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ABSTRACT

SMITH, C.G.; CULVER, S.J.; RIGGS, S.R.; AMES, D.; CORBETT, D.R., and MALLINSON, D., 2008. Geospatial analysis of barrier island width of two segments of the Outer Banks, North Carolina, USA: anthropogenic curtailment of natural self-sustaining processes. *Journal of Coastal Research,* 24(1), 70–83. West Palm Beach (Florida), ISSN 0749-0208.

A comparison of two sections of the Outer Banks, North Carolina, USA (Pea Island and Avon-Buxton areas), reveals the importance of the interplay between oceanic and estuarine shoreline dynamics to long-term changes in barrier island width. From 1852 to 1998, the northern portion of Pea Island experienced an average net increase in width of 431 m (3 m/y); this area experienced low to moderate rates of oceanic shoreline erosion and high rates of back-barrier land accretion via overwash and formation of flood tidal delta islands. In contrast, between 1852 and 1998, the width of the southern portion of Pea Island and the Avon-Buxton area decreased an average of 515 m (4 m/y) and 594 m (4 m/y), respectively, because of high rates of oceanic shoreline erosion and variable changes in estuarine shoreline accretion and erosion. Net gain or net loss of barrier island width is strongly dependent on the natural depositional processes of overwash and flood tide delta formation. Anthropogenic modifications to the barrier island, such as construction of barrier dune ridges, planting of stabilizing vegetation, and urban development, can curtail or even eliminate the natural, self-sustaining processes of overwash and inlet dynamics.

ADDITIONAL INDEX WORDS: *Flood tide delta, shoreline erosion, Pea Island, Avon-Buxton, overwash.*

INTRODUCTION

The Outer Banks are a chain of microtidal, wave-dominated, barrier islands that extend 320 km from Cape Henry, Virginia, to Cape Lookout, North Carolina (Figure 1). The portion of the Outer Banks located within North Carolina is presently dissected by five inlets (Oregon, Hatteras, Ocracoke, New Drum, and New Old Drum); these inlets act as conduits for water and sediment between the back-barrier estuaries (Currituck, Albemarle, Roanoke, Croatan, Pamlico, and Core Sounds) and the Atlantic Ocean. A considerable amount of work has addressed the origin and geologic history of the Outer Banks barrier island system (*e.g.,* CULVER *et al.,* 2006; FISHER, 1962; HOYT and HENRY, 1971; MALLINSON *et al.,* 2001; MOSLOW and HERON, 1979; PIERCE and COLQUHOUN, 1970; RIGGS, CLEARY, and SNYDER, 1995) and oceanic shoreline change (BENTON *et al.,* 1993; DOLAN and LINS, 1986; EVERTS, BATTLEY, and GIBSON, 1983; FENSTER and DOLAN, 1993). Recently, RIGGS (2001) and RIGGS and AMES (2003) focused on estuarine shoreline erosion. The majority of these oceanic and estuarine studies were conducted on a regional scale and do not provide detailed measurements for individual barrier island segments. None of these studies addressed both oceanic and estuarine shoreline change for a particular barrier island segment, resulting in a disconnect between shoreline change and total changes in barrier island width.

The increase in human population and associated development on the barrier island system of the North Carolina Outer Banks (OBCC, 2004) makes it essential that long-term patterns of oceanic and estuarine shoreline change and the effect on barrier island integrity be better documented and understood. Oceanic and estuarine shoreline changes are controlled by natural processes that can be curtailed by anthropogenic modifications to the barrier islands. Processes that maintain barrier island width (*i.e.,* flood tide transport, overwash, and eolian processes) have historically been disrupted by development (*e.g.,* roads, buildings) and coastal engineering (*e.g.,* constructed barrier dune ridges, planted vegetation, artificial inlet closures, inlet stabilization). The purpose of this paper is to compare two sites on the Outer Banks with

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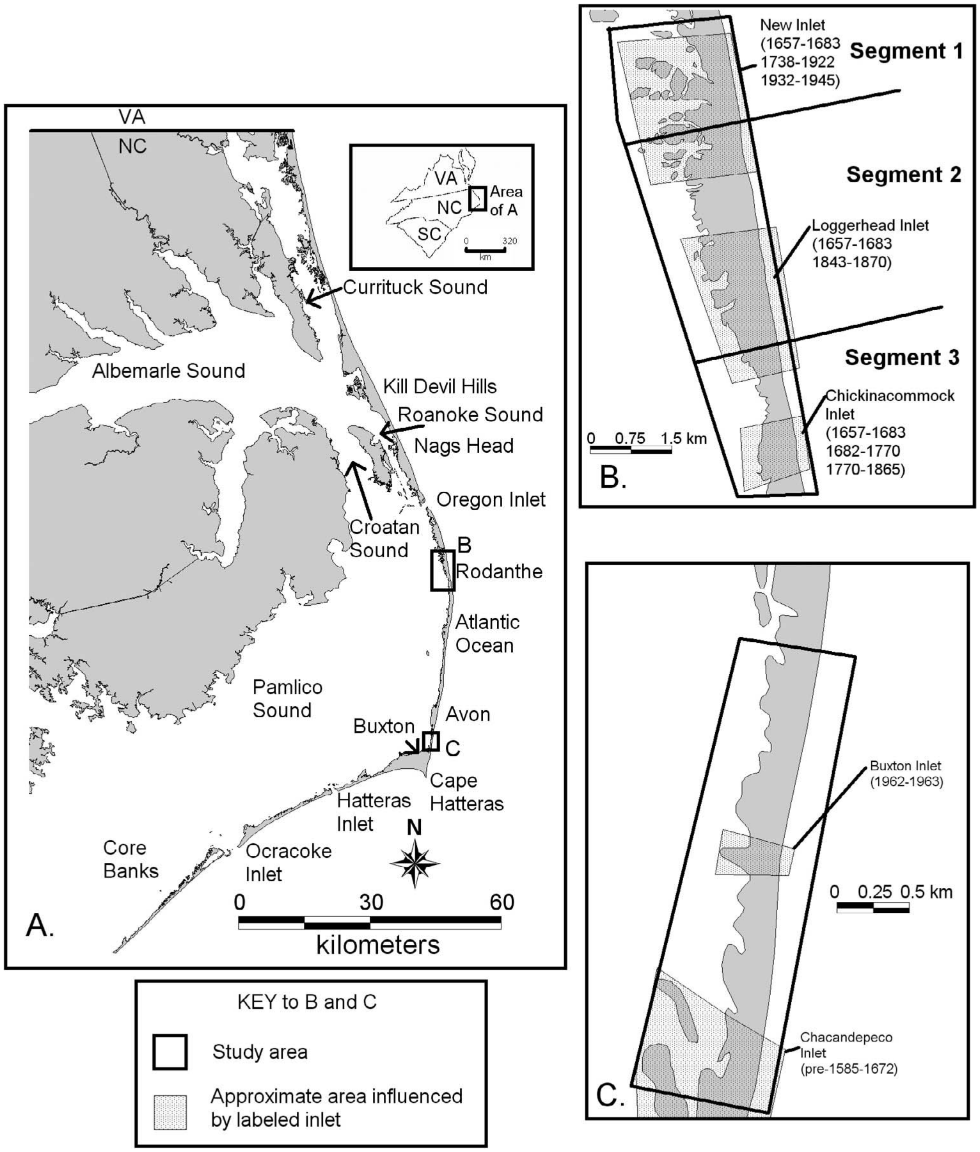

Figure 1. (A) Map of northeastern North Carolina shows the Outer Banks extending from the North Carolina–Virginia border south to Core Banks. The small boxes indicate the two study areas: Pea Island (B) and Avon-Buxton (C). The boxed areas in panels B and C are segments for which oceanic shoreline change measurements were made. Shading indicates the approximate areas influenced by former inlets. Dates of open inlets are taken from Fisher (1962).

different inlet histories to assess oceanic and estuarine shoreline change (accretion/erosion) through time and their effect on barrier island width.

METHODS

Digitally georeferenced aerial photographs and historic topographic and bathymetric surveys dating back to 1852 were used to quantify changes in barrier island width and oceanic and estuarine shoreline change along two sections of the Outer Banks (Pea Island and Avon-Buxton; Figure 1). The dates of the aerial photographs differed for each area and are listed in Table 1. The aerial photographs were digitally registered with MapInfo Professional Version 6.5 (Mapinfo Corporation, Troy, New York) to the 1983 United States State Plane Coordinate System (in meters), section 3200 (North Carolina), with the 1998 Digital Orthophotograph Quarter Quadrangles (DOQQ) as a reference. The registering process required a minimum of four control points with known x, y coordinates; these control points generally consisted of human infrastructure (*e.g.,* bridges, buildings) and occasionally isolated trees or shrubs. The historic surveys were registered to the same coordinate system by the intersections of lines of latitude and longitude that were present on the maps; the latitude and longitude coordinates were then converted to the United

Table 1. *Historic surveys and aerial photographs used in this study.*

Date of Survey/Aerial Photograph	Areas
1852 Coastal and Geodetic Survey topographic survey	Pea Island Avon-Buxton
1909 Coastal and Geodetic Survey hydrographic survey	Pea Island (New Inlet)
1917 Coastal and Geodetic Survey topographic survey	Pea Island Avon-Buxton
1932 Aerial photographs	Pea Island
1940 Aerial photographs	Avon-Buxton
1949 Aerial photographs	Pea Island
1962 Aerial photographs	Pea Island Avon-Buxton
1974 Aerial photographs	Avon-Buxton
1998 Digital orthophotograph quarter-quadrangles	Pea Island Avon-Buxton

States State Plane Coordinate System. MapInfo has a built-in algorithm that assists in the georeferencing process; the algorithm computes the approximate location of each point on the basis of the placement of other points (*cf.* triangulation technique) and reports a pixel error that indicates the pixel offset from the user's placement to that of the computed placement. In this study, all aerial photographs and surveys had pixel errors of less that two, which translates into an approximately 2 m error.

The 1998 DOQQs have a horizontal accuracy of ±10.8 m or less (as defined by the US Geological Survey [USGS] National Mapping Standards for DOQQs; USGS, 1996). Aerial photographs postdating 1952–53 have a horizontal error of ±14.8 m or less; this was determined with the use of segments of North Carolina Highway 12 as a control. Although the accuracy of the georeferenced aerial photographs predating 1952–53, as well as the historic surveys, could not be assessed with the use of North Carolina Highway 12 (these predate the road), the precision of the georeferenced material could be compared with previously published data (*i.e.,* Everts, Battley, and Gibson, 1983). A digitized version of Everts, Battley, and Gibson (1983) shoreline data was obtained from the Dare County (2005) Information Technology Geographic Information Systems Division and compared with digitized data presented in this study; the maximum difference between the shoreline data of the two independent data sets was 5 m.

Shore-normal profiles (40 for Pea Island and 18 for Avon-Buxton) spaced 200 m apart were used to evaluate changes in mean barrier island width and mean oceanic and estuarine shoreline change. Oceanic and estuarine shorelines for each historic survey and aerial photograph set were digitized at a scale of 1 cm = 32.68 m (1 in = 83 m). Oceanic and estuarine shoreline change measurements, made at 1 cm = 19.69 m (1 in = 50 m), were made approximately perpendicular to the two shoreline sections being compared following the procedure used by Everts, Battley, and Gibson (1983) and Fenster and Dolan (1993). Occasionally, the profiles were not exactly perpendicular to the estuarine shoreline because of its irregular nature. A similar methodology (at the same scale) was used to assess barrier island width; however, measurements were conducted from ocean shoreline to estuarine shoreline. Barrier island width change data were also interpolated from shoreline change measurements and compared with direct barrier island width measurements; the two methods agreed within an error of ±10 m. The data are presented as the mean and standard deviation of all profiles within a single segment. As a result of this simplistic statistical approach, the standard deviation exceeds the mean. In these cases, the variance is generally associated with one or two profiles. For this reason, we have included the raw data for each transect in the appendices (Appendix A, B) for completeness.

For presentation purposes, the barrier island width data have been divided into two categories: main barrier island width (MBIW) and back-barrier island width (BBIW) (Figure 2). This division is made for two reasons: (1) to distinguish between barrier island zones that are dominated by estuarine shoreline progradation from those that are dominated by a combination of estuarine shoreline progradation and back-barrier island formation and accretion and (2) to provide a time-dependent measurement that quantifies the transition from one barrier island zone to the other. MBIW is the measured width of the main subaerial barrier island excluding unconnected back-barrier islands (Figure 2A and 2B). BBIW excludes the main barrier island and represents the total (summed) width of detached back-barrier islands (Figure 2A). Thus, these divisions are quantitative values not geomorphic features.

RESULTS

Trends in Island Width

A visual, qualitative comparison of subaerial barrier island segments, digitized from georeferenced aerial photographs and historic surveys, shows changes in barrier island width through time (Figures 3 and 4). Pea Island segments 1 and 2 (profiles 1–10 and 11–30, respectively) experienced a net increase in barrier island width between 1852 and 1998 (Figure 3). In contrast, Pea Island segment 3 (profiles 31–40, Figure 3), as well as the entire Avon-Buxton study area (profiles 1–18, Figure 4), experienced a net loss in main barrier island width during the 146-year period. Measurements along the shore-normal profiles quantify these observations (Tables 2–4; Figure 5A).

Pea Island segments 1 and 2 experienced a mean MBIW increase of 431 ± 395 m between 1852 and 1998 at a rate of 3.0 ± 2.7 m/y(Table 3; Figure 5A). Between 1852 and 1917, mean MBIW for profiles within segments 1 and 2 that were not in the main inlet channels decreased 27 ± 196 m (Table 3; Figure 5A). In contrast, BBIW increased during this period (Table 2). Between 1917 and 1932, segment 1 continued to lose MBIW and gain BBIW; segment 2 increased in both MBIW and BBIW (Table 2; Figures 3B, 3C, and 5A). Mean MBIW for segments 1 and 2 increased 813 ± 576 m (47.8 m/y) and 327 ± 396 m (19.3 ± 23.3 m/y), respectively, between 1932 and 1949 (Tables 2 and 3; Figure 5A). Between 1949 and 1998, both segments lost MBIW (Tables 2 and 3; Figure 5A); segment 1 decreased an average of 77 ± 142 m (1.6 ± 3.0 m/y), and segment 2 decreased an average of 9 ± 76 m (0.2 ± 1.5 m/y).

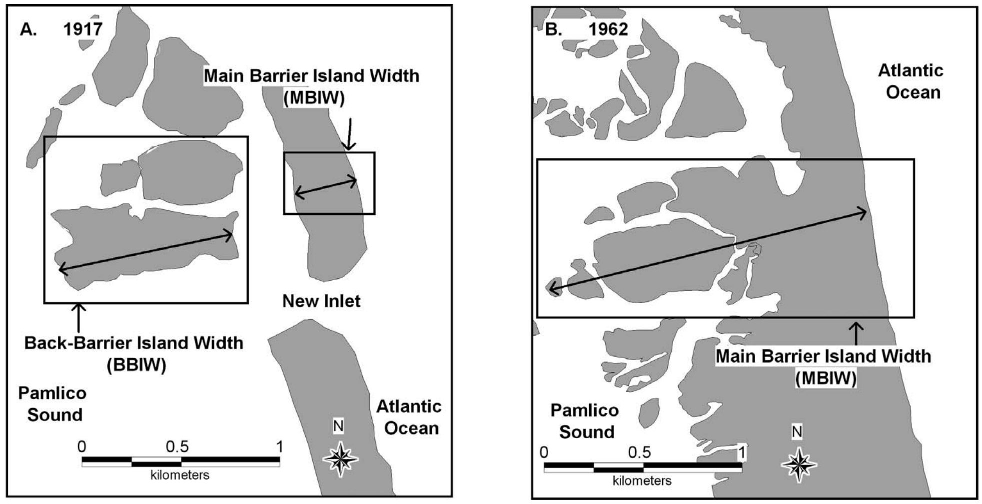

Figure 2. Shoreline traces of the 1917 topographic survey (A) and the 1962 aerial photograph (B) for northern Pea Island depicting the relationship between main barrier island width (MBIW) and back-barrier island width (BBIW) as used in this study. The small back-barrier islands present in panel A are not included in MBIW but are summed into BBIW. In panel B, however, the islands have become incorporated onto the main portion of the barrier island, resulting in a large increase in MBIW; subsequently, there is zero width for BBIW.

In strong contrast, Pea Island segment 3 and Avon-Buxton demonstrated net land loss (Tables 2 and 3; Figure 5). MBIW along Pea Island segment 3 (profiles 31–40; Figure 3) and Avon-Buxton (Figure 4) decreased an average of 515 ± 207 m (3.5 m/y) and 594 ± 15 m (4.1 m/y), respectively, between 1852 and 1998 (Tables 2 and 3; Figure 5). Both areas demonstrated net loss in MBIW during the entire 146-year period. Pea Island segment 3 experienced fairly consistent rates of MBIW loss (2–4 m/y), except for the interval of 1932–1949, in which rates peaked at 8.6 ± 2.0 m/y (Table 3; Figure 5). From 1852 to 1974, Avon-Buxton lost MBIW at a fairly consistent rate of 4.5 ± 0.6 m/y; after 1974, the rate of MBIW loss decreased to approximately 2.7 ± 4.7 m/y (Table 3; Figure 5).

Trends in Oceanic and Estuarine Shoreline Change

Pea Island segments 1 and 2 represent an average net gain of MBIW during the 146-year period (Tables 2 and 3) because of the accretion of back-barrier flood tidal delta islands (segments 1 and 2) and extensive overwash (segment 2, Figure 3). Along the oceanic shoreline, segments 1 and 2 receded 89 ± 27 m (0.6 ± 0.2 m/y) and 198 ± 103 m (1.4 ± 0.7 m/y), respectively, between 1852 and 1998 (Table 4; Figures 6 and

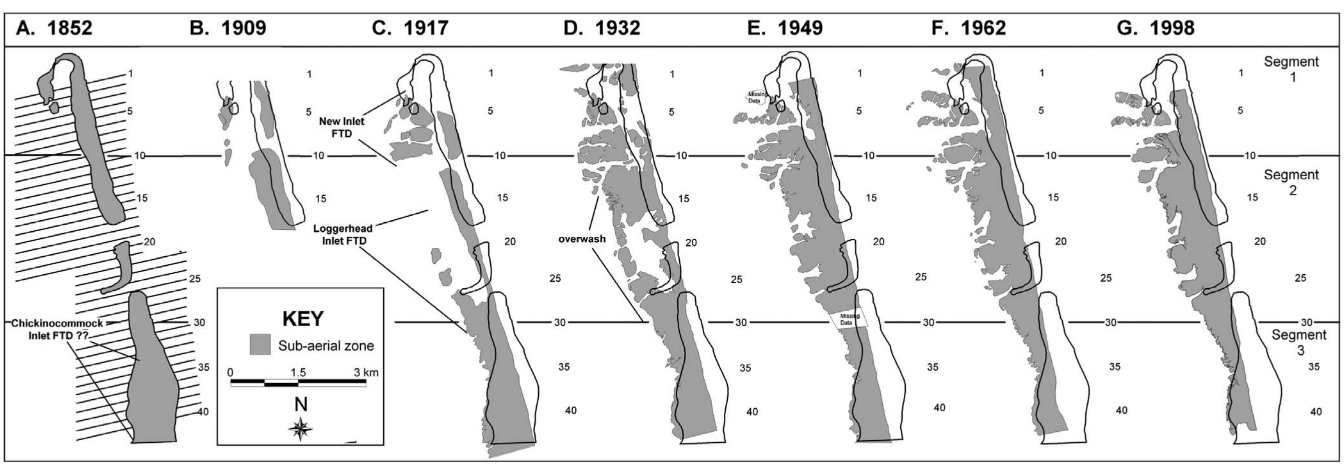

Figure 3. Time slice maps comparing barrier island width and morphology at Pea Island. The digitized areas (A–G) represent the subaerial barrier island as mapped from the aerial photographs and historic surveys. The 1852 shoreline is overlain on each panel. Measurements presented in Table 2 were obtained along the 40 profiles indicated in panel A. Areas influenced by historic inlets and extensive overwash are indicated. Profiles 1 to 10 = segment 1, profiles 11 to 30 = segment 2, and profiles 31 to 40 = segment 3.

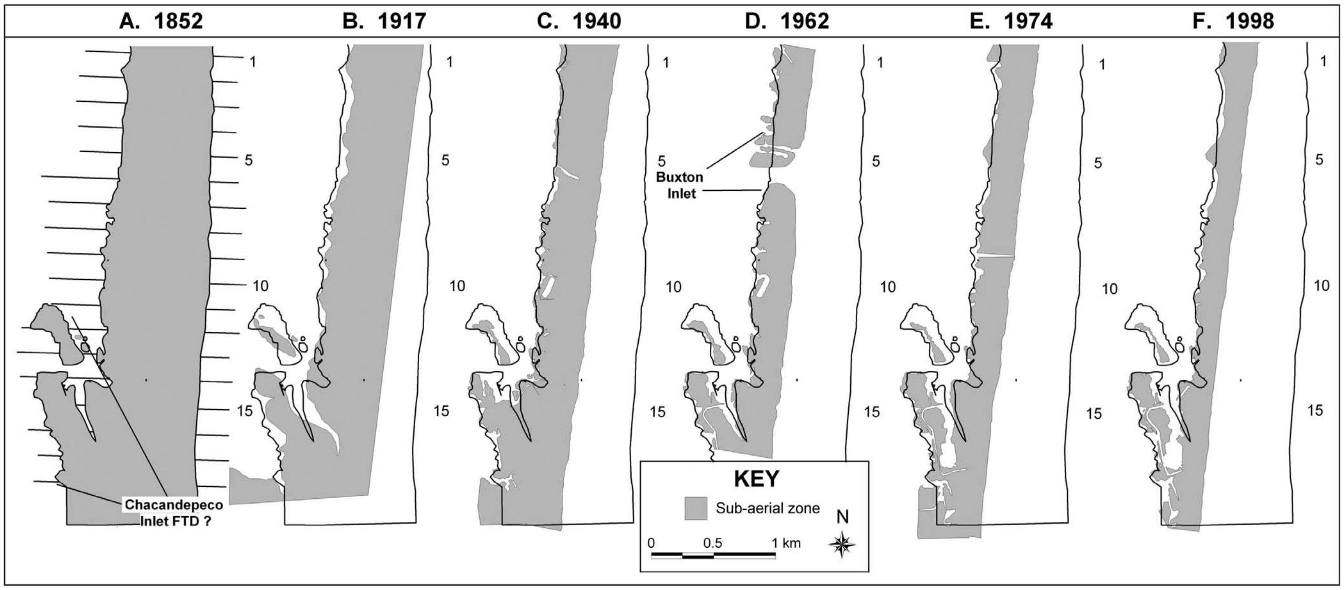

Figure 4. Time slice maps comparing barrier island width and morphology for the Avon-Buxton segment. The digitized areas (A–F) represent the subaerial barrier island as mapped from the aerial photographs and historic surveys. The 1852 shoreline is overlain on each panel. Measurements presented in Table 3 were obtained along the 18 profiles indicated in panel A. Areas influenced by historical inlets are indicated.

7A). Rates of oceanic shoreline change for shorter time intervals ranged from approximately +5 to −4 m/y (Table 4). Neither segment experienced high enough rates of oceanic shoreline erosion (average 1.0 m/y) (Table 4) to counterbalance the high rates of land gain (average 3.0 m/y) (Table 3) resulting from shoreline progradation, back-barrier flood tidal delta island accretion/incorporation and overwash.

Pea Island segment 3 and the Avon-Buxton area demonstrate net loss in MBIW (Figure 8). The mean rate of oceanic shoreline erosion for Pea Island segment 3 between 1852 and

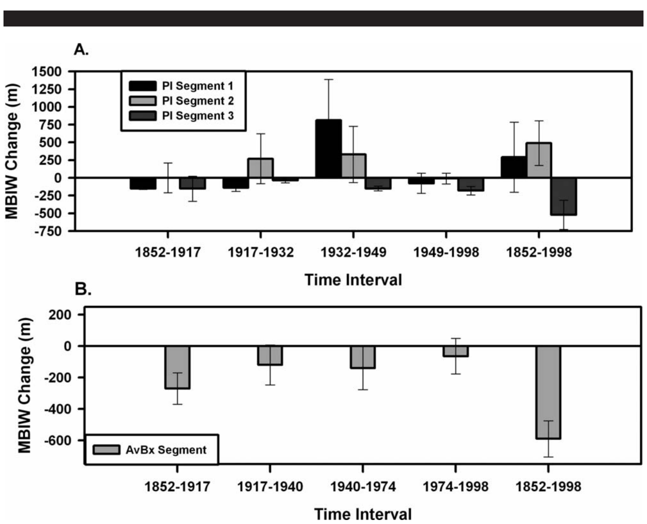

Figure 5. Bar graph showing the mean and standard deviation of main barrier island width (MBIW) change for each segment in Pea Island (A) and the Avon-Buxton area (B).

1998 was 4.3 ± 0.6 m/y (Table 4; Figure 7A and 7B). Oceanic shoreline erosion peaked between 1932 and 1949, which is congruent with the erosion peak in Pea Island segments 1 and 2. Before and after this interval, oceanic shoreline erosion rates were slightly lower, but still much greater than in segments 1 and 2 (Table 4). Pea Island segment 3 experienced a net progradation (0.8 ± 1.1 m/y) of the estuarine shoreline between 1852 and 1998 (Table 4). This amounts to approximately 24% of land loss from oceanic shoreline erosion. Thus, there is a net loss in MBIW. Estuarine shoreline progradation of approximately 2 to 3 m/y occurred before 1932, followed by estuarine shoreline erosion from 1932 to 1949. Estuarine shoreline progradation characterizes the 1949 to 1962 interval (Figure 7B), probably as a result of heavy storm overwash during the 1962 nor'easter, the Ash Wednesday Storm.

Between 1852 and 1998, the Avon-Buxton area experienced oceanic and estuarine shoreline erosion at rates of 3.9 ± 0.6 and 0.2 ± 0.4 m/y, respectively (Table 4). Oceanic shoreline erosion peaked at a rate of 7.4 ± 1.0 m/y, between 1917 and 1940. This same period showed a net accretion rate on the estuarine shoreline of 0.8 ± 1.9 m/y. Before and after this interval, rates of oceanic and estuarine shoreline erosion average 2 to 4 m/y and 0.2 to 0.4 m/y, respectively (Table 4; Figure 7B).

DISCUSSION

From 1852 to 1998, net gain in MBIW characterizes Pea Island segments 1 and 2 and net loss in MBIW characterizes Pea Island segment 3 and the Avon-Buxton site. These patterns demonstrate the importance of both oceanic and estuarine shoreline change to the overall width of a barrier is-

Table 2. *Average main barrier island width (MBIW) and average back-barrier island width (BBIW) measured for the two study areas (Pea Island and Avon-Buxton). Table excludes the profiles that lie within an inlet channel.*

	Year						
Study Area	1852	1909	1917	1932	1949	1962	1998
Pea Island segment 1 (profiles 1–10)							
Average MBIW (m)	416	287	291	190	796	701	708
±SD (n)	45 (10)	200 (10)	20 (5)	86 (7)	515 (10)	524 (10)	517 (10)
Average BBIW (m)	198	153	466	758	958	511	517
±SD (n)	95 (3)	87 (5)	192 (7)	380 (8)	2 (2)	131 (5)	167 (5)
Pea Island segment 2 (profiles 11–30)							
Average MBIW (m)	412	576	384	656	966	998	906
±SD (n = 20)	127	160	232	381	220	166	224
Average BBIW (m)	N/A	N/A	190	312	N/A	N/A	57
±SD (n = 20)	N/A	N/A	115	211	N/A	N/A	N/A
Pea Island segment 3 (profiles 31–40)							
Average MBIW (m)	933	N/A	781	744	598	523	418
±SD (n = 10)	323	N/A	218	183	173	157	124
	1852	1917	1940	1962	1974	1998	
Avon-Buxton (profiles 1–18)							
Average MBIW (m)	813	547	426	284	284	219	
±SD (n = 18)	120	79	79	43	37	38	
Average BBIW (m)	260	191	176	168	141	133	
±SD (n)	52 (5)	116 (5)	86 (5)	65 (5)	65 (6)	53 (7)	

Table 3. *Average change in main barrier island width (MBIW) in the two study areas (Pea Island and Avon-Buxton). These averages exclude profiles within 100 m of an inlet.*

	Interval				
Study Area	1852–1917	1917–1932	1932–1949	1949–1998	1852–1998
Pea Island segment 1 (profiles 1–10)					
Average change in MBIW (m)	−150	−141	813	−77	292
±SD (n)	13 (5)	52 (3)	576 (6)	142 (9)	494 (9)
Average rate of change in MBIW (m/y)	−2.3	−9.3	47.8	−1.6	2.0
±SD (n)	0.2 (5)	3.0 (3)	34 (6)	3.0 (9)	3.4 (9)
Pea Island segment 2 (profiles 11–30)					
Average change in MBIW (m)	1	271	327	−9	494
±SD (n)	211 (17)	353 (20)	396 (17)	76 (17)	314 (20)
Average rate of change in MBIW (m/y)	0.0	18.0	19.3	−0.2	3.4
±SD (n)	3.2 (17)	23.5 (20)	23.3 (17)	1.5 (17)	2.2 (20)
Pea Island segment 1 and 2 (profiles 1–30)					
Average change in MBIW (m)	−27	218	438	−32	431
±SD (n)	196 (22)	358 (23)	424 (23)	99 (26)	395 (29)
Average rate of change in MBIW (m/y)	−0.4	14.5	25.8	−0.7	3.0
±SD (n)	3.0 (22)	23 (23)	24 (23)	2.0 (26)	2.7 (29)
Pea Island segment 3 (profiles 31–40)					
Average change in MBIW (m)	−152	−37	−146	−180	−515
±SD (n = 10)	177	31	34	60	207
Average rate of change in MBIW (m/y)	−2.3	−2.5	−8.6	−3.7	−3.5
±SD (n = 10)	2.7	2.1	2.0	1.2	1.4
	1852–1917	1917–1940	1940–1974	1974–1998	1852–1998
Avon-Buxton (profiles 1–18)					
Average change in MBIW (m)	−267	−120	−142	−65	−594
±SD (n = 18)	100	127	138	113	15
Average rate of change in MBIW (m/y)	−4.2	−5.2	−4.1	−2.7	−4.1
±SD (n = 18)	1.5	5.5	4.1	4.7	0.1

Table 4. *Average oceanic and estuarine shoreline change and the rates of change in the two study areas (Pea Island and Avon-Buxton). These averages exclude profiles within 100 m of an inlet.*

Interval	1852–1917	1917–1932	1932–1949	1949–1962	1949–1998	1962–1998	1852–1998
Pea Island segment 1 (profiles 1–10)							
Average ocean shoreline change (m)	−14	11	4	−55	−76	−21	−89
±SD (n)	37 (5)	27 (5)	60 (5)	28 (9)	49 (9)	39 (9)	27 (9)
Average ocean shoreline rate of change (m/y)	−0.2	0.7	0.2	−4.2	−1.5	−0.6	−0.6
±SD (n)	0.6 (5)	1.8 (5)	3.5 (5)	2.1 (9)	1.0 (9)	1.1 (9)	0.2 (9)
Pea Island segment 2 (profiles 11–30)							
Average ocean shoreline change (m)	−209	66	−67	−46	−23	20	−198
±SD (n)	60 (17)	51 (20)	48 (17)	35 (17)	47 (17)	24 (20)	103 (17)
Average ocean shoreline rate of change (m/y)	−3.2	4.4	−5.2	−3.6	−0.5	0.5	−1.4
±SD (n)	0.9 (17)	3.4 (20)	2.8 (17)	2.7 (17)	1.0 (17)	0.7 (20)	0.7 (17)
Pea Island segment 3 (profiles 31–40)							
Average ocean shoreline change (m)	−281	−71	−119	−108	−155	−47	−626
±SD (n = 10)	77	22	20	19	13	21	80
Average ocean shoreline rate of change (m/y)	−4.3	−4.7	−7.0	−8.3	−3.2	−1.3	−4.3
±SD (n = 10)	1.2	1.4	1.2	1.4	0.3	0.6	0.6
Average estuarine shoreline change (m)	128	39	−27	36	−18	−58	122
±SD (n = 10)	130	21	28	26	40	55	154
Average estuarine shoreline rate of change (m/y)	2.0	2.6	−1.6	2.8	−0.4	−1.6	0.8
±SD (n = 10)	2.0	1.4	1.6	2.0	0.8	1.5	1.1
	1852–1917	1917–1940	1940–1962	1962–1974	1940–1974	1974–1998	1852–1998
Avon-Buxton (profiles 1–18)							
Average ocean shoreline change (m)	−252	−170	−97	1	−96	−59	−576
±SD (n = 18)	88	24	24	30	18	13	88
Average ocean shoreline rate of change (m/y)	−3.9	−7.4	−4.4	0.1	−2.8	−2.5	−3.9
±SD (n = 18)	1.4	1.0	1.1	2.5	0.5	0.5	0.6
Average estuarine shoreline change (m)	−27	19	3	−11	−8	−9	−29
±SD (n = 18)	56	43	20	30	33	17	63
Average estuarine shoreline rate of change (m/y)	−0.4	0.8	0.1	−0.9	−0.2	−0.4	−0.2
±SD (n = 18)	0.9	1.9	0.9	2.5	1.0	0.7	0.4

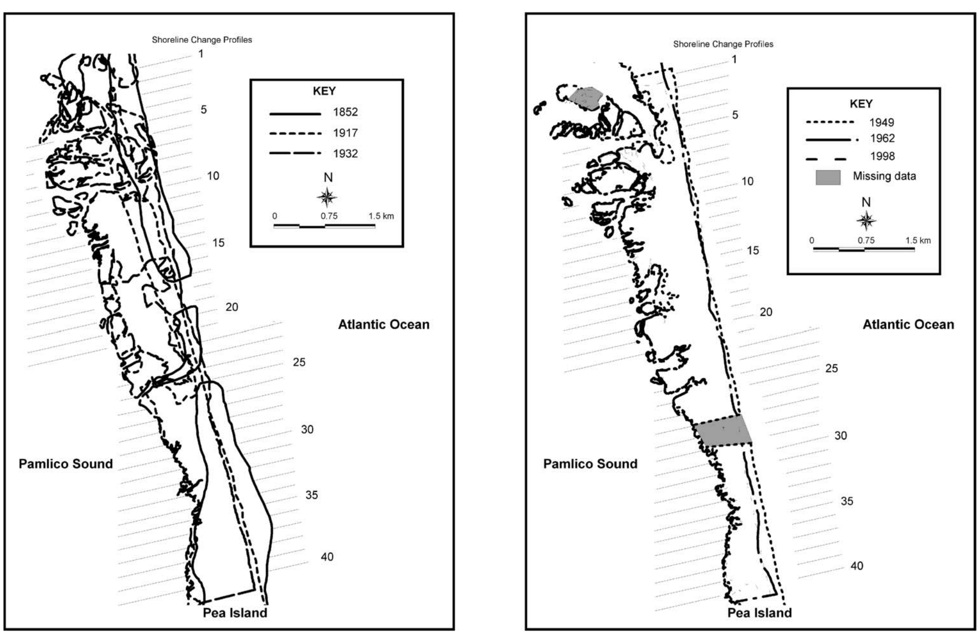

Figure 6. Shoreline traces are plotted for each time slice (1852, 1917, 1932, 1949, 1962, and 1998) and are used to determine long-term accretion/erosion rates observed along the 40 profiles within the Pea Island study area (Table 4). The shaded polygons represent data gaps in the 1949 aerial photographs. Shoreline change data are lacking for profiles 26 to 28. Areas proximal (<100 m) to inlets were not used.

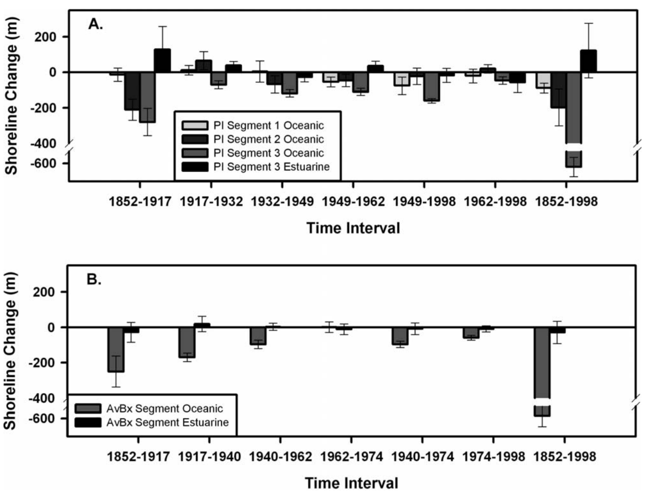

Figure 7. Summary bar graph of shoreline change for each of the segments in Pea Island (A) as well as the Avon-Buxton area (B).

land. Net gain (Pea Island segments 1 and 2) occurred where natural inlet processes transported sediment to the estuarine side and produced flood tide deltas that were later accreted onto the main portion of the barrier island (Figure 3). Overwash events also played a substantial role in widening certain portions of the barrier island. Net loss occurred along the portions of the barrier island where oceanic shoreline erosion was high and estuarine shoreline progradation rates were low (Pea Island segment 3) or net estuarine shoreline erosion occurred (Avon-Buxton area). In addition, these areas had limited inlet activity during the 146-year period treated by this study. No inlets occurred in Pea Island segment 3 during the 1852–1998 interval, and the inlet that formed between Avon and Buxton in 1962 was artificially closed in February 1963 (USACE, 1963).

Thus, segments that experienced barrier island widening over the 146-year period demonstrate the great importance of tidal inlet processes to the long-term integrity of barrier islands. Similar findings were reported by Barnhardt *et al.* (2002) at Tavira Island, southern Portugal, and by Cuffe (1991), Davis and Barnard (2003), and Davis and Zarillo (2003) along the barrier islands on the west coast of Florida. In 1852, Pea Island segments 1 and 2 were extremely narrow (comparable to the present day Avon-Buxton area), with an average MBIW of only 416 and 412 m, respectively (Table 2; Figure 9). Between 1852 and 1945, the migration of New Inlet (1755–1922 and 1932–1945) and Loggerhead Inlet (1843–1869) (dates of inlet openings/closings taken from Fisher [1962]) through these areas provided conduits for sediment and water from the Atlantic Ocean to Pamlico Sound. These conduits intersected the natural, longshore transport of sediment. Limited tidal exchange through these inlets and high wave energy resulted in the formation of small, discontinuous flood tide deltas. In Pea Island segment 1, a majority of the flood tide deltas formed between 1917 and 1932 (Figures 3 and 9). In Pea Island segment 2, sediments from a smaller flood tidal delta were reworked by estuarine wave energy, overwash, and aeolian processes into a back-barrier berm system known as Lagerhead Hills (Ames and Riggs, 2004). After the final closure of New Inlet in 1945, salt marsh vegetation began colonizing and stabilizing these subaerial sands, and the flood tide deltas were incorporated into the main portion of the barrier island (this process is continuing today). The formation and incorporation of flood tide deltas has increased the robustness of these two segments of the Outer Banks.

In contrast, Pea Island segment 3 and the Avon-Buxton area experienced net loss in MBIW (520 and 590 m, respectively) over the 146-year study interval (Table 3; Figure 7). In both areas, high rates of oceanic shoreline erosion affected the front side of the island while limited estuarine shoreline progradation or erosion occurred (Table 4; Figure 10). The

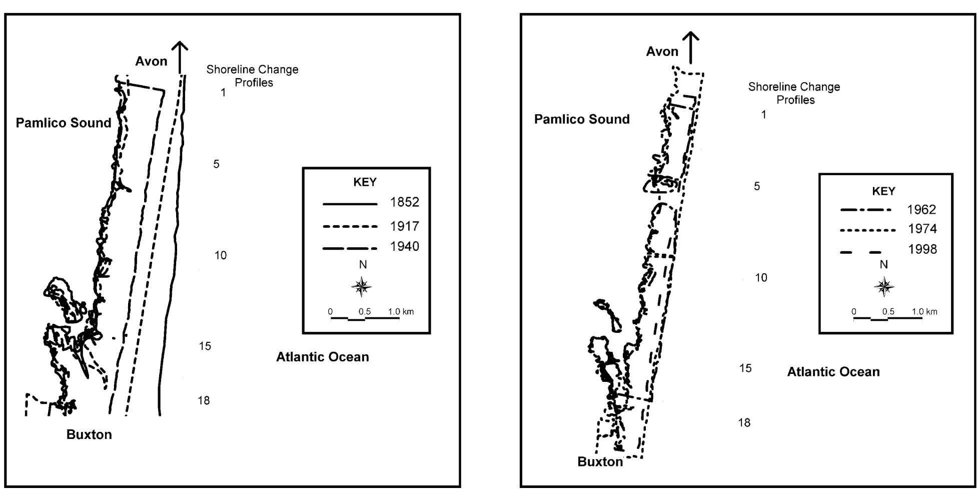

Figure 8. Shoreline traces are plotted for each time slice (1852, 1917, 1940, 1962, 1974, and 1998) and are used to determine long-term erosion rates observed along the 18 profiles within the Avon-Buxton study area (Table 4).

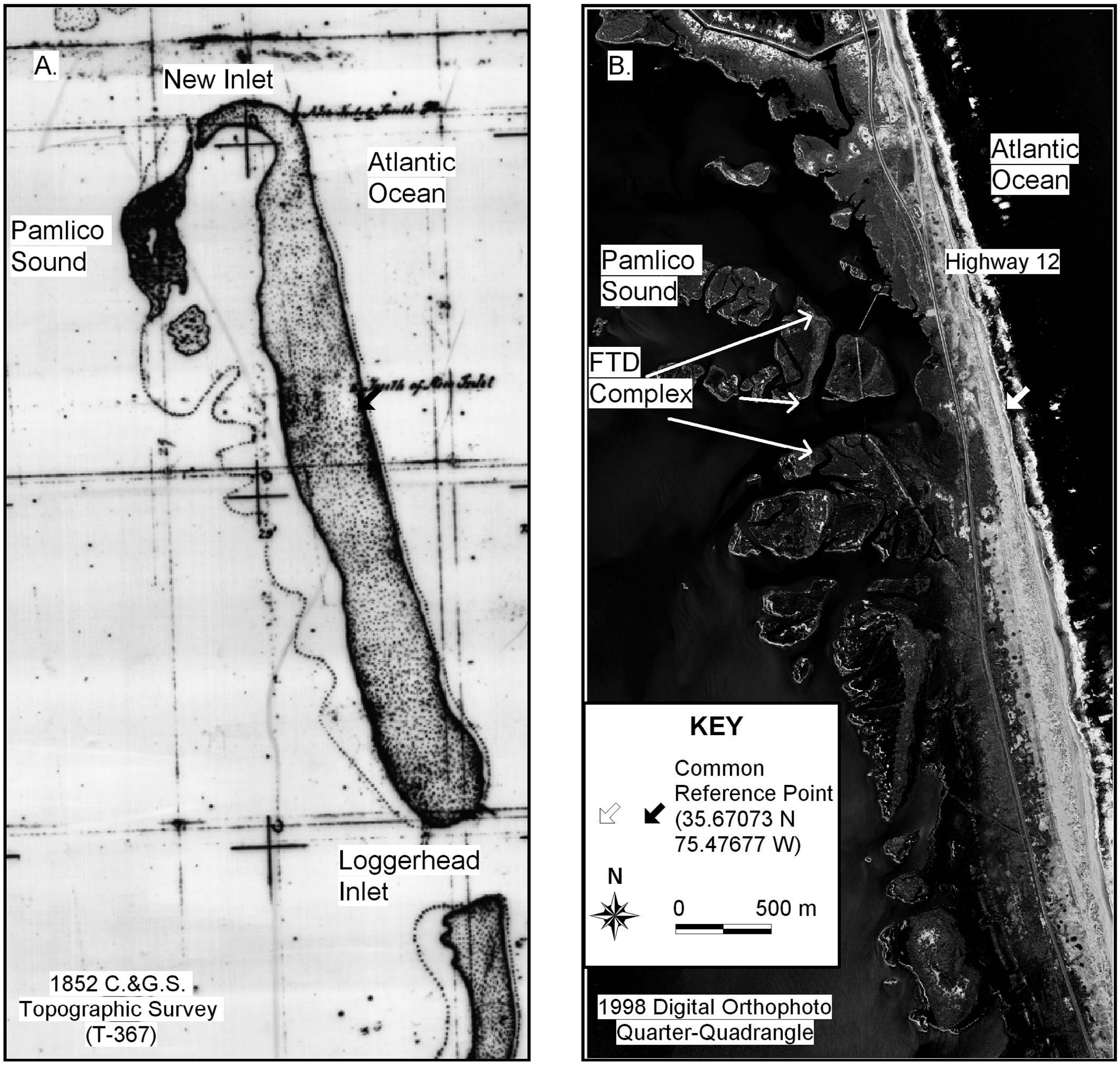

Figure 9. Time slice comparison of northern Pea Island (segment 1 and part of segment 2) in 1852 (A) and 1998 (B) shows the significance of back-barrier flood tide delta (FTD) islands of New Inlet to barrier island width.

elevated rates of oceanic shoreline erosion are associated with the geometry of the shoreline and the proximity to headland features (Hoyt and Henry, 1971; Riggs, Cleary, and Snyder, 1995).

Pea Island segment 3 (Figure 1) is located adjacent to a subtle headland and submarine shoal complex known as "False-Cape Rodanthe" and Wimble Shoals, respectively. Likewise, the Avon-Buxton area is the northern limb of Cape Hatteras. Offshore bathymetric highs at the headlands refract waves toward the coastline and focus energy onto the limbs of the cape structures (Hoyt and Henry, 1971). North of False-Cape Rodanthe, the barrier island chain trends northwest to southeast, making them particularly susceptible to the erosive waves of the common nor'easter winter storms (Dolan, 1987; Dolan and Lins, 1986).

As shown by the northern segments of Pea Island, barrier island width is maintained and enhanced by the redistribution of sediment in the form of flood tide deltas and overwash fans. However, human modification can have deleterious effects on these systems. For example, artificial barrier dune

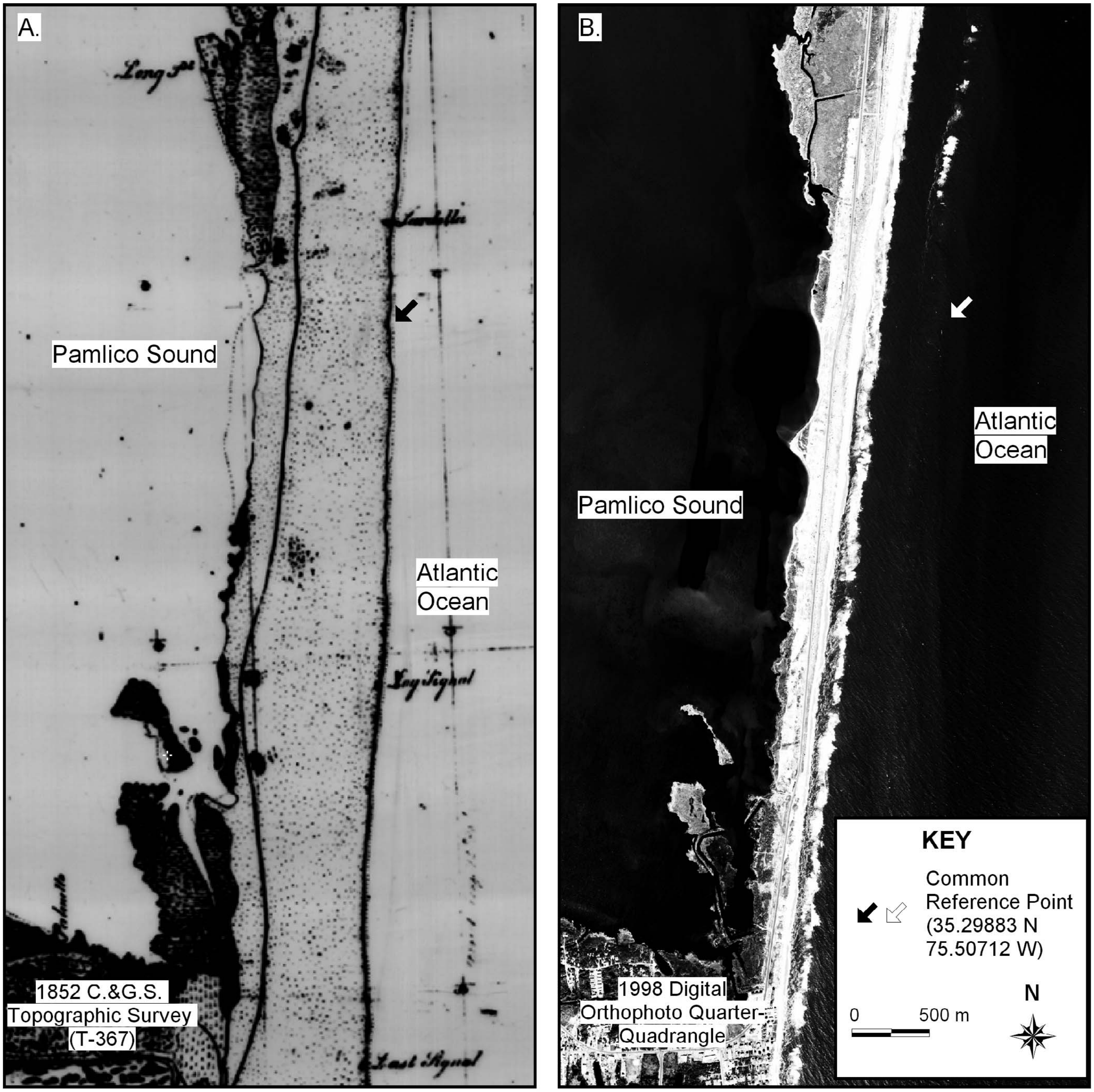

Figure 10. Time slice comparison of the Avon-Buxton study site in 1852 (A) and 1998 (B) shows the effect of long-term oceanic and estuarine shoreline erosion.

ridges built along the Outer Banks since the late 1930s have drastically reduced the transport of sediment from the oceanic to the estuarine side of the barrier island. Before this time, estuarine shoreline change along Pea Island segment 3 shows progradation rates that are half the oceanic shoreline erosion rates (Table 4; Figure 7). After the construction of these dune ridges, estuarine shorelines began receding (Table 4; Figure 7). Similarly, artificial inlet closures curtail important natural barrier-widening processes. For example, the inlet that opened between Avon and Buxton in 1962 was closed less than a year after it opened, preventing sand from being transported to the estuarine side. Thus, estuarine shoreline progradation and vertical aggradation because of overwash has been curtailed, and the potential for flood tidal delta accretion has been completely eliminated.

If the rates of barrier island narrowing demonstrated in this work continue into the future, Pea Island segment 3 and the Avon-Buxton area will only survive as barrier islands for up to 120 and 50 years, respectively. But, of course, rates of erosion are episodic and not constant through time, thus 120 to 50 years are likely maximum estimates of barrier island existence at these sites.

CONCLUSIONS

Reduction of main barrier island width (MBIW) is of growing concern along numerous segments of the North Carolina Outer Banks. Narrowing areas pose a significant threat to the maintenance and, indeed, continuance of the infrastructure that connects the barrier island communities and that is heavily used by increasing numbers of tourists. As seen in northern Pea Island (segments 1 and 2), these narrowing zones tend to rebound naturally, if permitted, through tidal inlet processes and oceanic overwash. Attempts to protect the barrier islands through construction and maintenance of artificial barrier dune ridges and through rapid closure of inlets (*e.g.,* Buxton Inlet in 1963 and Isabel Inlet in 2003) promote the opposite result.

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Appendix A. *Measurements of main barrier island width (MBIW) change for individual profiles.*

		Change in MBIW (m)				
Segment	Profile	1852–1917	1917–1932	1932–1949	1949–1998	1852–1998
Pea Island						
1	1			212		
	2			340	−192	−46
	3				−124	−148
	4				−274	−154
	5	−163			125	−49
	6	−144	−187	186	41	−104
	7	−157			71	905
	8	−158	−84	1400	−61	1098
	9	−130	−152	703	−34	388
	10			1434	−245	665
2	11	−9	772	34	−41	756
	12	−50	666	97	−12	702
	13	−79	789	3	2	714
	14	−86	786	−76	−9	615
	15	−136	749	−62	−113	438
	16	−104	−107	402	123	314
	17	−35	−91	444	179	496
	18		246	528	−27	
	19		62	915	−46	1183
	20	−54	−90	913	−12	758
	21	−98	157	690	90	838
	22	−70	152	409	−83	408
	23	−121	169	785	1	834
	24	−492	71	835	−55	360
	25		889	−57	−90	
	26	384	178	−145	−11	406
	27	305	25			232
	28	254	25			141
	29	237	−15			37
	30	175	−3	−148	−41	−18
3	31	84	−27	−124	−126	−193
	32	71	−12	−109	−150	−199
	33	−43	−82	−111	−144	−380
	34	−273	−48	−107	−125	−552
	35	−327	−61	−189	−254	−830
	36	−390	−16	−134	−126	−666
	37	−319	20	−200	−167	−667
	38	−239	−43	−162	−181	−625
	39	−93	−76	−160	−242	−571
	40	6	−27	−160	−289	−470
		1852–1917	1917–1940	1940–1974	1974–1998	1852–1998
Avon-Buxton area						
	1	−75	−137	−60	−87	−359
	2	−170	−124	−120	−60	−474
	3	−207	−110	−126	−78	−520
	4	−191	−114	−140	−87	−532
	5	−222	−119	−43	−32	−415
	6	−205	−186	−85	−67	−542
	7	−231	−178	−130	−61	−599
	8	−277	−144	−116	−45	−582
	9	−279	−159			−642
	10	−281	−175	−133	−57	−646
	11	−291	−122	−156	−72	−640
	12	−260	−173	−84	−83	−599
	13	−278	−114	−158	−65	−614
	14	−172	−160	−161	−62	−555
	15	−385	−61	−134	−62	−643
	16	−494	351	−379	−76	−598
	17	−355	−155	−297	−58	−865
	18	−425	−289	−100	−51	−865

Appendix B. *Measurements of oceanic and estuarine shoreline change for individiual profiles.*

		Oceanic Shoreline Change (m)						
Segment	Profile	1852–1917	1917–1932	1932–1949	1949–1962	1949–1998	1962–1998	1852–1998
Pea Island								
1	1							
	2			5.5	−8.7	−3.3	−1.4	−0.9
	3				−5.1	−2.9	−2.2	−0.9
	4				−2.8	−1.5	−1.1	−0.6
	5	−0.6			−1.3	−1.5	−1.6	−0.7
	6	0.1	1.0	−1.1	−3.0	−1.4	−0.8	−0.4
	7	0.3	2.2		−5.5	−1.6	−0.2	−0.5
	8	0.1	1.5	−3.9	−3.4	−0.6	0.4	−0.4
	9	−1.0	−1.9	−1.2	−3.4	−0.4	0.6	−0.5
	10			1.7	−4.9	−0.7	0.9	−0.5
2	11	−3.6	9.4	1.8	−4.6	−0.6	0.9	−0.6
	12	−3.4	7.2	−1.0	−2.3	0.2	1.1	−0.8
	13	−3.5	6.4	−0.3	−1.7	0.5	1.3	−0.8
	14	−3.6	6.9	−2.4	1.1	0.4	0.1	−1.1
	15	−4.4	7.9	−4.8	1.0	0.6	0.4	−1.5
	16	−4.2	5.4	−4.3	−1.2	0.6	1.2	−1.6
	17	−3.9	5.7	−5.6	−0.9	0.5	1.1	−1.6
	18		4.4	−4.3	−3.4	0.0	1.2	
	19		1.7	−2.7	−7.0	−0.4	2.0	−0.3
	20	−3.1	3.6	−3.9	−3.5	−0.2	1.1	−1.5
	21	−2.3	5.1	−6.1	−3.1	0.0	1.1	−1.2
	22	−2.2	6.9	−6.3	−4.1	−1.0	0.2	−1.3
	23	−1.5	6.7	−7.5	−4.4	−1.1	0.1	−1.2
	24	−0.9	5.4	−0.3	−4.5	−1.3	−0.2	−0.3
	25		7.1	−9.2	−5.8	−1.9	−0.4	
	26	−3.8	3.7	−6.7	−7.3	−1.9	0.0	−2.8
	27	−4.0	0.2					
	28	−3.6	−1.9					
	29	−3.4	−1.6					
	30	−3.0	−2.9	−3.7	−9.0	−2.4	−0.1	−2.9
	31	−3.6	−2.8	−5.3	−8.7	−2.7	−0.6	−3.4
	32	−4.2	−3.9	−5.8	−8.5	−3.2	−1.2	−4.0
	33	−4.3	−3.7	−6.2	−7.9	−2.9	−1.1	−4.0
	34	−4.9	−3.8	−6.6	−7.1	−3.1	−1.6	−4.4
	35	−4.9	−7.2	−6.1	−7.9	−3.5	−1.9	−4.8
	36	−5.9	−4.7	−6.8	−9.0	−2.9	−0.7	−4.9
	37	−5.7	−3.9	−8.1	−10.6	−3.4	−0.9	−5.0
	38	−4.5	−4.6	−8.6	−10.3	−3.4	−0.9	−4.6
	39	−2.8	−7.0	−7.9	−7.3	−3.3	−1.9	−4.0
	40	−2.2	−5.6	−8.4	−5.8	−3.2	−2.3	−3.6
		1852–1917	1917–1940	1940–1962	1962–1974	1940–1974	1974–1998	1852–1998
Avon-Buxton area								
	1	−94	−185	−123	41	−82	−44	−405
	2	−102	−192	−116	28	−88	−55	−436
	3	−151	−177	−131	48	−82	−69	−480
	4	−163	−182	−117	33	−84	−60	−490
	5	−167	−177	Bl	Bl	−110	−49	−503
	6	−191	−160	Bl	Bl	−112	−45	−507
	7	−203	−193	−133	35	−98	−48	−542
	8	−241	−171	−111	−2	−114	−61	−587
	9	−277	−158	−91	−9	−100	−79	−614
	10	−308	−152	−95	−14	−108	−60	−628
	11	−311	−144	−75	−8	−83	−77	−615
	12	−320	−154	−75	−14	−89	−84	−647
	13	−307	−138	−98	−14	−112	−66	−622
	14	−351	−120	−86	−59	−144	−69	−685
	15	−328	−155	−61	−14	−74	−45	−603
	16	−320	−194	−76	−15	−91	−50	−655
	17	−328	−200	−64	−22	−86	−45	−659
	18	−366	−209			−69	−55	−699

Appendix B. *Continued*

Segment	Profile	Oceanic Shoreline Change (m)						
		1852–1917	1917–1932	1932–1949	1949–1962	1949–1998	1962–1998	1852–1998
		Estuarine Shoreline Change (m)						
		1852–1917	1917–1932	1932–1949	1949–1962	1949–1998	1962–1998	1852–1998
Pea Island								
3	31	4.9	1.0	−2.0	3.4	0.2	−1.0	2.1
	32	5.3	3.1	−0.6	2.0	0.1	−0.6	2.7
	33	3.7	1.7	−0.3	0.7	0.0	−0.3	1.8
	34	0.7	0.6	0.3	4.0	0.5	−0.7	0.6
	35	−0.1	3.1	−5.0	7.6	−1.7	−5.0	−0.9
	36	−0.1	3.6	−1.1	2.2	0.3	−0.4	0.3
	37	0.8	5.2	−3.7	3.1	0.0	−1.1	0.5
	38	0.9	1.8	−0.9	2.6	−0.3	−1.3	0.4
	39	1.4	1.9	−1.5	1.1	−1.6	−2.6	0.1
	40	2.2	3.8	−1.1	1.1	−1.2	−3.2	0.9
		1852–1917	1917–1940	1940–1962	1962–1974	1940–1974	1974–1998	1852–1998
Avon-Buxton area								
	1	−19	54	29	22	50	−56	29
	2	−68	77	−41	−5	−46	7	−30
	3	−56	85	10	−51	−41	−8	−20
	4	−28	63	38	−75	−37	−31	−32
	5	−54	75	Bl	Bl	−37	6	−10
	6	−14	0	Bl	Bl	−65	−22	−101
	7	−27	−16	19	−19	−1	−16	−60
	8	−35	36	13	−20	−7	18	11
	9	−3	9	−6				−30
	10	−27	−9	−1	4	3	0	−32
	11	−20	−47	−5	−40	−45	8	−105
	12	−61	12	15	17	32	3	−13
	13	−29	−34	0	−14	−14	−4	−81
	14	179		−2	6	4	−10	173
	15	−44		−6	12	6	−16	−54
	16	−92	−5	−17	25	8	−13	−102
	17	−39	−10			44	−11	−16
	18	−59				11	−2	−50