EROSION AND OVERWASH: TRACKING AND NUMERICAL MODELING OF COASTAL BARRIER EVOLUTION AT LITTLE HOMER POND, MARTHA'S VINEYARD, MASSACHUSETTS

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Abstract

Several different modeling approaches based on the concept of "equilibrium slope" are developed and ultimately applied to attempt to recreate coastal barrier evolution over a 55-year time span at Little Homer Pond, Martha's Vineyard, Massachusetts. Unlike some models (strict "Bruun rule" models) for barrier evolution which simply move a stagnant barrier profile up the regional slope, these dynamic models transport sediment to maintain equilibrium slopes relative to sea level, and also overwash sediment from the front to the back of the barrier based on certain parameters. The first version of this dynamic "equilibrium slope" model is tested by successfully reproducing the critical width concept of Leatherman (1979) as observed at Assateague Island, Maryland. Next, ground-penetrating radar (GPR) studies are performed on the Little Homer Pond barrier, Martha's Vineyard, which identify three sedimentary units that are likely washover deposits. After changes in the barrier are analyzed from aerial photographs during the period 1952-2007, two modeling approaches are used to attempt to recreate the barrier's evolution. These include (1) a "pure" equilibrium slope model, and (2) a periodic storm surge model, which incorporates the discrete effects of storm events into the model. Historical data and the previously-identified washover deposits are used to estimate the "storminess" parameters for this model. However, the "pure" equilibrium slope model is unsuccessful at recreating the very fast shoreline retreat rates observed, and the periodic storm surge model, while successful in several scenarios, is unstable and suspiciously sensitive to one parameter. While the successful scenarios are consistent in their estimates of mass fluxes, and therefore may provide some insight in this regard, it is suggested that the assumptions made in applying the "equilibrium slope"

concept to this barrier are invalid. In particular, one possibility is proposed: that the barrier—much steeper than those further south along the U.S. east coast, and located at the edge of a terminal moraine—may be in the midst of a long response to glacial deposition at the Last Glacial Maximum (LGM). Consequently the models have difficulty recreating the observed barrier evolution because the assumption that the equilibrium slopes are close to their present values are false, and the true equilibrium slopes have yet to be achieved after thousands of years of oceanic forces gradually making the profile shallower.

I. Introduction

Coastal barriers have always been extremely dynamic features: always in motion due to the ease with which their sediments (usually sand) can be moved, and the overwhelming power of wave energy, ocean currents, and the consequent erosion and sediment transport. The dynamic nature of barriers has become a major concern in recent years, as much high-density coastal development along the U.S. East Coast in particular has been on coastal barriers. Modeling how these barriers might develop and respond naturally to changes in sea level, such as those predicted by the Intergovernmental Panel on Climate Change for the next century (IPCC 2001), is of major interest to geologists, coastal engineers, as well as those with vested interests in these areas.

There have been several approaches to modeling barrier response to sea level rise over the past half century—a common feature of these has been the concept of an equilibrium profile that is preserved relative to sea level*. One of the earlier methods used by Bruun (1962) simply shifted the profile up and back along the mean shoreface slope (S_{sf}); this principle could not be applied to barriers, however, without either eventually drowning the barrier or violating conservation of mass. A "modified Bruun rule" has been developed more recently (Dean and Maurmeyer 1983, Cowell et al. 1995) which instead shifts the entire barrier profile along the underlying regional slope (S_r). This approach seems to be more consistent with general observations of coastal barriers, but it is still a simple geometric principle that does not account for the phenomena that cause such movement of the barrier.

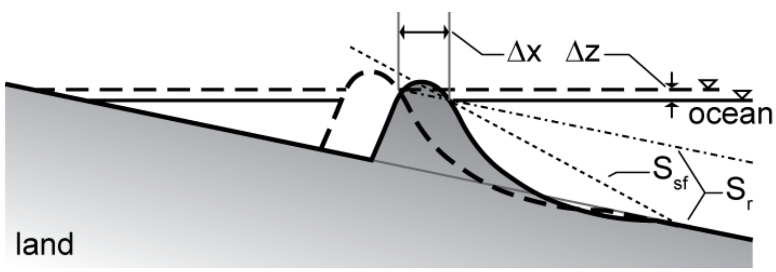

Figure 1. Taken from Ashton (2008) presentation

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* The terms "equilibrium profile" and "equilibrium", as used in this article, refer to a profile or slope configuration in which forces on the sediment at each point are in balance over time scales that are short relative to the model—a dynamic equilibrium or steady-state configuration that can change over the course of the model, and not a thermal or static equilibrium.

While erosion due to wave action is mainly responsible for sediment losses at the front of the barrier, there are several mechanisms that could be responsible for sediment deposition at the back of the barrier. In the absence of a nearby inlet or channel, overwash is likely to be the dominant such mechanism. With the exception of very low-lying barriers that do not rise above the tidal zone, overwash is generally limited to major storm events. Barriers can be overwashed either through wave runup, which typically results in very localized overwash deposits, or through inundation from storm surges, which results in much broader zones of overwash deposition (Donnelly et al. 2006). These different modes of overwash result in significantly different morphologies; however, in consideration of a single cross-section these two types of overwash are typically modeled in the same way, with mass conserved within the cross-section and no net lateral deposition from wave runup overwash elsewhere along the coast.

II. Methods - Basic Components of an Equilibrium Slope Model

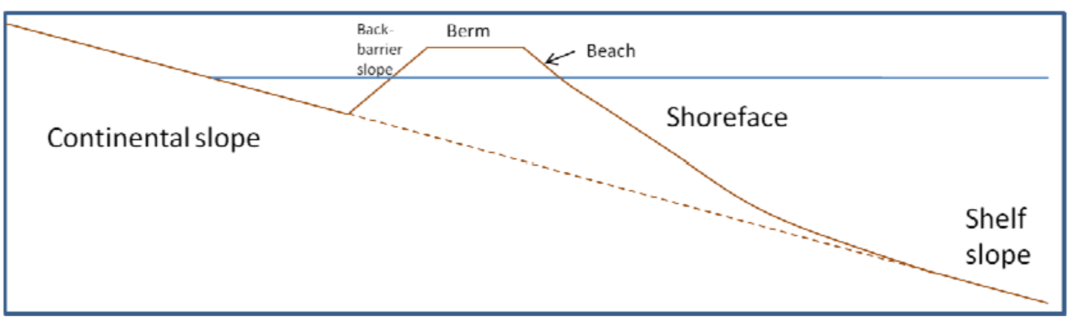

Figure 2. Schematic diagram of the model barrier, with the individual components labeled.

The models in this study take a more dynamic approach than models based on the modified Bruun rule: they does not simply move an equilibrium profile, but move sediment around as sea level changes to achieve equilibrium slopes based on this profile. The concept of "equilibrium slope" is taken from Dean (1991), with the resulting sediment flux and transport calculations taken from Ashton (2008) with minor modifications. For each point on the "model barrier", an equilibrium slope (S_{eq}) is set, except for the shoreface at the front of the barrier, which varies as a function of depth below sea level:

$$S_{eq} = A[(SL - z) + c]^{-\frac{1}{2}} \qquad (1)$$

for z < SL, where z is absolute elevation of a point on the profile, where SL is sea level, SL – z is (positive) depth below sea level, A is a constant, and c is an offset parameter to prevent infinite slope as z → SL. Derived from Dean profile (Dean 1991).

Sediment is then moved along the front of barrier to allow local slopes to approach the equilibrium profile. If the actual slope is too steep, sediment is moved offshore; if the actual slope is too shallow, sediment is moved onshore:

$$\int_{x_0}^{x} \frac{\partial z}{\partial t} dx - \int_{x}^{x_{end}} \frac{\partial z}{\partial t} dx = \Phi_{onshore} = K(S_{actual} - S_{eq}) \qquad (2)$$

where x_0 and x_{end} are the onshore and offshore extents of the model respectively, x is the horizontal position of a point on the beach or shoreface and z is its absolute elevation, $\Phi_{onshore}$ is the onshore flux of sediment at a given location along the profile, $S_{actual} = \frac{\partial z}{\partial x}$ is the actual slope, S_{eq} is the equilibrium slope as defined in equation (1), and $K = K'\left[\frac{1}{1+(SL-z)}\right]$, where (SL – z) is depth below sea level and K' is a constant.

Once sediment is distributed along the beach and shoreface, the beach and uppermost part of the shoreface is eroded (by a set parameter), and a certain percentage of this eroded sediment is overwashed:

$$\int_{x_0}^{x_b} \frac{\partial z}{\partial t} dx - \int_{x_b}^{x_{end}} \frac{\partial z}{\partial t} dx = OW_{rate} = E_{rate} * e^{-C\left(H_{eff} - b_0\right)} \qquad (3)$$

Where x_b is the horizontal position of the top of the beach (i.e. the front of the berm), OW_{rate} is the time-averaged overwash rate (in m^3/m/year), E_{rate} is the input parameter that determines what volume (or cross-sectional area) of the beach and upper shoreface will erode (apart from natural fluxes), C is a constant affecting how quickly overwash tapers off, b_0 is a baseline barrier height (relative to sea level) below which all the eroded sediment overwashes, and H_{eff} is effective barrier height, as given by:

$$H_{eff} = H_{actual} + \frac{w_{actual}}{w_{ref}} \qquad (4)$$

where H_{actual} is the actual barrier height (relative to sea level), w_{actual} is the actual barrier width, and w_{ref} is the barrier width considered equivalent to 1 m additional barrier height in preventing overwash.

The parameter w_{ref} represents the influence of barrier width on overwash rate—a wider barrier can slow down overwash deposition, and is also more likely to have a higher maximum elevation even though in this model the flat berm is set at the same height, regardless of width. The use of an "equivalent barrier height" allows the overwash rate to depend on both barrier width and height simultaneously (equation (4)), and the use of a exponential tapering function with increasing height precludes the need to completely stop overwash at a critical height or critical width as in some models (Jiménez and Sánchez-Arcilla 2004, Masetti et al. 2008). The exponential tapering function allows the most intense storms, however infrequent, to overwash the barrier and play a role in the model barrier's evolution.

This model does have some weaknesses: the set erosion rate parameter may be unnecessary, as overwash could also be drawn from sediment eroded from the beach and top part of the shoreface in accordance with equation (2). The model also does not account for asymmetries in the wave climate or currents along the shoreface that might influence erosion rates in the upper shoreface, and consequently overwash rates (Stive and de Vriend 1995). Compared to Bruun rule-based models, however, this dynamic modeling approach is more consistent with basic Newtonian physics—mass is conserved, and the equilibrium slope (and consequently the equilibrium profile) is a result of force balances on the sediment grains at each location in the profile. Rather than simply forcing an end result, this model can provide insight into the phenomena that lead to that result, and demonstrate how a barrier might respond to sudden changes before it reaches equilibrium.

II.a. Test Runs of an Equilibrium-Slope Model: Recreating Barrier Evolution at Assateague Island, Maryland

After running and refining the model, the parameters of the model were calibrated to resemble as closely as possible the conditions observed by Leatherman (1979) in studies of Assateague Island, Maryland. This study was chosen due to Leatherman's clear observations there of a "critical width" range: the width of the barrier island generally does not fall below 400 m or exceed 700 m. When the island's width falls below 400 m, overwash sediments fill in the back barrier faster than the front of the barrier can be eroded; when the island's width exceeds 700 m, overwash sediments do not reach the back barrier, and erosion is the dominant process. While some models stop overwash at a critical width explicitly, as mentioned before, in this case the existing model parameters (set erosion rate, C, w_{ref}) were adjusted to see if this behavior would arise naturally from the model. Sea-level rise was set to 2 mm/yr or 0.2 m rise over 100 years, in accordance with tide gauge relative sea-level rise rates for the U.S. East Coast (Lombard et al. 2005).

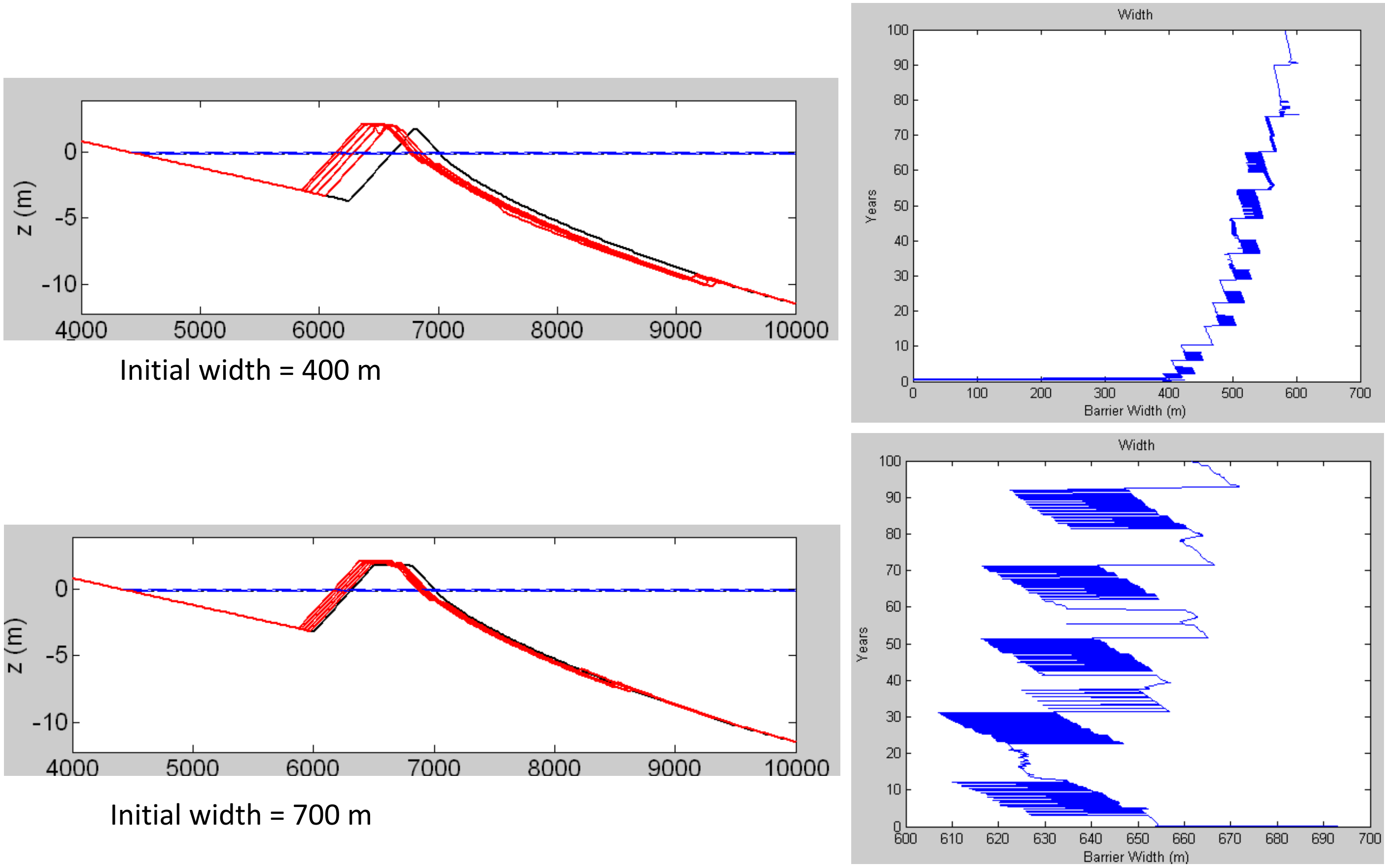

Figure 3. Model runs for 0.2 m sea-level rise over 100 years (2 mm/yr). Black outline on two left plots indicates the initial barrier profile, red lines indicate the shape of the barrier profile at successive 20-year intervals. Blue dashed lines indicate the gradually rising sea level at 20-year intervals. Right plots indicate the change in barrier width over time in these two scenarios (initial width 400 m and 700 m respectively).

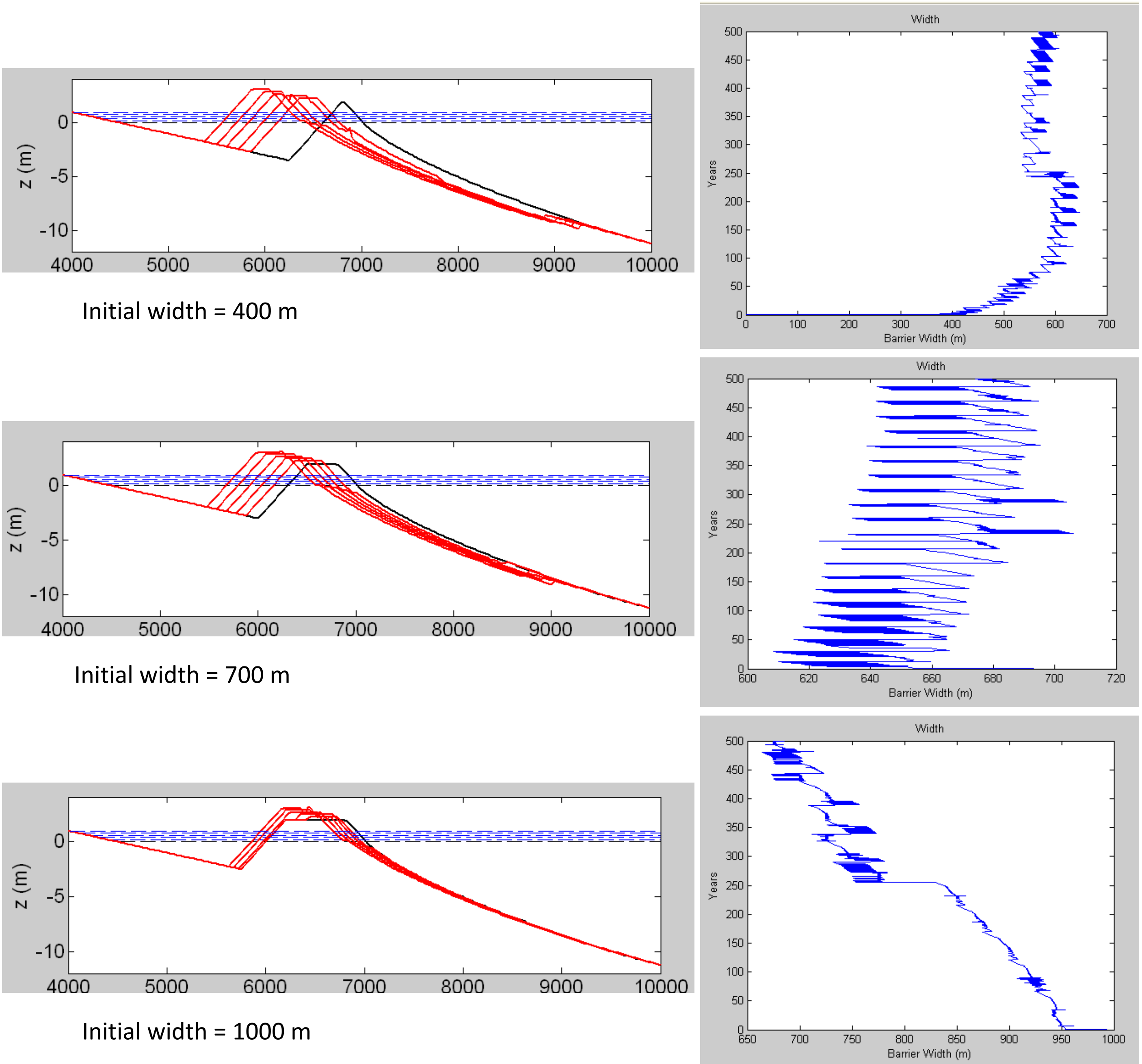

Figure 4. Model runs for 1 m sea-level rise over 500 years (2 mm/yr). Red outlines indicate shape of the barrier profile at 100-year intervals. Black outline on left plots indicates the initial barrier profile, red lines indicate the shape of the barrier profile at successive 100-year intervals. Blue dashed lines indicate the gradually rising sea level at 100-year intervals. Plots on right indicate the change in barrier width over time in these three scenarios (initial width 400 m, 700 m, and 1000 m respectively).

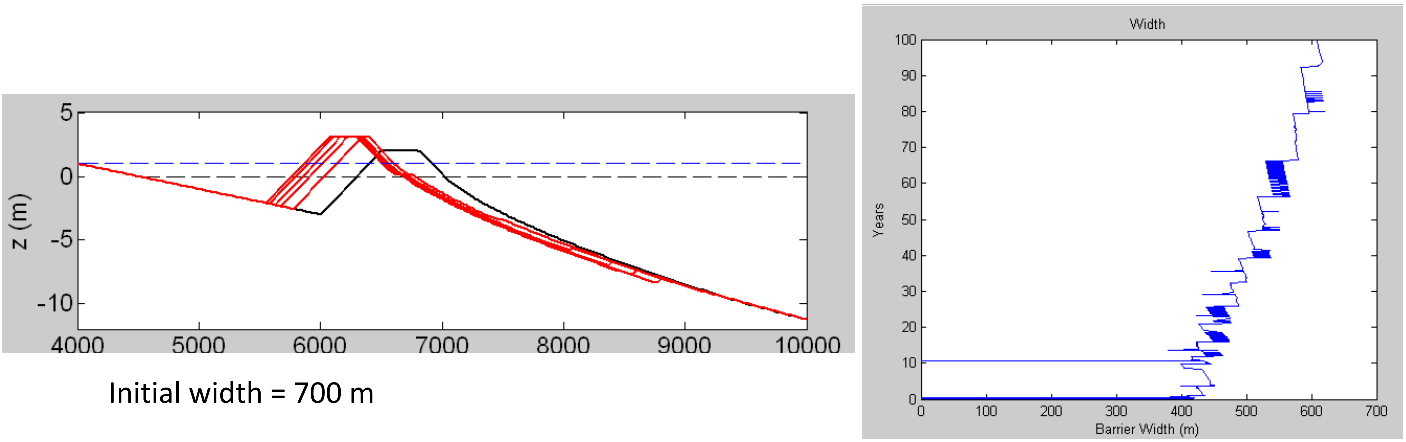

Figure 5. "Catastrophic" scenario: instant 1 m rise in sea level. Black outline on left plots indicates the initial barrier profile and the sea level (dashed line), red lines indicate the shape of the barrier profile at successive 100-year intervals. Blue dashed line indicates the new sea level after the catastrophic rise. Plots on right indicate the change in barrier width over time.

The two model runs ($C = 7\ m^{-1}$, $w_{ref} = 1000$ m, set erosion rate = 0.02 m/yr taken from the beach and top shoreface, or about ~6.5 m^2/yr) shown in Figure 3 illustrate results similar to Leatherman's findings. The barrier that starts with 400 m width is eroded at first, but once this eroded sediment overwashes to the back barrier, the island widens to approach a constant barrier width at close to 600 m. The barrier that starts with 700 m width is also eroded, but this overwash takes longer to reach the back barrier; only after about 30 years and narrowing to 610-640 m does overwash catch up and the barrier begin to slowly widen. The same model was also run with this sea-level rise rate over a time span of 500 years to verify whether this equilibrium concept holds true for longer time scales. The results at longer time scales (Figure 4) were similar: the barrier with initial width 400 m settled at an equilibrium width between 550-600 m, and the barrier with initial width 700 m reached an equilibrium range of 640-690 m. A barrier with initial width 1000 m is also shown; no overwash reaches the back of this barrier until 300 years after the start of the model run (at width ~750 m), and is still decreasing in width at 500 years, though the width is below 700 m and is beginning to stabilize.

Finally, a model run was carried out for a "catastrophic" scenario—in which the sea level rises instantly by 1 m, then stays constant for 100 years—to see how the barrier might respond differently to a sudden impulse (Figure 5). The example shown, with initial width 700 m, narrows very rapidly to 400 m, and the barrier has almost completely overturned within 20 years. After the barrier overturns, overwash becomes the dominant phenomenon, widening the barrier once again to an equilibrium range close to 600 m.

It should be noted that while this model demonstrates the Assateague Island critical width of 400-700 m fairly accurately, other aspects of the model are not consistent with the observations made by Leatherman. The shoreline retreat rate observed on Assateague Island was approximately 7 m/yr, while these model runs show shoreline retreat rates of only 2-3 m/yr; in other words, much larger volumes of sediment are being transported in reality than portrayed in the model. Pierce (1969) estimated that 70% of the sediment transport from the front to the back of the barrier was the result not of overwash but of transport via a nearby inlet; only 30% is due to overwash and eolian processes. If this estimate is correct, then the overwash component of sediment transport may be accurately modeled, but the presence of an alternate sediment transport mechanism makes Assateague Island a less than ideal site for studying overwash. In order to model a barrier cross-section realistically, it was necessary to study a barrier where inlets are not a factor, and where overwash is the dominant mechanism of landward sediment transport.

III. Study Area: Little Homer Pond, Martha's Vineyard

III.a. Detecting Washover Deposits

In order to detect washover deposits—with the goal of ultimately quantifying overwash rates in a given area to incorporate into the model—ground-penetrating radar (GPR) studies were performed on two different barrier environments along the southeast Massachusetts coastline. Very few barriers in this region are long islands with large back bays such as is the case with Assateague Island; most are short, sandy isthmuses separating the open ocean or sound from a small inner bay, glacial pond or sapping valley. Subsurface data was collected from two sites in this region: South Cape, which separates Waquoit Bay (a 1.7 km wide, 3.5 km long inner bay) from Nantucket Sound; and the barriers in front of Big and Little Homer Ponds, 2 small ponds (200 m and 90 m wide respectively in the longshore direction) on the ocean-facing coast of Martha's Vineyard (Figure 6). A Geophysical Survey Systems Inc. SIR-2000 GPR system was used, with a 400-MHz antenna. Barriers in this region can typically be studied using a lower-frequency antenna at depths up to 10-15 m (Buynevich 2006), but most clearly identifiable overwash deposits are within 2-3 m of the surface—consequently a higher frequency (400-MHz) antenna was chosen to obtain more detailed data at shallower depths.

The first site (South Cape) initially appeared promising, despite the presence of an inlet 0.5 km from the study area—a sandy neck with only light vegetation across the barrier was an indicator of recent deposition on top of the barrier. However, subsurface studies of this site using GPR revealed that most of the deposition in this section was actually the result of progradation, or sediment accreted at the front of the barrier. Historical shoreline data confirmed this finding; the shoreline in this part of the barrier has actually advanced significantly into Nantucket Sound since 1846 (Mass. Shoreline Change Project). Since other nearby sections of shoreline have eroded and retreated during the same time period, it seems reasonable to assume that longshore transport is dominant at this site.

(a)

(b)

Figure 6. (a) Location map of the two GPR study sites, southeastern Massachusetts. (b) Map showing the grid of transects taken at Little Homer Pond, Martha's Vineyard.

The second study area (Big and Little Homer Ponds) has sandy washover fans clearly visible on the surface, and no inlets in the vicinity at present. Historical shoreline data also showed fairly consistent erosion along the front of the barrier, with shoreline retreat rates averaging 2.15 m/yr over the past century. Subsurface results from both of these sites revealed reflectance signatures indicative of overwash; the best results came from Little Homer Pond, where a grid of GPR transects enabled the identification of multiple sedimentary units that appear to be washover fans. In the transects shown in Figure 7, these units are most visible; the unit circled in red in Figure 6b appears to be most recent, with two barely overlapping units under the red unit. In the topmost transect shown, the unit identified in green appears to overlie the unit in blue; as a result it seems likely that the blue unit was deposited first, followed by the green and then the red unit. These units were identified throughout the transects and their approximate physical extents are outlined in Figure 8. The blue unit's origin is the most questionable of the three; as none of the transects extend into the dunes on the southeast side of Little Homer Pond, it is not possible to tell definitively whether the blue unit is an overwash deposit or an extension of these sandy dunes. At the very least, more GPR transects would be needed in this area to resolve this issue. Nonetheless, it is fairly certain that the other two units are the result of overwash, and these units could potentially be quantified from the transects obtained, although the back extents of the green and blue units are not known; more transects and/or historical maps/photos would be helpful in determining this as well.

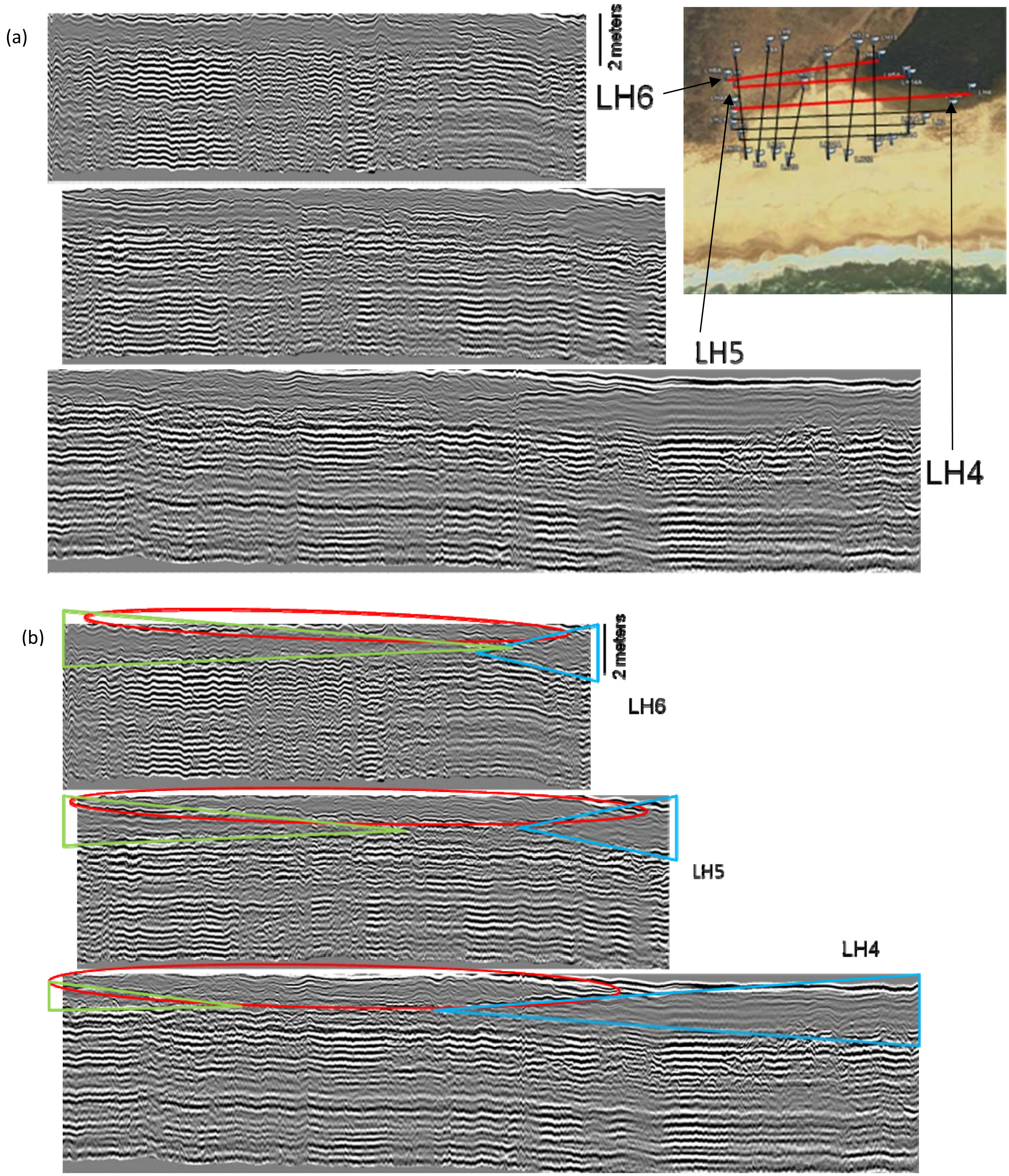

Figure 7. (a) Three longshore GPR transects at Little Homer Pond, identified in red on the inset map. Vertical exaggeration approximately 3:1 (i.e. vertical scale bar of 2 m corresponds to approximately 6 m in horizontal direction. (b) Same transects with three units (likely overwash fans) highlighted in red, green, and blue. Data collected using 400-MHz antenna; scale portrayed assumes dielectric constant for dry sand of 15 ns/m (Jol and Bristow 2003).

Figure 8. Map outlining the three sedimentary units likely to be overwash fans (red is most recent, blue is probably oldest).

III.b. Results of the GPR Studies, and Implications for Modeling

From these GPR studies multiple washover deposits have been identified; knowing approximately the area these deposits cover, as well as the depth of these deposits (1.5-2 m) will enable the volume of these deposits to be quantified, at least to within an order of magnitude. In order to convert these approximate area and depth measurements into long-term overwash rates it is still necessary to determine the timing of the deposition of these units (and the intervals between overwash events), which could be done directly through radioisotope dating or possibly through examining historical maps or photos to find when these deposits were first visible on the surface. If it is possible to successfully determine that all of these three units are washover deposits, and the timing of these overwash events, then a fairly reliable measurement of the overwash rate at this site may be calculated.

In order for this site to be modeled accurately, however, the slopes of the various parts of the “model” barrier had to be significantly altered. The width of the barrier in front of Little Homer Pond is only 75-85 m, as opposed to the 400-700 m equilibrium width of Assateague Island. This is due in large part to the nature of the sediment in this region; as opposed to the fine-grained sands further south, the beaches of Martha’s Vineyard are made up of coarse-grained sediment of glacial origin, which can maintain steeper slopes. While the highest parts of the cross-section of the barrier are still close to 2 m, the much narrower width of the barrier necessitates a much steeper beach slope, and consequently a steeper Dean profile for the shoreface as well. The back barrier slope also had to be changed: where the pond is located the slope drops off steeply in the back barrier region, whereas in the marshy area to the west of the pond the back barrier slope is much shallower.

III.c. Analysis of Little Homer Pond with Historical Aerial Photographs and Storm Data

The preliminary analysis of the units identified in the GPR transects as likely washover fans indicates that the back half of the barrier is covered nearly uniformly by these units to a depth of ~ 2 meters. However, the transects themselves still give no indication of when or under what conditions these units were deposited. To gain insight on the timing (and therefore the rates) of overwash, aerial photographs of the region were also examined. The earliest of this series (Figure 9a) from 1952 shows a barrier that was much wider, with a sandy tongue extending inland far past the beach to Little Homer Pond. When compared with the 2007 photograph, it seems that erosion at the front of the barrier has significantly outpaced the accumulation of washover sediment at the back of the barrier.

Figure 9a. Aerial photograph of the vicinity of Little Homer Pond, Martha's Vineyard, 1952 (courtesy of University of Massachusetts-Amherst historical aerial photograph collection). Little Homer Pond and the barrier in front of it are circled in yellow.

Figure 9b. Satellite photograph of the vicinity of Little Homer Pond, Martha's Vineyard, 2007 (courtesy of Google Maps). Little Homer Pond and the barrier in front of it are circled in yellow.

Figure 10. Satellite photograph of Little Homer Pond, 2007 (courtesy of Google Maps). Outlined are the positions of the shoreline and Little Homer Pond in 1952 (orange) as determined from an aerial photograph, and the approximate extent of washover units as identified using GPR in 2008 (red).

The next logical step might be to trace these washover units to specific storm events, and in doing so estimate the frequency of storm events that cause this barrier to be overwashed. In the Northeast U.S., both mid-latitude cyclones ("nor'easters") and hurricanes can be potent enough to cause significant coastal flooding and erosion. However, hurricanes are far more likely to expose the south-facing coastline at Little Homer Pond to significant storm surges, due to both the speed and direction of the winds that are associated with them. During the interval 1952-2007, six storms of hurricane strength passed very near or to the west of Martha's Vineyard that could have produced the southerly winds and storm surge necessary to overwash the barrier: Carol (1954), Edna (1954), Donna (1960), Esther (1961), Gloria (1985), and Bob (1991) (NOAA CSC). It is interesting to note that four of these six storms occurred before 1971, perhaps explaining why much more of Little Homer Pond was filled in prior to 1971, as opposed to 1971-2007.

Given the timing of these storms, it might seem expedient to trace the two most recent washover units to Hurricanes Gloria and Bob, since there is no evidence of either unit in the 1984 photograph. It might also seem convenient to identify the oldest of the three units as originating from one of the earlier hurricanes prior to 1971. However, the time series of photographs is not sufficient to conclusively determine which storms deposited each unit—and it is also possible that a particularly strong mid-latitude cyclone could be responsible for a washover fan. What it does seem fairly reasonable to conclude is that at least two washover units were deposited from 1984-2007, and that at least six storms between 1952-2007 were potentially capable of overwashing this barrier, indicating an average overwash frequency of ~10 years. Given the possibility that not all of these storms actually did overwash the barrier, an average frequency in the range of 10-15 years might be expected.

IV. Another Modeling Approach: The "Pure" Equilibrium Slope Model and its Application to the Little Homer Pond Barrier

IV.a. Model Components and Parameters

The modeling approach previously used to recreate Leatherman's prototypical barrier may have been useful in looking at barrier response to a variety of sea level rise scenarios. However, this approach required the input of a set erosion rate without providing much insight into what caused this erosion rate. An ideal dynamic model that shifts sediment according to an equilibrium slope rule would not require a set erosion rate, but would only obtain sediment to be eroded and overwashed from parts of the shoreface not already in equilibrium. This type of model intentionally overlooks the short-term processes that cause erosion and overwash in favor of the long-term fluxes that move sediment over the barrier and across the shoreface to an equilibrium state. It was initially decided to use this kind of model to attempt to recreate the barrier evolution seen at Little Homer Pond over the period 1952-2007.

In order to use this type of model, it is necessary to establish that the ocean and wave energy are the dominant mechanisms of transport, and that aeolian processes and vegetation are not major factors. The barrier at Little Homer Pond is in a windy location, and the many mid-latitude cyclones that affect the area each year (as well as less frequent hurricanes) could be capable of transporting fine-grained sediment across the barrier. However, the GPR transects seem to show that the sediment deposited in the back of the barrier exists in several cohesive units, rather than in a number of smaller deposits. This suggests that only the most powerful storms (the hurricanes that might cause overwash) are transporting most sediment across the barrier, as opposed to the gales that bring high winds to the region multiple times a year. Additionally, while some vegetation appears to be present on at least part of the barrier in aerial photographs from 1971 and 1984, it is not present in aerial photographs from 1952 and 2007. There appears to be no noticeable difference in erosion rates between vegetated and non-vegetated parts of the coastline (or between 1952/2007 and 1971/1984), so vegetation does not seem to be a major influence on the barrier evolution here either.

To model the changes in the barrier at Little Homer Pond, a profile of the cross-shore transect at Little Homer Pond was first constructed to represent the actual topography and bathymetry of the site as closely as possible. This was accomplished by examining bathymetric and topographic maps (NOAA OCS, USGS) of the region. An abrupt transition from a relatively constant slope to a steadily steepening slope approaching land (600 m offshore, 9 m depth) was chosen as the bottom of the shoreface. Other crucial parameters calculated for this profile were the shelf slope (0.0025), continental slope (0.0107), beach slope (0.085), and back barrier slope (0.05). An initial Dean profile of the form

$$z = SL - A'(x + C)^{\frac{2}{3}} \tag{5}$$

where z is elevation (as a function of x), SL is sea level, x is the distance offshore, and A' and C are constants was calculated for the shoreface (where z is elevation, SL is sea level, and x is the distance offshore) to fit the boundary conditions z(x = 0 m) = SL, z(x = 600 m) = SL – 9 m, and z'(x = 0 m) = 0.085. The resulting best-fit values were A' = 0.12819 $m^{1/3}$ and C = 1.0164 m. It is important to keep in mind that this Dean profile is simply an initial state and is not reinforced in the model run; only the equilibrium slopes derived from this profile are used to determine sediment transport, as shown in equations (1) and (2).

$$S_{eq}\Big|_{t=0} = A\left[(SL - z) + c\right]^{-\frac{1}{2}} \approx \frac{dz}{dx} = -\frac{2}{3}A'\left(x + C\right)^{-\frac{1}{3}} \quad (6)$$

However, one major assumption is still required, as summarized in equation (6): that the profile of the shoreface as mapped by NOAA (and used as the initial profile in the model) is at or very close to an equilibrium state, and hence that the slopes derived from this profile are also very close to their equilibrium values. If this assumption is not valid, then a model focusing only on long-term processes reaching equilibrium will be insufficient to recreate the observed conditions.

Given these initial conditions, the model was run with a steady relative sea level rise rate of 2 mm/yr (or 0.11 m over 55 years) as taken from tide gauge data (Lombard et al. 2005). The overwash rate was determined using a modification of equation (3) that substitutes in for E_{rate} the sediment already made available by flux calculations and unstable slopes:

$$\int_{x_0}^{x_b} \frac{\partial z}{\partial t} dx - \int_{x_b}^{x_{end}} \frac{\partial z}{\partial t} dx = OW_{rate} = \frac{V_{avail}}{t_{model}} * e^{-C(H_{eff} - b_0)} \qquad (7)$$

where V_{avail} (total available sediment) is the difference in cross-sectional area between the actual shoreface profile and the closest profile in which $|S_{actual} - S_{eq}| \leq \Delta S_{crit}$ for every point on the profile shoreward of d_{ow}, t_{model} is the timestep in between each loop of the model, C is the overwash blocking input parameter; x_b, OW_{rate}, b_0 are as defined in equation (3), and H_{eff} is as defined in equation (4).

Here ΔS_{crit} is the critical difference from the equilibrium slope beyond which the sediment becomes unstable and is free to be transported. Hence this model has 5 input parameters that can be varied to change the way the barrier evolves: C, d_{ow}, w_{ref}, K', and ΔS_{crit}. All of these parameters were varied in an attempt to reconstruct the 100 m shoreline retreat and narrowing of the barrier (from 135 m to 95-105 m*) at Little Homer Pond during a 55-year time span.

IV.b. Results of the Pure Equilibrium Slope Model

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* Note: The actual width of the barrier at its narrowest point as determined from aerial photographs was 115 m in 1952, and 75-85 m in 2007. However, the surface of Little Homer Pond is about 1 m above mean sea level; therefore, if the back of the barrier were at sea level (with a back-barrier slope of 0.05), the barrier would have actually narrowed from 135 m to 95-105 m.

Table 1. Final barrier width and shoreline retreat from the pure equilibrium slope model as a function of varied input parameters.

C	$z(d_{ow}) - SL$ (m)	w_{ref} (m)	K' (m^3/yr)	ΔS_{crit}	Final barrier width (m)	55-year shoreline retreat (m)
0.001	-1.88	50	25,000	0.0001	150-160	21
0.01	-1.88	50	25,000	0.0001	140-160	21
0.1	-1.88	50	25,000	0.0001	143	17
1	-1.88	50	25,000	0.0001	122.5	7
0.01	+0.43	50	25,000	0.0001	129	11
0.01	-1.12	50	25,000	0.0001	137	13
0.01	-1.88	50	25,000	0.0001	140-160	21
0.01	-2.87	50	25,000	0.0001	180-190	34.5
0.01	-4.47	50	25,000	0.0001	200-210	41
0.01	-1.88	50	25,000	0.0001	140-160	21
0.01	-1.88	70	25,000	0.0001	150-160	21
0.01	-1.88	100	25,000	0.0001	150-160	21
0.01	-1.88	50	5000	0.0001	155-175	27.5
0.01	-1.88	50	10,000	0.0001	155-165	25
0.01	-1.88	50	25,000	0.0001	140-160	21
0.01	-1.88	50	50,000	0.0001	137	12.5
0.01	-1.88	50	125,000	0.0001	120-130	3-5
0.01	-1.88	50	25,000	0.00002	178-190	33
0.01	-1.88	50	25,000	0.00005	116-148	13-19
0.01	-1.88	50	25,000	0.0001	140-160	21
0.01	-1.88	50	25,000	0.0003	218-228	42
0.01	-1.88	50	25,000	0.0005	215-230	43

IV.c. Conclusions about the Pure Equilibrium Slope Model

Some of the results of this model are consistent with intuitive physical explanations, but there are some results that are more difficult to understand. These include the effect of K' on shoreline retreat; it would seem that higher susceptibility to transport would cause more erosion and shoreline retreat, but in fact the opposite seems to be the case. And while increases in ΔS_{crit} leading to higher shoreline retreat rates is unsurprising (more sediment allowed to accumulate downslope leading to further erosion upslope), it seems that extremely low values of ΔS_{crit} also lead to higher shoreline retreat rates. The effect of C on the model—higher values of C (blocking more overwash) leading to a narrower barrier and less shoreline retreat—was the expected result, as less overwash prevents widening at the back of the barrier but also keeps more sediment in front of the barrier and slows down erosion. Unsuprisingly as well, setting d_{ow} further offshore (and therefore $z(d_{ow}) - SL$ deeper) resulted in more overwash and hence erosion from the front of the barrier, while varying w_{ref} made little difference in the barrier's evolution.

However, as it turns out, this model was indeed insufficient to reproduce the fast shoreline retreat rates observed at Little Homer Pond. The reason for this is simple and intuitive: the ultimate response of a Dean profile to changes in sea level will be to translate the profile along the underlying regional slope (S_r) according to the modified

Bruun rule (as in Dean and Maurmeyer 1983). Even though this model only reinforces equilibrium slopes, translating the entire profile according to the modified Bruun rule is the only solution that satisfies mass conservation and preserves S_{eq} as a function relative to sea level. Since S_r in this case should be between the shelf slope (0.0025) and the continental slope (0.0107), 0.11 m of sea level rise over 55 years should result in ~10-44 m of shoreline retreat. Even by varying the input parameters considerably, no model runs of this pure equilibrium slope model produced shoreline retreat rates close to the 100 m observed over the past 55 years.

V. Incorporating Storminess – The Periodic Storm Surge Model

As just described, the previous model's failure to recreate the rapid shoreline retreat rates observed at Little Homer Pond may be the result of the basic underlying principle behind the models (the modified Bruun rule) not being applicable in this location at this timescale. The assumption was made in both of the previous models that the shoreface profile was at or close to an equilibrium state relative to sea level, but this may not in fact be the case. One possibility is that the shoreface profile is slowly being reworked towards a steady state as part of a long recovery process from the Last Glacial Maximum—since the coarse-grained glacial till might take a long time to respond to forcing from waves.

But another possibility is that the previous assumption that short-term processes could be overlooked completely in favor of long-term equilibria is not valid. In particular, much of the wave energy may be reworking the shoreface at times when the sea level is not equal to mean sea level. Thus the equilibrium slope at a given point along the profile is defined not only relative to gradually changing mean sea level, but relative to the sea level during storm events when much of the sediment transport actually takes place. Previous studies modeling dune erosion during storms (Vellinga 1982, Kriebel and Dean 1985, Larson et al. 2004, van Rijn 2009) have found that the storm surge level has a noticeable impact on the quantity of erosion on the beach, and at least one modeling study (Vellinga 1982) shows the development of a "storm profile" relative to the storm surge level, that remains immediately following a storm. To create such a profile, sediment is eroded from the top of the shoreface and redeposited further downslope.

This concept of a storm profile was developed in reference to the short-term evolution of a dune and shoreface during and after a storm, but it could also be useful in modeling the long-term evolution of a shoreface from multiple storms. And though these earlier studies did not specifically consider a barrier or overwash, it seems reasonable that the sediment that overwashes comes from the sediment churned up and eroded when this storm profile forms. Therefore, with some modifications, it is possible to incorporate the concepts behind these dune erosion models into the equilibrium slope model.

V.a. Components and New Parameters in the Periodic Storm Surge Model

In order to accomplish this, it was necessary to include additional input parameters in the model. These dune erosion models of the effects of individual storms include parameters such as storm surge height, wave height, incident wave angle (relative to the shoreline), and grain size of sediment. However, incident wave angle can not be represented in a two-dimensional cross-section model, and as there is no noticeable difference in shoreline retreat rates here from any part of the nearby coastline, longshore transport does not seem to be a major factor anyway. Additionally, grain size of sediment is a parameter whose transport properties can be represented in the K' and ΔS_{crit} parameters. This leaves storm surge height and wave height as variables to incorporate into the model, as well as a parameter for the frequency of such storms (to model the effects of multiple storms).

The new model, or "periodic storm surge model", included 7 input parameters (d_{ow}, w_{ref}, ΔS_{crit}, K', SL_{storm}, W_{stddev}, t_{storm}) that could be varied (for more detailed descriptions see the Appendix). At periodic intervals determined by t_{storm}, the equilibrium slopes on the upper part of the shoreface are recalculated relative to a temporary "storm surge" sea level, and sediment is eroded to form a storm profile. In this model the extent of sediment that can be overwashed (d_{ow}) is also the lower extent of the storm profile formation (or the lower extent of sediment that is churned up by the storm). A fraction of the eroded sediment is then overwashed based on what percentage of a standard distribution of waves overtops the barrier:

$$\int_{x_0}^{x_b}(\Delta z)dx - \int_{x_b}^{x_{end}}(\Delta z)dx = OW_{storm} = V_{storm} * e^{-\frac{(H_{eff} - SL_{storm})^2}{2W_{stddev}^2}} \quad (8)$$

where OW_{storm} is the amount (cross-sectional area) of sediment overwashed during a storm, V_{storm} is the cross-sectional area of sediment eroded and made available to be overwashed in a storm (i.e. sediment liberated by the creation of the storm profile), SL_{storm} and W_{stddev} are input parameters as described in the Appendix, and H_{eff} is equivalent barrier height as defined in equation (4).

The eroded sediment that does not get overwashed is redistributed along the front part of the barrier following the storm event.

Ideally, through the use of this model, it would be possible to identify a limited set of input parameters that successfully recreate the shoreline retreat and barrier evolution observed at Little Homer Pond. However, with 7 input parameters that can be varied to produce just 2 output parameters (final barrier width and 55-year shoreline retreat), it is more likely that a very large set of input parameters will yield the same results. To narrow down this field, it is possible to define realistic ranges for some of the input parameters based on historical storm data and previous erosion studies. As determined previously from hurricane tracks and washover fans at Little Homer Pond, the frequency of overwash (t_{storm}) at this barrier is likely 10-15 years. Data from major hurricanes (Birkemeier et al. 1998, NWS) and maximum sea level frequency studies in the region (Walton 2000, Huang et al. 2008) suggest that the mean storm surge (SL_{storm}) from the largest hurricanes to hit the area lies in the range 1.5-2.0 m. Wave heights are the most difficult parameter to obtain data for. One study (Birkemeier et al. 1998) has found significant wave heights, defined as the mean height of the tallest waves, of 1.2-3.0 m above the storm surge level along the Northeast coast during major storms. Since the standard deviation of wave heights would be slightly less than this value, it is reasonable to define a range of likely values for W_{stddev} of 1.0-2.0 m. Even the extent of the storm profile can be estimated based on a dune erosion modeling study (Vellinga 1982) that found the storm profile extends to a depth below the storm surge of 0.5 to 0.8 times the significant wave height. From this study the approximate relationship $z(d_{ow}) – SL \approx SL_{storm} - W_{stddev}$, yielding a range of -0.5 m to 1.0 m for $z(d_{ow}) – SL$. Finally, w_{ref} should lie in or near the range of 50-100 m, as estimated from the topography of the Little Homer Pond barrier.

V.b. Results and Discussion: Effects of Varying Input Parameters (K' and Storminess Parameters) on the Periodic Storm Surge Model

Table 2. Final barrier width and shoreline retreat with varying K' and $SL_{storm}/W_{stddev}/t_{storm}$ ($z(d_{ow})$ – SL = 0.43 m, w_{ref} = 50 m, ΔS_{crit} = 0.0001 are held constant).

K' (m^3/yr)	SL_{storm} (m)	W_{stddev} (m)	t_{storm} (yr)	Final barrier width (m)	55-year shoreline retreat (m)
5000	1.5	1.0	10	109	21
8000	1.5	1.0	10	98	82
9000	1.5	1.0	10	112-122	11
9500	1.5	1.0	10	107-117	12
10000	1.5	1.0	10	109	21
10300	1.5	1.0	10	104-116	20
10400	1.5	1.0	10	93-105	164
10450	**1.5**	**1.0**	**10**	**95-105**	**104**
10500	1.5	1.0	10	113	97
11000	1.5	1.0	10	92-104	164
12000	1.5	1.0	10	94-105	165
15000	1.5	1.0	10	93-104	164
10450	1.5	1.0	10	95-105	104
10450	1.7	1.0	10	108-118	22.5
10450	**2.0**	**1.0**	**10**	**92-107**	**98**
10450	1.5	1.5	10	95-105	105
10450	1.5	2.0	10	94-104	108
10450	1.5	1.0	15	96-105	45
10450	1.5	1.0	20	98-108	42
5000	1.7	1.5	15	102	18
8000	1.7	1.5	15	96-106	50

9000	1.7	1.5	15	113	17
9400	1.7	1.5	15	93-103	165
9500	1.7	1.5	15	110-120	23
9545	**1.7**	**1.5**	**15**	**98**	**101**
9600	1.7	1.5	15	95-104	164
10000	1.7	1.5	15	93-104	164
15000	1.7	1.5	15	93-103	133

The most surprising outcome of these model runs was the extremely high sensitivity of barrier evolution to small changes in K'. As expected, very small values of K' (representing coarse-grained sediment and/or very slow sediment transport) led to slower shoreline retreat, and very high values of K' (representing fine-grained sediment and/or energetic shoreface currents) led to much faster shoreline retreat. But the transition zone between these two modes was not a smooth, steady increase in shoreline retreat, but rather a series of rapid oscillations in shoreline retreat outputs as K' was increased in successive model runs. While several scenarios were identified (marked in bold in Table 2) that recreated very closely the actual shoreline retreat and overwash deposition observed at Little Homer Pond, varying K' very slightly (by less than 1%) from these values resulted in changes in shoreline retreat of 50% or more (nearly 80% reduction when K' was changed from 9545 m^3/yr to 9500 m^3/yr in Table 2). Varying the new "storm" parameters added in this model did have an effect on the outputs, though the model was not as sensitive to 1% changes as was the case with K'. Increasing SL_{storm} did not result in an increase in shoreline retreat and erosion, in contrast to the results of previous storm-related erosion studies (Vellinga 1982, Kriebel and Dean 1985, van Rijn 2009), but rather some erratic fluctuations as well. Increasing t_{storm} (longer interval between major storms) had a more consistent effect of slowing down shoreline retreat, whereas varying W_{stddev} caused very little noticeable effect on the model at all, consistent with Kriebel and Dean's (1985) finding that wave height had much less of an effect than storm surge height on storm-related erosion.

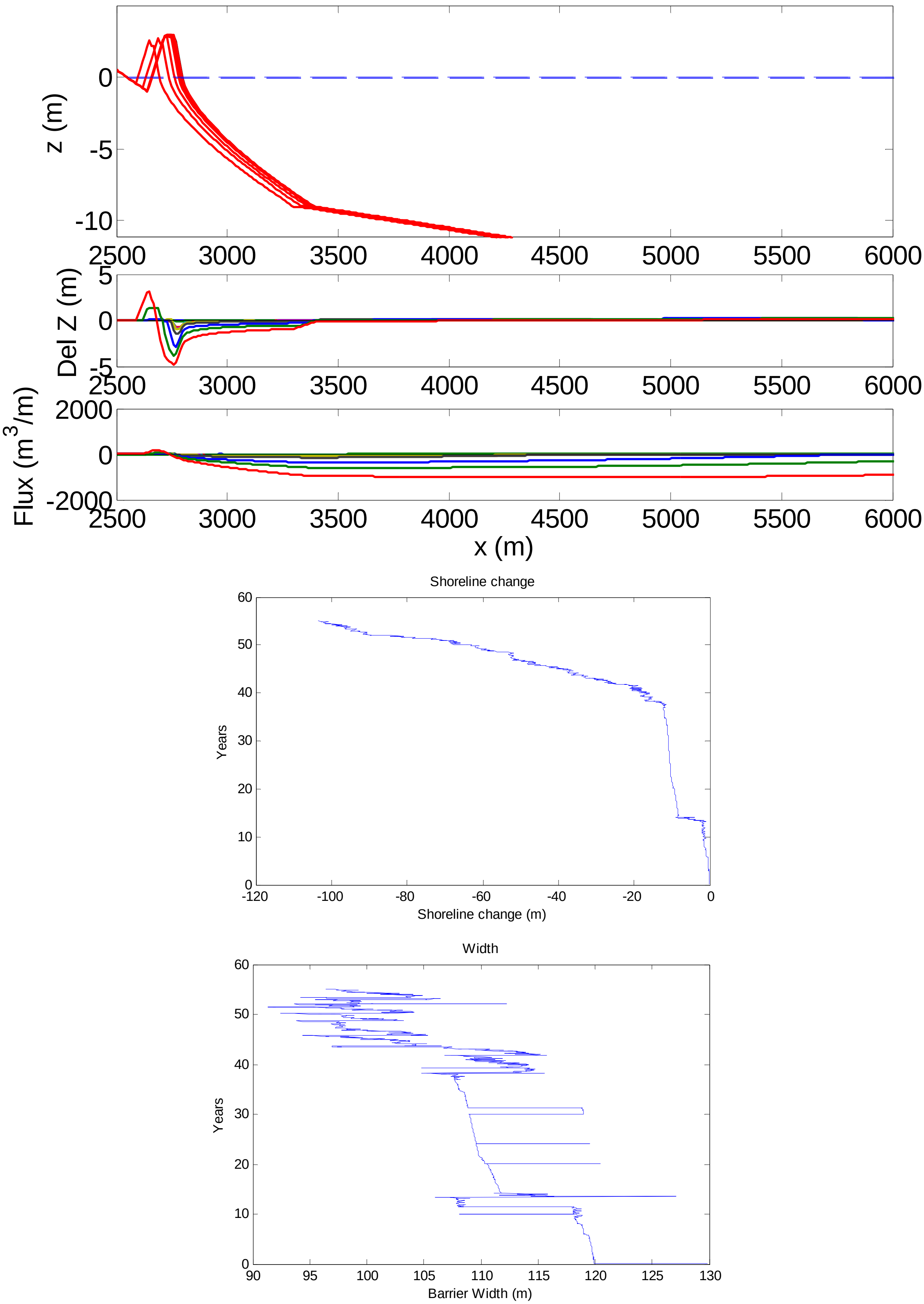


Figure 11. Periodic storm surge model run. Red outlines in the top figure indicate the shape of the barrier at 5.5-year intervals (leftmost outline is final barrier shape), while colored curves indicate the change in elevation (2nd plot) from the initial state and cumulative onshore flux (3rd plot) at 5.5-year intervals. Parameters K' = 10450 m^3/yr, S_{crit} = 0.0001, $z(d_{ow}) - SL$ = +0.43 m, w_{ref} = 50 m, SL_{storm} = 1.5 m, W_{stddev} = 1.0 m, t_{storm} = 10 yr.

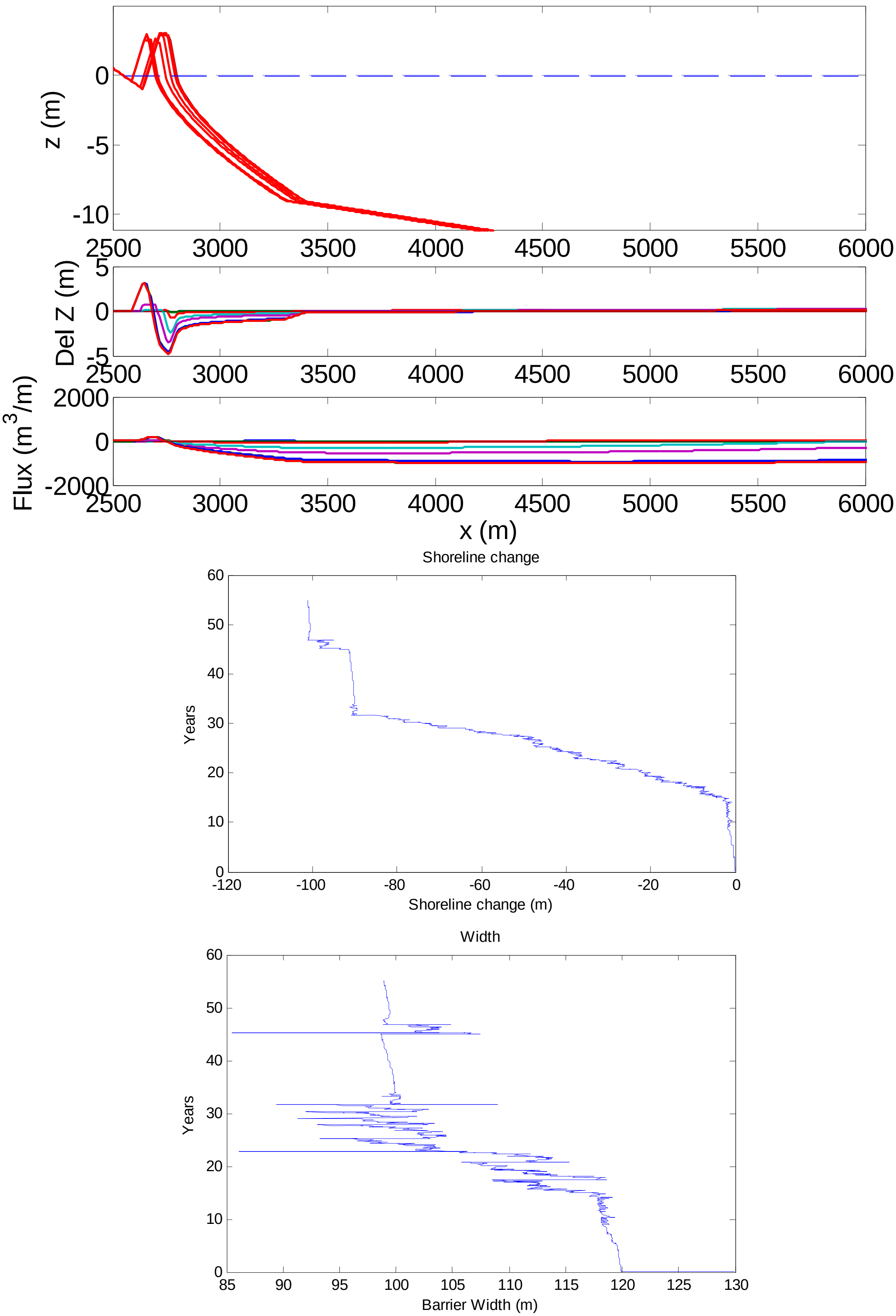


Figure 12. Periodic storm surge model run. Red outlines in the top figure indicate the shape of the barrier at 5.5-year intervals (leftmost outline is final barrier shape), while colored curves indicate the change in elevation (2nd plot) from the initial state and cumulative onshore flux (3rd plot) at 5.5-year intervals. Parameters K' = 9545 m^3/yr, S_{crit} = 0.0001, $z(d_{ow})$ – SL = +0.43 m, w_{ref} = 50 m, SL_{storm} = 1.7 m, W_{stddev} = 1.5 m, t_{storm} = 15 yr.

V.c. Results and Discussion: Effects of Varying d_{ow}, w_{ref}, and ΔS_{crit}

Table 3. Final barrier width and shoreline retreat with varying d_{ow} (varying extents of beach/shoreface erosion).

K' (m^3/yr)	**SL_{storm}/W_{stddev}/t_{storm}**	**$z(d_{ow})$ – SL (m)**	**w_{ref} (m)**	**ΔS_{crit}**	**Final barrier width (m)**	**55-year shoreline retreat (m)**
10450	1.5/1/10	+1.28	50	0.0001	98	42
10450	**1.5/1/10**	**+0.43**	**50**	**0.0001**	**95-105**	**104**
10450	1.5/1/10	-0.42	50	0.0001	95-105	165
10450	1.5/1/10	-1.88	50	0.0001	113	88
9545	1.7/1.5/15	+1.28	50	0.0001	93-103	166
9545	**1.7/1.5/15**	**+0.43**	**50**	**0.0001**	**98**	**101**
9545	1.7/1.5/15	-0.42	50	0.0001	107-117	43

Table 4. Final barrier width and shoreline retreat with varying w_{ref}.

K' (m^3/yr)	**SL_{storm}/W_{stddev}/t_{storm}**	**$z(d_{ow})$ – SL (m)**	**w_{ref} (m)**	**ΔS_{crit}**	**Final barrier width (m)**	**55-year shoreline retreat (m)**
10450	**1.5/1/10**	**+0.43**	**50**	**0.0001**	**95-105**	**104**
10450	1.5/1/10	+0.43	100	0.0001	91-103	70
9545	**1.7/1.5/15**	**+0.43**	**50**	**0.0001**	**98**	**101**
9545	1.7/1.5/15	+0.43	100	0.0001	93-103	132

Table 5. Final barrier width and shoreline retreat with varying ΔS_{crit}.

K' (m^3/yr)	**$SL_{storm}/W_{stddev}/t_{storm}$**	**$z(d_{ow})$ – SL (m)**	**w_{ref} (m)**	**ΔS_{crit}**	**Final barrier width (m)**	**55-year shoreline retreat (m)**
9545	1.7/1.5/15	+0.43	50	0.0005	114	5.5
9545	**1.7/1.5/15**	**+0.43**	**50**	**0.0001**	**98**	**101**
9545	1.7/1.5/15	+0.43	50	0.00002	109	21
1909	1.7/1.5/15	+0.43	50	0.0005	118-124	11
19090	1.7/1.5/15	+0.43	50	0.00005	104	36

The results of varying these three variables are mostly inconclusive as well, and again probably a reflection of instabilities in the model. The hypothesized result based on intuition was that storms that churn sediment up to a deeper level would result in higher rates of both shoreline retreat and overwash (hence greater barrier widths). The latter expectation may be supported by the model results in Table 3, in which final barrier width increases with deeper extents of storm erosion. However, even as storm erosion extends further down the shoreface, shoreline retreat rates only increase with the first scenario (K' = 10450 m^3/yr) and even then only up to a point. In the second scenario (with only slightly different K') the trend is reversed: shoreline retreat actually diminishes with increased churning up of sediment.

With w_{ref} it is the second scenario (K' = 9545 m^3/yr) rather than the first that actually supports the intuitive expectation. A higher value of w_{ref} would be associated with smoother or lower topography, so more shoreline retreat and overwash might be expected. Yet there is no noticeable effect of w_{ref} on final barrier width, and shoreline retreat actually decreases with smoother topography in the first scenario (higher K').

The value of ΔS_{crit} has no clear relationship with either shoreline retreat or final barrier width; one possible inference to draw from this is that $\Delta S_{crit} = 0.0001$ is near an "optimal value" for allowing the maximum shoreline retreat possible. There may be a physical basis for this result, although it is difficult to determine directly from the model. If ΔS_{crit} is too high, then sediment may not be forced far enough downslope and returns to the beach and top shoreface. If ΔS_{crit} is too low, then the rest of the shoreface profile may not be able to accommodate the extra sediment, so the best way to keep the profile closest to equilibrium slopes is to return the sediment to where it originated. The last two model runs listed in Table 5 change the values of K' and ΔS_{crit} simultaneously by inverse quantities. If the actual slopes were almost always close to critical slope values (i.e. $|S_{actual} - S_{eq}| \approx \Delta S_{crit}$), then this should have very little effect on the barrier evolution, since the product $K' * \Delta S_{crit}$ remains the same:

$$\Phi_{onshore} = K' * \left(S_{actual} - S_{eq}\right) * \frac{1}{1 + \left(SL - z\right)} \approx K' * \left(\pm \Delta S_{crit}\right) * \frac{1}{1 + (SL - z)} \qquad (9)$$

with the first part of equation (9) taken from equation (2).

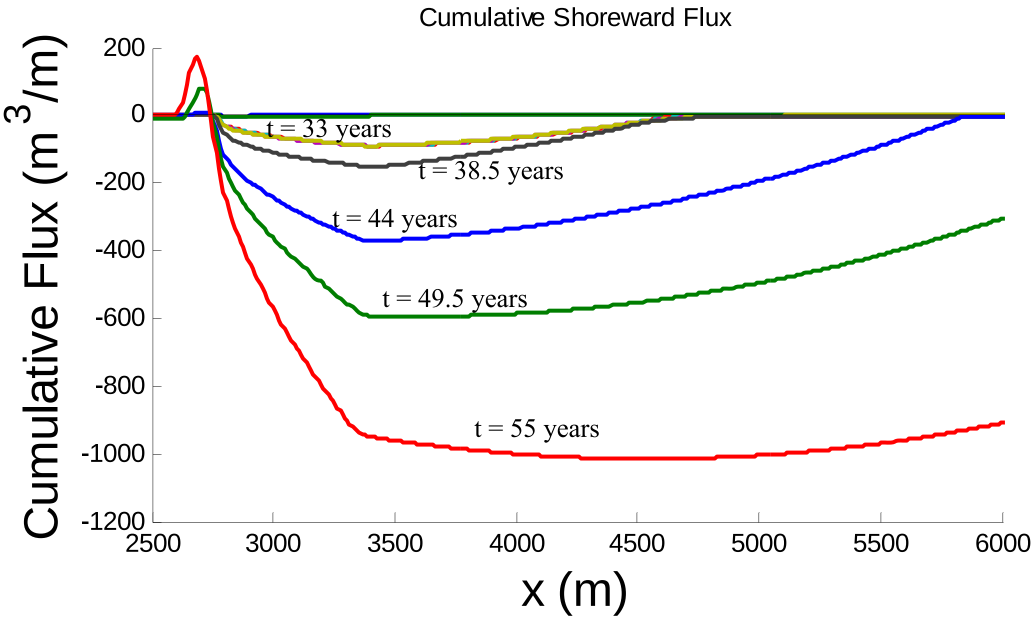
But this is not the case: K' and ΔS_{crit} do not have inverse effects on the model outputs. This would indicate that much of the sediment that is transported is moved when the slopes are not near critical values, and consequently that gradual shifts along the shoreface are more important than absolute limits on slope (i.e. that K' has more influence than ΔS_{crit} in determining sediment transport).

In short, the only variables that seemed to have the effects hypothesized were parameters just added to the periodic storm surge model (W_{stddev}, t_{storm}). Yet even changes due to variations in these parameters were insignificant compared to changes due to variations in K'. The model's extreme sensitivity to values of K' is unexpected; while it was to be expected that the properties of the sediment and local turbulent currents (both represented in the value of K') would have an effect on the short-term dynamic evolution of the barrier, variations of less than 1% in K' resulting in changes of 50% or more in shoreline retreat rates seems unlikely. Particularly suspect are the rapid oscillations with slight changes in K'—not only does shoreline retreat (and barrier width) change very rapidly for transitional values of K', but the barrier evolution switches between fast and slow erosion modes several times as K' is increased. This unstable behavior would suggest that even slight, almost imperceptible changes in the way that sediment responds to forces could result in 2 m/yr differences in shoreline retreat rates—a result that seems unlikely given the nearly uniform erosion rates along the coastline within several kilometers of Little Homer Pond.

VI. Conclusions from the Models and this Case Study

VI.a. Sediment Fluxes

With the input parameters producing unexpected and inconsistent results, it may seem difficult to use any of these models to gain reliable insights into the barrier evolution at Little Homer Pond. However, the model runs still contain valuable information, regardless of what input parameters produced them. One potentially useful result is the calculation of sediment fluxes across the shoreface and the barrier itself. The amount of sediment that is overwashed can be approximated from the GPR studies performed, but there is no similar observational method for estimating the amount of sediment that was eroded and deposited further offshore. However, with the model outputs it is possible to identify (or at least estimate) the mass fluxes of sediment over time, and in particular the relative quantities of overwashed sediment vs. sediment deposited offshore. The model scenarios that best recreate the barrier evolution (in the periodic storm surge model) have very similar mass fluxes and quantities of sediment being moved—even though they were produced by different input parameters. Over the 55-year period, the models show that about 1000 m^3/m of sediment is moved and deposited offshore, but only about 190 m^3/m is overwashed. In addition, most of the sediment deposited offshore is deposited 2-10 km offshore, not immediately offshore of d_{ow} as suggested by Vellinga's (1982) single-storm erosion modeling. Such a result implies that even sediment that is deposited just below the water level immediately after a storm could later be transported further offshore to maintain equilibrium slopes as closely as possible.



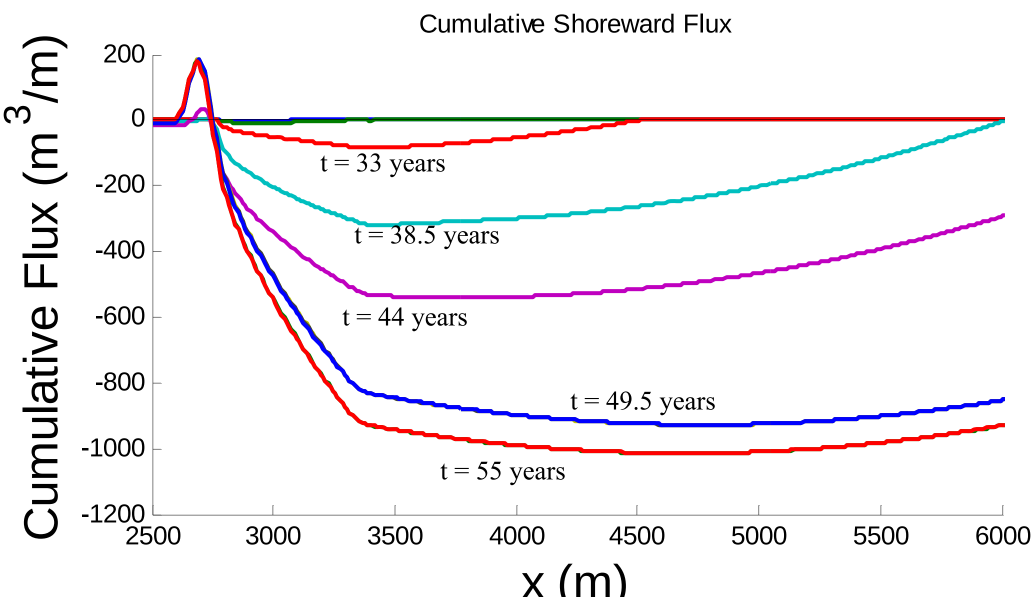


Figure 13. Model calculations of cumulative shoreward mass flux (negative indicates net offshore flux) at 5.5-year intervals over the 55-year time span. Both plots were produced using the periodic storm surge model, with $z(d_{ow}) - SL = +0.43$ m, $w_{ref} = 50$ m, $S_{crit} = 0.0001$. Individual plots were produced with parameters K' = 10450 m^3/yr, $SL_{storm} = 1.5$ m, $W_{stddev} = 1.0$ m, $t_{storm} = 10$ yr (top), K' = 9545 m^3/yr, $SL_{storm} = 1.7$ m, $W_{stddev} = 1.5$ m, $t_{storm} = 15$ yr (bottom).

This conclusion also requires that sediment be transported further and further offshore over time, so that the model barrier is not a closed system (i.e. there is no technical limit to how far offshore eroded sediment can travel). Such transport is still plausible, however, since the rapid shoreline retreat rates indicate that this barrier is not following traditional Bruun rule evolution. There are some reasons to consider it likely that the flux calculations are valid, even if the model that produced them is probably flawed. First, all of the scenarios identified (two of which are shown in Figure 13) that yield the shoreline retreat and final barrier width closest to that observed at Little Homer Pond also output nearly identical sediment fluxes. The flux of mass over the barrier indicated in these model runs is also consistent with the quantities of overwash observed with GPR in the back barrier region. The GPR transects show the likely washover units as extending to a depth of 2 m; as seen in Figure 14, this corresponds on average to the thickness of new sediment that should exist in this part of the barrier according to model runs. The total cross-sectional area of the units identified in the GPR transects is ~70-80 m^3/m, while the model indicates that 190 m^3/m of sediment should overwash over the 55-year span. If the model runs are correct in reproducing the correct mass fluxes, then the overwash units identified should account for ~40% of the total overwash during this time span. If the rate of overwash were consistent, this would correspond to the overwash during the last 22 years, but of course the periodic nature of storms does not lead to steady overwash rates over short time scales (i.e. over time spans close to t_{storm}).

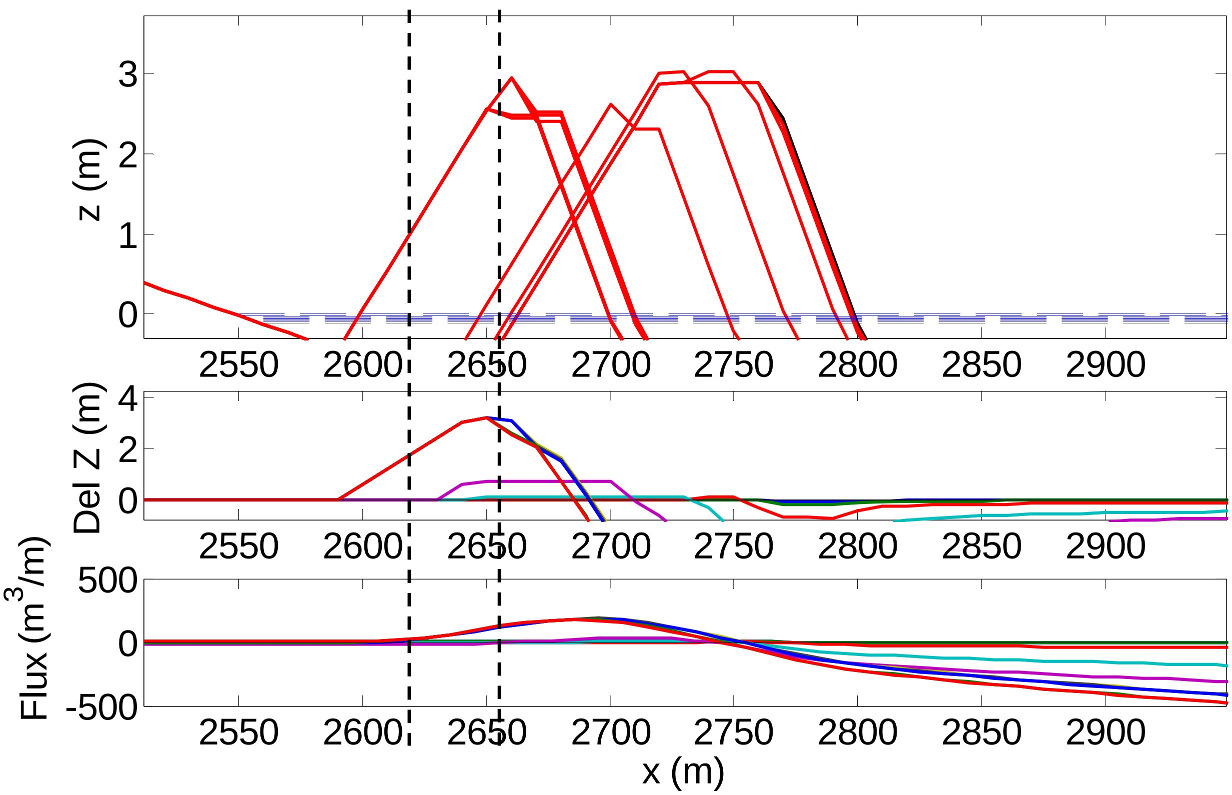


Figure 14. Enlarged portion of the cross-section of barrier evolution, periodic storm surge model. Red outlines in top figure indicate barrier shape at 5.5-year intervals (leftmost outline is final barrier shape). Multicolored curves indicate change in elevation from the initial state (2nd plot) and cumulative flux (3rd plot), with leftmost red curve corresponding in both plots to the final state (t = 55 years). SL_{storm} = 1.7 m, W_{stddev} = 1.5 m, t_{storm} = 15 yr, K' = 9545 m^3/yr, S_{crit} = 0.0001, w_{ref} = 50 m, $z(d_{ow})$ – SL = +0.43 m. The dotted lines indicate the part of the cross-section corresponding to the probable washover units identified in GPR transects.

VI.b. Problems with Model Assumptions, and Possible Relation to the Glacial Origins of the Terrain

Even with these useful insights into mass transport, however, the periodic storm surge model does not seem to represent the entire process of barrier evolution accurately. Aside from the effects of the input parameters (and K' in particular) being very suspect, the rates of shoreline retreat are not as steady as observed in the actual data and aerial photographs from Little Homer Pond. In the model, the vast bulk of the shoreline retreat appears to happen in the last 20 years of the 55-year time span. While this might be explainable due to the fact that more sediment would overwash as the barrier gets narrower—further reducing the amount of sediment in front of the barrier—the observational data do not support this erratic pattern of shoreline retreat.

Another question, perhaps related, is whether the concept of equilibrium slope used as the basis for these models is actually representative of the barrier. As discussed previously, the models used in this study all assume that the slopes along the shoreface (as mapped by NOAA) are very close to their equilibrium values, and that the response time to return to these equilibrium values is very short. Yet the shoreline retreat observed here is much too fast to be consistent with the traditional Bruun rule or the concept of equilibrium slope derived from it. It is quite possible that these slopes are not near equilibrium values, but that the barrier is responding very slowly to an unstable configuration over centuries-long or even millennial time scales. The shoreline retreat observed here is much too fast to be consistent with the traditional Bruun rule or the concept of equilibrium slope derived from it. Many processes influencing shoreline change and retreat cause long-term cycles or oscillations over timescales of 150 years or more (Camfield and Morang 1996). But while Little Homer Pond (and the nearby coastline) could be in the faster phase of such a cycle, these cycles usually occur only where inlets or longshore transport are significant factors. Faster retreat rates and landward rollover also tend to predominate in areas where relative sea-level rise rates are higher, as is the case along the Louisiana coastline (McBride et al. 1995), where extremely fast retreat rates can not be accounted for by the Bruun rule and related equilibrium concepts (List et al. 1997). However, the subsidence that is largely responsible for such high relative sea-level rise rates in Lousiana does not appear to be a factor at Martha's Vineyard. At this point it might be tempting to abandon the Bruun rule or the notion of an equilibrium profile entirely (as suggested by Cooper and Pilkey 2004), but there is another potential explanation that faults not the concept of equilibrium slopes, but rather the lack of knowledge of equilibrium slope values for this case study.

Ultimately, the key to understanding barrier evolution at Little Homer Pond (and elsewhere along the south coast of Martha's Vineyard) could be the fact that Martha's Vineyard itself is a terminal moraine, with steep slopes uncharacteristic of most of the U.S. east coast. Shoreline retreat rates faster than the Bruun rule would indicate, and significant sediment transport offshore, all point to a shoreface profile that is getting shallower (i.e. less steep). Glacial detritus deposited along this coastline at the Last Glacial Maximum was most likely drastically steeper than the equilibrium slope configuration, and it is possible that the coastline has been gradually shifting towards this shallower equilibrium over the past 18,000 years—and has still not reached it yet. It might seem that the millennial time scales required of such barrier evolution are irrelevant when considering the decadal-scale changes tracked by the models in this study. However the volumes of sediment that must necessarily be transported offshore to maintain the observed shoreline retreat rates require either a depositional range that extends hundreds of kilometers offshore, or a profile that is evolving faster than the (relatively) gradual changes in sea level would force it to evolve.

All this is of course speculation; the extreme fine-tuning of parameters necessary (particularly in the periodic storm surge model) may just be the result of an intrinsic problem with the model. However, shifts in equilibrium from gradual sea level changes (the pure equilibrium slope model) can not explain the fast shoreline retreat rates here. Nor can the periodic storm surge model recreate shoreline retreat scenarios that are both accurate and steady, without introducing erratic behavior not observed at Little Homer Pond. It is true that these dynamic models are not strictly based on the Bruun rule, and are in fact intended to show barrier response to non-equilibrium configurations. But if the equilibrium slopes are not known to begin with—as would be the case if the barrier is still in the process of reaching them after thousands of years of evolution—then these dynamic models will still not be able to recreate the observed changes. Hence LGM sediment deposition, followed by a millennial-scale recovery that has still not reached equilibrium, is a simple yet plausible explanation. It does not fault the models themselves, but rather the timescales used and assumptions made to apply them, and is certainly worth further consideration.

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Appendix: Description of Input Parameters (Variables) Used in the Models

Set erosion rate (E_{rate}). Determines what volume (or cross-sectional area in the model) of sediment is eroded from the beach and upper shoreface (to ~2 m depth); this sediment is also available to be overwashed (as specified in equation (3)). Makes calibrating the model to actual erosion and shoreline retreat rates easier, but the physical basis for it is unclear; consequently it is abandoned in the models for the Little Homer Pond simulations in favor of using C (in the pure equilibrium slope model) or SL_{storm} and W_{stddev} (in the periodic storm surge model) to determine how much sediment can be overwashed.

Overwash blocking parameter (C). Determines what percentage of available sediment will be overwashed, given a certain height of the barrier above mean sea level. Lower values allow more overwash ($C << 0.1$ allows almost all the sediment shoreward of d_{ow} to overwash), while higher values ($C >> 1$) prevent almost all sediment from overwashing. In the periodic storm surge model the function of this parameter is replaced by SL_{storm} and W_{stddev}.

Extent of sediment that can be overwashed (d_{ow}). This is the furthest (horizontal) distance offshore from which eroded sediment can be overwashed. Further offshore from this point, sediment that is unstable will be redistributed only along the front of the barrier. This variable can also be expressed as $z(d_{ow}) - SL$, the height/depth relative to sea level above which sediment can be overwashed. In the periodic storm surge model this variable also marks the lowest extent of the formation of the "storm profile".

Reference width of barrier (w_{ref}). This is the width of the barrier considered equivalent to 1 m of additional barrier height, for the purposes of blocking overwash. It is intended to incorporate the effects of friction and uneven topography, as well as the fact that a wider barrier is likely to have higher topography, even though the models assume a flat berm at the top. A lower value blocks more overwash than a higher value. Based on the width and topography at Little Homer Pond, w_{ref} for this barrier probably lies in the range 50-100 m.

Flux parameter (K'). K' (in units of m^3/yr) affects how susceptible sediment is to be transported, and also the time scale of transport. Small values (K' << 5000 m^3/yr) indicate coarse-grained sediment and/or relatively tranquil shoreface currents that will only move sediment very slowly even when on an unstable slope (not close to S_{eq}). Large values (K' >> 50000 m^3/yr) indicate fine-grained sediment or very turbulent conditions on the shoreface that will quickly move sediment towards a stable steady-state profile. While these values seem extraordinarily large, the actual physical fluxes are obtained by multiplying this parameter by $S_{actual} - S_{eq}$, which rarely has a value larger than 0.0005 (resulting in actual offshore fluxes of 0.01-25 m^2/yr at any given point along the shoreface).

Critical slope offset (ΔS_{crit}). This is a maximum limit on the amount by which the slope at a given point along the profile is allowed to deviate from the equilibrium slope (S_{eq}). If $|S_{actual} - S_{eq}| > \Delta S_{crit}$, then the slope will automatically be considered unstable and the sediment eroded and transported to a more stable part of the profile. Values for this in the models range from 0.00002 to 0.0005, but values near 0.0001 yield the most accurate, consistent results.

Storm surge level (SL_{storm}). The height by which the sea level is raised temporarily during storm events in the periodic storm surge model. It is the reference sea level from which slopes shoreward of d_{ow} are calculated to form the "storm profile". This value is an average of the storm surge levels from the most powerful storms to hit the region (particularly those that cause overwashing of the barrier); data from major hurricanes and sea level frequency studies (Birkemeier et al. 1998, NWS, Walton 2000, Huang et al. 2008) suggests it should lie in the range 1.5-2.0 m.

Wave height standard deviation (W_{stddev}). In the periodic storm surge model, the standard deviation of a standard distribution of waves during overwashing storms, relative to the storm surge level. This value determines what percentage of waves (and how much sediment) is likely to overtop the barrier in a given storm. From the data given by Birkemeier et al. 1998 for the coastal Northeastern U.S., a range of 1.0-2.0 m seems reasonable for this value.

Frequency of overwashing storms (t_{storm}). The frequency in the model at which the sea level is temporarily raised to a height SL_{storm} above mean sea level and an erosion “storm profile” is formed. This represents the impact of a storm powerful enough to cause overwash; studies of GPR transects, aerial photographs, and historical data indicate that this value is likely in the range of 10-15 years.