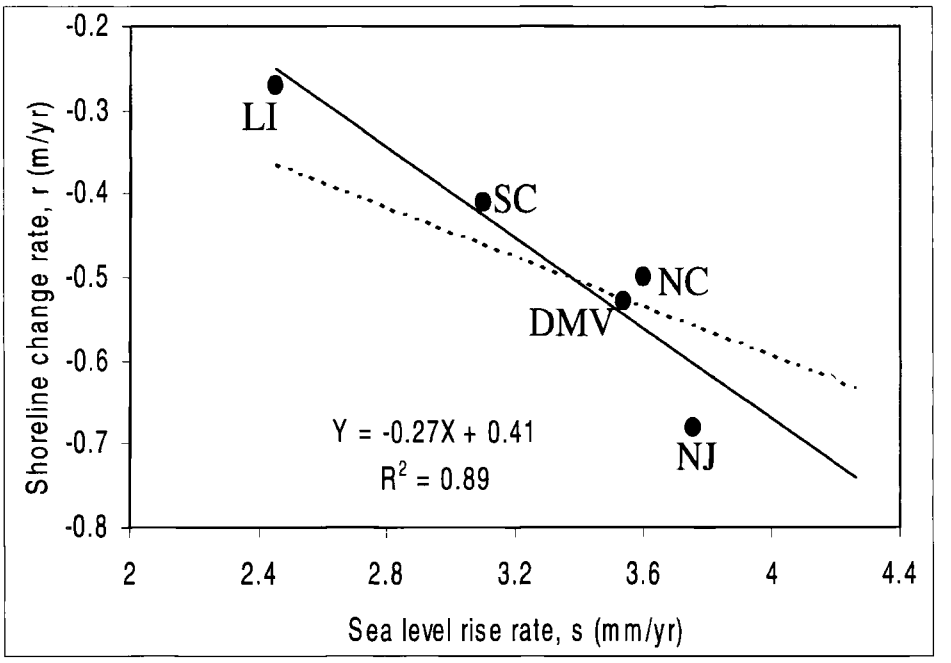

Fig. 3. Relationship between rates of sea level rise and shoreline retreat for erosional sections not influenced by inlets or coastal engineering projects for the five coastal compartments. The solid line is the best linear fit (r^2 = 0.89). The dashed line is the best fitting line that also passes through the origin. (Figure is after Zhang *[1998].)*

Long-term Rates Computed

The long-term shoreline change rates for our study were computed by linear regression at a lateral spatial interval of 100 m along the U.S. east coast for five coastal areas: Long Island, New York; New Jersey; Delmarva (Delaware, Maryland, and Virginia); North Carolina; and South Carolina. The political boundaries and Delmarva grouping correspond to coastal geomorphic compartments [*Fisher*, 1967] for analysis purposes.

Three methods were used to compute the long-term change rates for the areas: (1) simple averaging of all shoreline rates for each compartment, (2) averaging the shoreline change rates over both erosional and accretional sections not influenced by inlets and coastal engineering projects, and (3) averaging the shoreline change rates only for erosional sections not influenced by inlets and coastal engineering projects. The last of these corresponds physically most closely to the Bruun model. Tens to hundreds of kilometers of shoreline were utilized in each of these "samples" to determine average beach behavior (Table 1).

Beaches influenced by inlets and coastal engineering projects display large spatial variations in long-term shoreline change rates (Table 1, column 2, "Erosion rate for entire area"). The deviations are greatly reduced if beaches affected by inlets and engineering projects are eliminated (see column 3), indicating the overwhelming influence of inlets in terms of beach erosion, and the stabilizing influence of coastal engineering projects in the case of New Jersey.

A few shoreline segments not influenced by human interference nor inlet effects actually exhibit stability or slight accretion. In addition, one erosion "hot spot" with a very high erosion rate was found. These are areas influenced by gradients in longshore sediment transport resulting from changes in shoreline orientation or onshore/offshore sediment transport, and hence are atypical. These segments of shoreline were eliminated for the calculations shown in column 5 because the Bruun model only applies to beaches with no significant net change of sediment supply.

There is good agreement between sea level rise and average long-term shoreline change for eroding beaches. The ratio of shoreline retreat rate to sea level rise rate ranges from 110 to 181 for these undisturbed beach segments, confirming that there is indeed an association between long-term sea level rise and shoreline retreat.

Figure 3 illustrates the high correlation (r^2 = 0.89) between sea level rise and beach erosion. However, the ratios of shoreline change rate versus sea level rise rate vary, as noted, from 110 to 181 (Table 1, last column), larger on average than the 50 to 200 in Bruun's [1962] calculation. The variability of the response to sea level rise undoubtedly reflects some of the geological complexities lacking in the Bruun model. But the model is confirmed in that the trend is always at least two orders of magnitude greater than the rate of sea level rise. Forcing the regression line to pass through the origin (zero erosion for zero sea level rise) yields an average shoreline change rate that is about 150 times the rate of sea level rise.

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