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Cyclic Spit Morphology in a Developing Inlet System

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Abstract

A spit attached to the north end of South Beach, a barrier island in Chatham, Massachusetts, exhibits a cyclic pattern of accretion, breaching, and shoal generation. The flood-oriented spit is within a large (2 km wide) developing tidal inlet system that was formed when Nauset Beach was breached in January 1987. Five cycles of spit growth and breaching have been observed in two years. Each cycle is characterized by: 1) elongation of spit for several months; 2) gradual narrowing and eventual breaching of the spit's mid-section, which creates a small tidal channel and terminates the growth cycle; and 3) evolution of the detached distal portion of the spit from a supratidal island to subtidal shoals. The growth and breaching of this spit is are significant processes causing landward sediment transport within the inlet system. A conceptual model is offered which explains the cyclic behavior of this system as the result of interrelated morphological, tidal, and climatic controls.

Introduction

The cyclic growth and breaching of barrier beaches and spits is a subject of great interest in coastal geology (DeBoers, 1964; Goldsmith, 1972; Ogden,

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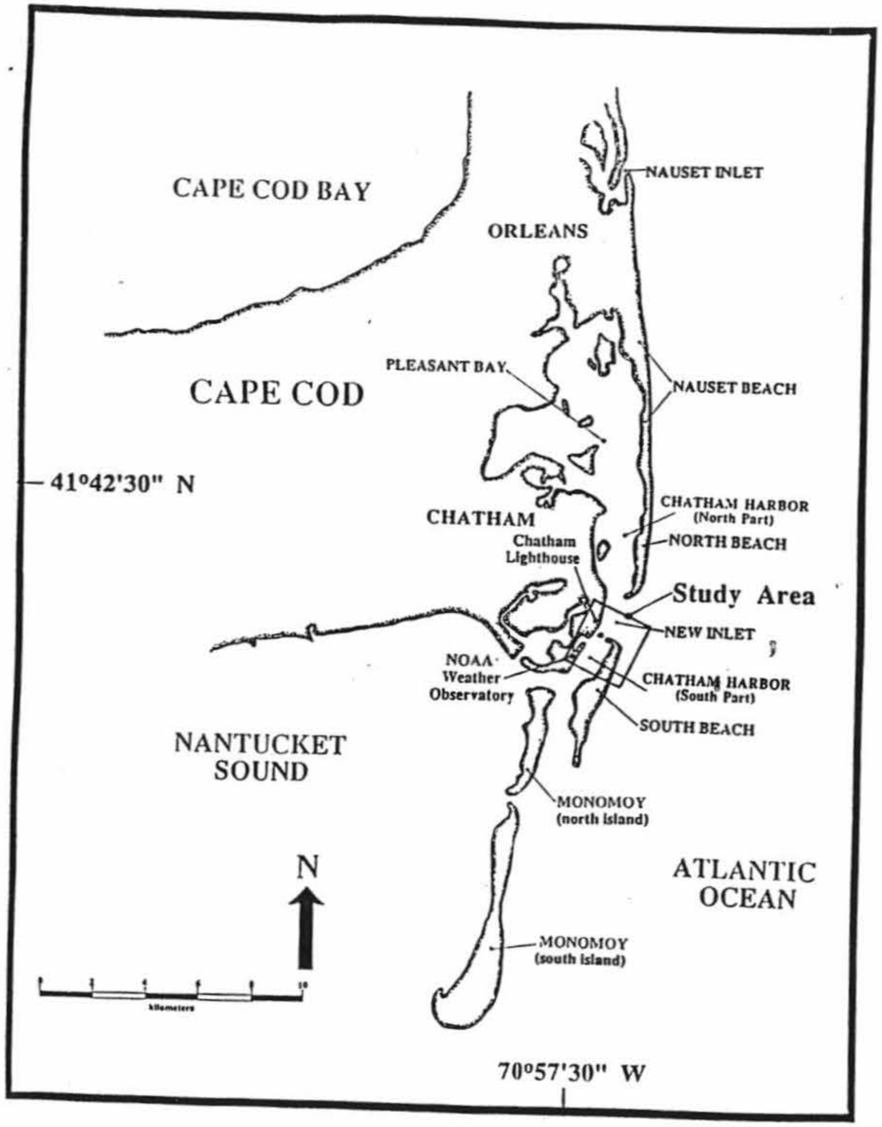
1976; McClennen, 1979; Aubrey and Gaines, 1982; Nicholls, 1984; Giese, 1988). These periodic systems, once identified, can act as natural laboratories to improve our understanding of inlet-genesis and barrier beach/spit evolution. However, the investigational challenges imposed by the large spatial scales (1-10's km) and the long periodicities (10-100's yrs) of most previously described systems make it difficult to verify the morphological models derived from them. The modest physical scale of the spit system along the northern end of South Beach in Chatham, Massachusetts, and its frequent recurrence of spit elongation, breaching, and tidal inlet formation, provide an opportunity to overcome these earlier limitations.

The study area is located on the northern portion of South Beach, a barrier island approximately 1 km east of the mainland coast of Chatham, Massachusetts (Figs. 1 & 2). The island is 5 km long, 200-800 m wide, and has a north-south orientation. South Beach became an island when Nauset Beach was breached during a severe northeast storm that coincided with perigean tides on January 2, 1987. The breach's development shortened the path of tidal flow into and out of the Chatham Harbor and Pleasant Bay system (~25 km²), and as a result the mean tidal range within Chatham Harbor increased from a pre-breach 1.8 m to a post-breach 2.1 m (U.S. Army Corps of Engineers, 1989). Prior to the 1987 breach, Nauset Beach extended 17 km south from its mainland attachment at Orleans and had been the focus of a number of morphological investigations (U.S. Army Corps of Engineers, 1957, 1968; Goldsmith, 1972; Hine, 1975, 1979; Giese, 1978; McClennen, 1979; and Hayes, 1981). Several studies (Goldsmith, 1972; Giese, 1978, 1988; McClennen, 1979) have outlined a cyclic history of spit accretion, inlet-migration, breaching, and deterioration of Nauset Beach opposite the Chatham mainland with a period of 100-150 years. As part of this larger cycle, South Beach, the deposits of which represent the last 50 yrs of Nauset Beach's growth (Hayes, 1981), is expected to erode during the next several decades, with its sediments moving southward and westward (Giese, 1988).

Since the inception of the new inlet through Nauset Beach, flood-oriented spits have formed on both sides of the inlet (Fig. 3). The term "inlet-spit" was coined (Weidman and Ebert, 1988; Ebert and Weidman, 1989) to distinguish these recent, unvegetated, and rapidly changing depositional features from the older, vegetated, and relatively stable barrier systems to which they are attached. The morphology of the inlet-spits in Chatham must be considered



within the context of the developing inlet system which widened from less than 100 m to over 2000 m from January 1987 to January 1990. This widening is part of the continuing adjustment of the system to the greater hydraulic efficiency and greater tidal prism afforded by the new inlet. The enlargement

of the inlet is produced by: 1) tidal currents which scour and deepen the inlet; and 2) waves which erode the inlet's margins. These processes provide an abundant sediment supply which allows for the construction of inlet-spits. At the same time, tidal currents and wave action provide a basis for the inlet-spits' unstable existence by eroding their inlet-facing beaches and causing the inlet-spits to narrow even as they grow in length.

The inlet-spits on both sides of the inlet have displayed a repeating pattern of accretion and breaching. The inlet-spit attached to North Beach breached twice in two years, whereas the inlet-spit attached to South Beach breached five times during the same period. This difference may reflect the asymmetry in the sedimentological and hydrodynamic processes affecting the New Inlet system. The orientation of South Beach leaves its northern end vulnerable to

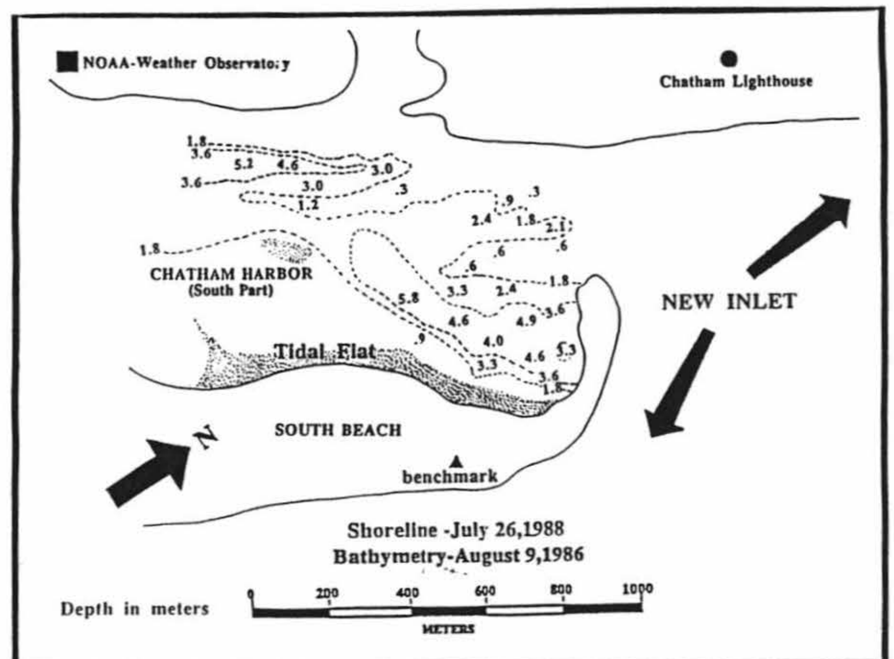


Figure 2. Map of the study area on the north end of South Beach. The spit and barrier shoreline are from a post-breach (1987) survey (on July 26, 1988), while the harbor bathymetry is pre-breach (from NOAA-National Ocean Service Chart #13248, corrected to August 9, 1986). Note the deepest parts of the harbor adjacent to the spit are opposite the spit's mid-section.

the dominant storm wave approach (northeast), whereas the orientation of North Beach's southern end is relatively sheltered during these same storms. Further, North Beach is the present distal part of Nauset Beach and its sediment is derived from longshore transport along the 15 km of shoreline south of Nauset Inlet, whereas South Beach is down-drift of the new inlet and its sediment supply is derived only from sediment eroded from the northern end of South Beach and from sediment able to bypass the inlet.

Figure 3. Aerial survey photograph (September 1, 1988) of the New Inlet area in Chatham showing the inlet-spits attached to the older barriers on both sides of the inlet. Note the recently-formed breach channel in the mid-section of the inlet-spit attached to South Beach. The square-ish shoal to the upper left of the detached distal end of the South Beach inlet-spit is also a former detached distal end from an earlier (January 1988) breach.

This paper documents five cycles of growth and breaching of the inlet-spit attached to the northern end of South Beach, and confirms that the inlet-spit is an important avenue of landward sediment transport within the inlet system. The observations are used to develop a conceptual model of inlet-spit evolution which explains the cyclic morphology of this feature as a product of morphological, tidal, and meteorological controls. Components of the model, supported by previous studies of barrier and spit evolution, can also provide some insight to the general problem of barrier and spit breaching.

Methods

Fieldwork began on November 14-15, 1987, and a benchmark (for horizontal control) was established on the northern end of South Beach from which to repeat surveys (Fig. 2). Barrier scarpline retreat on the north end of South Beach was measured from fixed markers placed every 30 m in a series of lines parallel to the axis of South Beach. Since the inlet-spit was subject to overwash and breaching, it was resurveyed during each field visit by running a baseline of temporary markers (spaced every 30 m) along the axis of the spit and tied into the benchmark on South Beach. Cross-sectional distances from the baseline markers on the spit's axis to the toe of the spit's foreshore and backshore were measured at low tide. The detached distal ends of the inlet-spit were surveyed in this same manner, but the accuracy of their shoreline positions is less certain than the shoreline positions of the spit because of their isolation from the benchmark on South Beach. These measurements were used to construct a map of the inlet-spit's low tide shoreline and the adjacent barrier's scarpline for each field visit. Survey schedules were dictated largely by convenience, though efforts were made to resurvey as soon as possible after a breach was reported by local observers. The durations of intervals between successive surveys varied from 1-9 weeks with an average interval duration of 30 days.

Hourly weather summaries were acquired from the NOAA Weather Observatory-Chatham Station, located 1.5 km from the study area (Fig. 2). The hourly data were sub-sampled to obtain the wind velocities for only the 3 hrs before and the 3 hrs after the time of the forecast high tides (Tide Tables, 1987, 1988, 1989). These 6-hr blocks of wind data were then reduced to a single resultant wind velocity vector for each high tide (referred to as the "high-tide-wind"). This method was chosen in order to emphasize wind conditions at the time of high tide when storm-induced changes to the inlet-spit would be maximized, and to de-emphasize wind conditions at the time of low tide when these changes would be minimized. The "high-tide-winds" were compiled for each of the intervals between successive surveys to produce two indices which were relevant to the morphology of the inlet-spit: 1) storm frequency — the percentage of an interval's "high-tide-winds" with onshore direction (0°- 200°) and speeds > 10.0 kts (18.5 km/hr); 2) storm intensity — the mean wind speed of these stormy "high-tide-winds" (stormy being defined in the same manner as the storm frequency index). Indices derived in this way have been successfully used previously to model scarp erosion on South Beach (Weidman, 1988; Weidman and Ebert, 1988, 1989).

Results

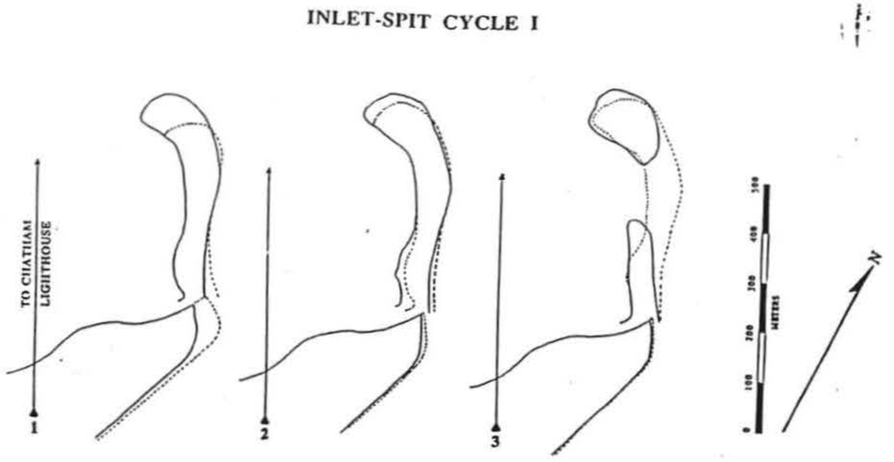
Two years of field mapping document five cycles of inlet-spit growth, breaching, and shoal generation. Consecutive shoreline positions of the inlet-spit and the adjacent barrier scarpline are presented along with morphological and meteorological characterizations for each interval between surveys (Figs. 4-8). These interval characterizations include: survey dates; duration; barrier scarpline erosion rate (linear retreat rate at the spit base/barrier boundary); spit growth rate (length and area); and storm indices (frequency and intensity). Intervals are grouped according to cycle, where the term "cycle" is defined as the period of inlet-spit growth between successive breachings. Breachings generally resulted in the formation of a subtidal breach channel, causing a significant shortening of the spit and detachment of its distal end. Composites of each of the five inlet-spit growth cycles are presented along with each cycle's morphological and meteorological summary (Fig. 9). The summaries do not include intervals in which breaches occurred, since during these intervals' morphological changes could not be ascribed to a particular cycle. For the entire two-year (707 days) period of study, 330 meters were eroded from the northern end of South Beach for a mean barrier erosion rate of 0.5 m/day, and inlet-spit growth rates averaged 1.9 m/day for length and 160 m²/day for area. The sediment volumes transported into Chatham Harbor from the growth of the inlet-spit on South Beach can be roughly (and

conservatively) calculated if the thickness of the inlet-spit deposits are assumed to be about the same as the tidal range (~2 m) and subtidal volume and beach slope effects are neglected. The results of this calculation over the duration of this study is a total transported sediment volume of ~210,000 m³ or an average of ~300 m³/day. Storm frequency and storm intensity indicies for the entire study were 16.8% and 26.6 km/hr respectively.

Cycle I

Documentation of Cycle I (Fig. 4) is incomplete since the investigation began with the first cycle already in progress. Oblique air photos (Kelsey-Kennard Airviews, 1987) indicate a prior breach occurring sometime in mid-June 1987, and the spit is assumed to have grown uninterrupted throughout the summer and fall of 1987. The north end of South Beach and the base of the inlet spit eroded much faster than the study's mean rate during interval 1 and about the same as the mean rate during interval 2. Inlet-spit elongation was much faster during interval 1 than during interval 2, though the areal growth rate was nearly three times as great during interval 2 as during interval 1. Distal accretion was oriented to the west for both of the intervals — giving the spit a pronounced recurve. During interval 1, the mid-section narrowed to 50 m and a washover fan prograded on the bay side of the proximal spit during interval 2. Intervals 1 and 2 were both characterized by moderate (average) storm frequencies, whereas the storm intensity index was highest (and well above the mean) during interval 2.

The inlet-spit was reported to have breached on January 19-20, 1988, ending a 7-month long cycle of inlet-spit growth. The interval in which the breach occurred was characterized by low storm frequency and storm intensity indices. The breach coincided with peak spring tides and moderate intensity onshore (southeast) winds. The breach channel was just over 100 m wide and its center was located about 250 m from the base of the spit when it was surveyed 11 days later on January 31, 1988. The remnant spit was 200 m long, 50 m wide, and its axis had rotated 15° counterclockwise from its previous orientation. The detached distal portion of the spit was a supratidal island, 170 m long and 100 m wide.



Interval #	Dates	Duration (days)	Barrier Erosion Rate (m/day)	Spit Length Growth Rate (m/day)	Spit Area Growth Rate (m^2/day)	Storm Frequency %	Storm Intensity (km/hr)
1	11/15/87-12/28/87	43	0.72	2.49	100	16	26
2	12/28/87-1/12/88	15	0.43	1.80	287	14	32
3	1/12/88-1/31/88	19	0.39	BREACH	BREACH	11	22

INLET-SPIT SHORELINE AND BARRIER SCARPLINE AT START OF INTERVAL ----------

INLET-SPIT SHORELINE AND BARRIER SCARPLINE AT END OF INTERVAL ———

Figure 4. Inlet-spit Cycle I: showing successive shoreline and barrier scarpline positions for intervals #1-3 along with morphological and meteorological characterizations for each interval. This cycle's documentation is incomplete since the study began several months into the spit's growth cycle. The spit was reported breached on January 19-201, 1988.

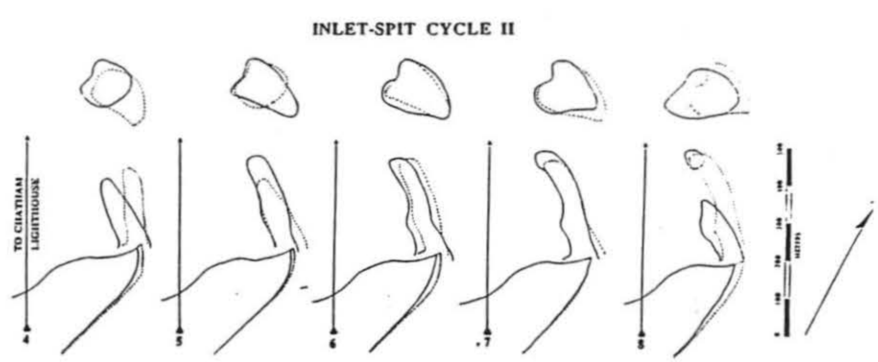
Cycle II

Intervals 4-8 (Fig. 5) comprise the study's first completely documented cycle of inlet-spit growth. Less than 3 months in duration, it was the briefest of the five cycles and was fully within a winter climate. Barrier erosion rates were generally above the mean throughout the cycle. During the stormier intervals (4, 6, 8), the spit shifted laterally to the west via overwash. Spit growth (length and area) was slow during these same intervals. Elongation of the spit was greatest during interval 5 and 7, which had the cycle's milder storm intensities.

The detached distal section (from the January 1988 breach) eroded on its eastward side and these sediments were redeposited on its bay side causing

the island to migrate westward. The apparent increase in the island's area as this migration occurred was the result of an overall lowering and spreading of the island's sediments from wave action and overwash. In this way, the island's supratidal area was gradually reduced, and it became an intertidal shoal during the same week that the spit was breached.

On April 6th, the spit was a modest 310 m long and a narrow 50-60 m wide. Overwash of the spit's mid-section was observed during this field visit, which had a "high tide wind" of 13.2 kts (24.5 km/hr) and 13°(~NNE). For about an hour at high tide, swash bores crossed a ~50 m wide swath of the spit's mid-section from the inlet side to the bay side. The inlet-spit was breached sometime during the following interval 8, which was only one week long and characterized by a high storm frequency index and a moderate storm intensity index. Though the interval coincided with neap tides, the constant storm conditions were apparently sufficient to cause a breach in the mid-section about 230 m from the base of the spit. Only a small distal section was detached



Interval #	Dates	Duration (days)	Barrier Erosion Rate (m/day)	Spit Length Growth Rate (m/day)	Spit Area Growth Rate (m^2/day)	Storm Frequency %	Storm Intensity (km/hr)
4	1/31/88-2/25/88	25	0.59	-4.23	108	14	30
5	2/25/88-3/12/88	16	0.61	4.30	213	19	22
6	3/12/88-3/28/88	16	0.76	0.01	81	16	30
7	3/28/88-4/6/88	9	0.00	4.33	111	17	34
8	4/6/88-4/13/88	7	3.46	BREACH	BREACH	43	36

INLET-SPIT SHORELINE AND BARRIER SCARPLINE AT START OF INTERVAL ----------

INLET-SPIT SHORELINE AND BARRIER SCARPLINE AT END OF INTERVAL ———

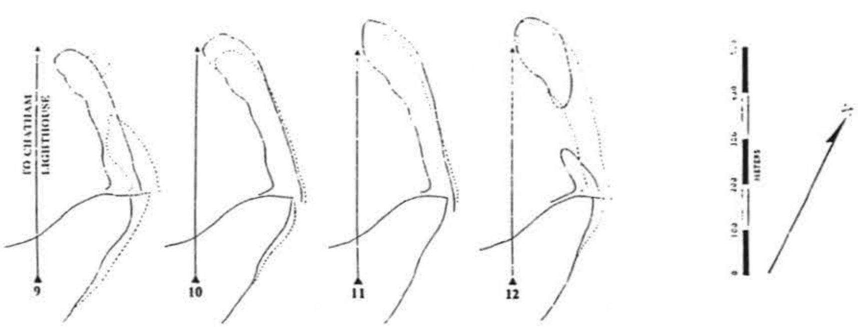
Figure 5. Inlet-spit Cycle II: showing successive shoreline and barrier scarpline positions for intervals 4-8 along with morphological and meteorological characterizations for each interval. This is the briefest of the five cycles with a short spit length at the time of breaching. Note the westward migration of the detached distal section.

because of the abbreviated length of the spit, and when the spit was surveyed on April 13th, the detached distal section was an intertidal shoal. The remant spit was 180 m long, 70 m wide, and its axis had rotated 10° counterclockwise from its previous orientation.

Cycle III

Intervals 9-12 (Fig. 6) comprise a 4-1/2 month-long cycle. Storm frequencies and intensities decreased for the first three intervals, reflecting a seasonal passage from early spring to summer. The overall barrier erosion rate for the cycle was near the study's mean, whereas growth rates for the spit were the highest for all cycles. Erosion of the adjacent barrier was well below the mean during the mild intervals 10 and 11, and above the mean during the stormy intervals 9 and 12. During interval 9, the spit's bay side shoreline prograded and elongation of the spit was most rapid.

INLET-SPIT CYCLE III



Interval #	Dates	Duration (days)	Barrier Erosion Rate (m/day)	Spit Length Growth Rate (m/day)	Spit Area Growth Rate (m^2/day)	Storm Frequency %	Storm Intensity (km/hr)
9	4/13/88-6/7/88	55	0.83	3.04	198	21	24
10	6/7/88-7/5/88	28	0.16	1.57	96	9	24
11	7/5/88-7/26/88	21	0.00	1.95	214	7	20
12	7/26/88-8/29/88	34	0.75	BREACH	BREACH	14	24

INLET-SPIT SHORELINE AND BARRIER SCARPLINE AT START OF INTERVAL ....

INLET-SPIT SHORELINE AND BARRIER SCARPLINE AT END OF INTERVAL ———

Figure 6. Inlet-spit Cycle III: showing successive shoreline and barrier scarpline positions for intervals 9-12 along with morphological and meteorological characterizations for each interval. Note the oceanward shift of the transition point from erosion to accretion on the inlet-spit between interval 10 and interval 11 as conditions became milder. The spit was breached on August 27-28, 1988.

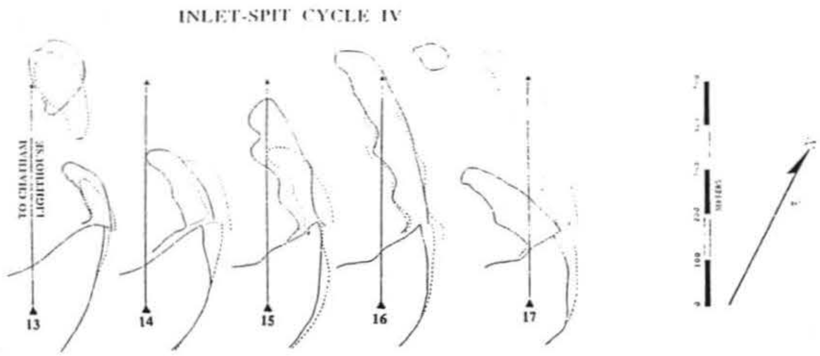
During intervals 10 and 11, the distal end widened by accretion on the inlet-side beachface. This lateral accretion combined with the proximal beachface erosion caused a clockwise rotation of the spit axis. No overwash occurred during these mild intervals and the proximal- and mid-section narrowed to 50 m.

The spit was about 420 m long when the third breach was reported on August 27, 1988, during peak spring tides coincident with moderate onshore storm winds. Two days later on August 29th, the breach channel was measured to be 90 m wide and was centered about 170 m from the spit's base. The remnant spit was 110 m long, 40 m wide, and its axis had rotated 17° counterclockwise from its previous orientation.

Cycle IV

Intervals 13-17 (Fig. 7) comprise a 6-to-7 month long cycle. The ambiguity in cycle duration is due to the uncertainty of the timing of the breach during interval 17. This cycle was the "stormiest" of the five cycles with storm frequencies and intensities generally above the mean, reflecting a seasonal passage from early fall to late winter. Barrier erosion was greatest during interval 14 and 17, the stormiest intervals. Elongation of the spit was also slowest during stormy interval 14, but most rapid during interval 16 which had an average storm frequency and a high storm intensity. Bay side progradation of the spit via overwash occurred during intervals 14 and 15. The spit's mid-section narrowed to less than 60 m during interval 16, the last interval before breaching.

The date of the fourth breach is uncertain, but it occurred sometime between February 20-March 15, 1989. The meteorological record suggests two triggering events, a 2-day northeaster on February 23-25th, and a 4-day northeaster on March 6-10th. Tide Table forecasts indicate the latter storm as the triggering event since it coincided with peak spring tides. The breach channel (measured at least 6 weeks later) was centered about 320 m from the base of the spit and was 230 m wide. The size of the detached distal section near the time of the breach is unknown, but a small supratidal island was surveyed on April 23, 1989. The remant spit (at least 6 weeks into its growth



Interval #	Dates	Duration (days)	Barrier Erosion Rate (m/day)	Spit Length Growth Rate (m/day)	Spit Area Growth Rate (m^2/day)	Storm Frequency %	Storm Intensity (km/hr)
13	8/29/88-9/26/88	28	0.42	1.57	125	19	24
14	9/26/88-10/31/88	35	1.37	1.09	129	27	30
15	10/31/88-12/28/88	58	0.11	1.90	195	18	28
16	12/28/88-2/18/89	52	0.53	2.79	154	17	32
17	2/18/89-4/23/89	64	0.76	BREACH	BREACH	26	32

INLET-SPIT SHORELINE AND BARRIER SCARPLINE AT START OF INTERVAL

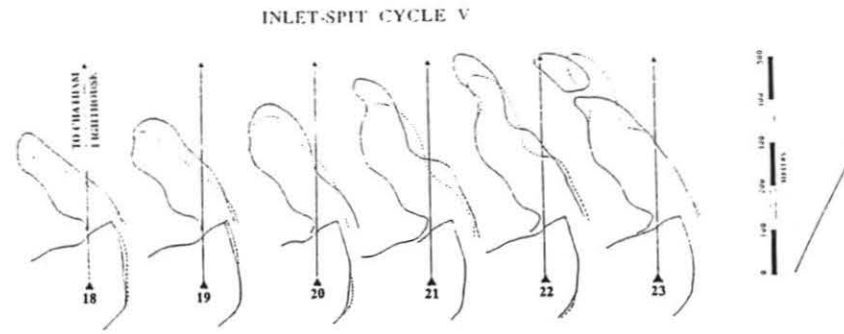
INLET-SPIT SHORELINE AND BARRIER SCARPLINE AT END OF INTERVAL

Figure 7. Inlet-spit Cycle IV: showing successive shoreline and barrier scarpline positions for intervals 13-17 along with morphological and meteorological characterizations for each interval. This is the stormiest of the five cycles. Interval 14, one of the stormiest intervals, has the cycle's highest barrier erosion rate and the slowest growth rate of the inlet-spit. The spit was breached sometime between February 20 - March 15, 1989.

cycle) was 240 m long, 70 m wide, and its axis had rotated 32° counterclockwise from its previous orientation.

Cycle V

The fifth cycle (Fig. 8) began during interval 17 and extended at least seven months until late October, 1989, when a breach occurred in the distal section of the spit. This cycle was the mildest of the five cycles and characterized by low storm frequencies and intensities during the spring and summer intervals and by moderate-to-high storm frequencies and intensities during the later fall periods. The cycle's barrier scarpline erosion rate was practically negligible. The elongation rate was the least of the five cycles, though the areal growth rate was near the mean. During most of the cycle's intervals, the entire spit-beachface accreted and the mid-section eventually widened to more than



Interval #	Dates	Duration (days)	Barrier Erosion Rate (m/day)	Spit Length Growth Rate (m/day)	Spit Area Growth Rate (m^2/day)	Storm Frequency %	Storm Intensity (km/hr)
18	4/23/89-5/23/89	30	0.00	1.57	233	12	24
19	5/23/89-6/28/89	36	0.20	0.42	128	11	24
20	6/28/89-8/20/89	53	0.00	0.54	112	10	24
21	8/20/89-9/16/89	27	0.00	2.70	188	6	26
22	9/16/89-10/9/89	23	0.00	2.58	178	18	22
23	10/9/89-10/22/89	13	0.00	BREACH	BREACH	24	30

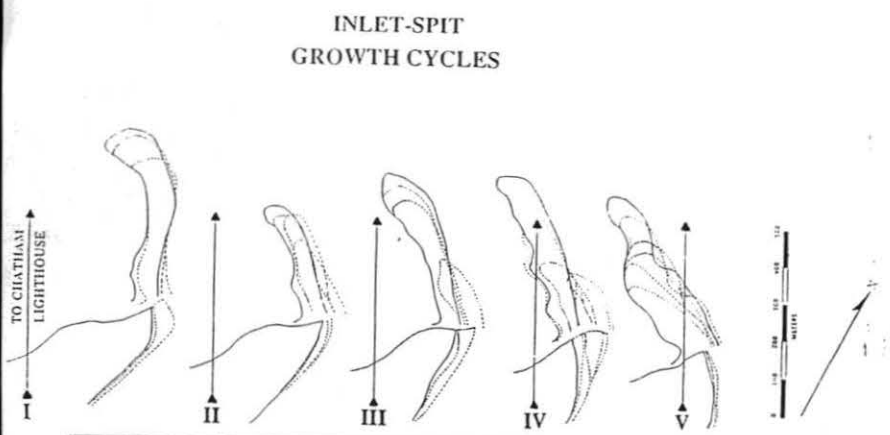
INLET-SPIT SHORELINE AND BARRIER SCARPLINE AT START OF INTERVAL

INLET-SPIT SHORELINE AND BARRIER SCARPLINE AT END OF INTERVAL

Figure 8. Inlet-spit Cycle V: showing successive shoreline and barrier scarpline positions for intervals 18-23 along with morphological and meteorological characterizations for each interval. This cycle has the lowest storm frequencies. Barrier erosion is negligible and the entire spit widens. The spit's distal section was breached on October 18-20, 1989.

100 m. The spit axis rotated clockwise as distal beachface accretion was greater than proximal accretion, however the spit axis still retained a pronounced westward orientation throughout the cycle. During intervals 20-23, a large lobe of sediment migrated downspit along the spit-beachface. Its advance was preceded by an area of erosion, causing an embayment which propagated downspit as well.

The inlet-spit was breached during a 3-day northeast storm (October 18-20, 1989) coincident with spring tides. At this time, the embayment was opposite a narrow portion of the distal section about 350 m from the base of the spit, and was likely an important factor in the spit's breaching at this location. The detached section was a small intertidal shoal when measured a few days later, and the breach channel was only 20 m wide. The remnant spit was 340 m long.



Cycle #	Dates	Duration (days)	Barrier Erosion Rate (m/day)	Spit Length Growth Rate (m/day)	Spit Area Growth Rate (m^2/day)	Storm Frequency %	Storm Intensity (km/hr)
1	11/15/87-1/12/88	58	0.65	2.31	148	15.5	27.6
2	1/31/88-4/6/88	66	0.56	1.80	127	13.9	27.2
3	4/13/88-7/26/88	104	0.48	2.42	174	14.9	23.2
4	8/29/88-2/18/89	172	0.54	1.95	158	19.8	29.1
5	4/23/89-10/9/89	169	0.04	1.32	158	10.8	24.5

Figure 9. Composites of inlet-spit growth cycles along with morphological and meteorological summaries for each cycle. The summaries do not include data from intervals in which breaches occurred (intervals 3, 8, 12, 17 and 23), because morphological changes during these intervals could not be ascribed to a particular cycle. The width of the barrier increases as the north end of South Beach erodes. The inlet-spit rotates clockwise as it grows owing to erosion on its prosximal- and mid-sections while it accretes on its distal end.

This last breach did not fully terminate a cycle as defined above, but was a temporary interruption in a continuing cycle. The breach did not significantly shorten the inlet-spit and the detached distal portion was only a small intertidal shoal. The small breach channel was submerged for only part of the tide and was closed soon after the last survey by a resumption of spit growth.

Discussion

The morphology of inlet-spits can be discussed in the context of four processes:

Barrier and Proximal-Spit Erosion

The erosion of the South Beach barrier has been the most critical of the processes affecting the cycle of spit growth and breaching. The erosion of the barrier from wave action and tidal currents supplies the sediments that form the spits, though some sediment may also be derived from other sources to the north of the inlet, and from scouring processes within the inlet. At the same time, the erosion narrows the proximal- and mid-section of the spit which eventually allows for overwash and breaching. The barrier erosion rate is generally correlated with an interval's storminess and has been modeled previously as a function primarily of storm frequency (Weidman, 1988; Weidman and Ebert, 1989). However, there has been an overall decrease in the rate of barrier retreat on South Beach that cannot be fully explained by variations in storm frequency and intensity. Another control on barrier retreat may be the width of the South Beach's north end. The breach through Nauset Beach in 1987 cut through one of the narrowest sections of the barrier, and the inlet has been eroding the edges of successively wider regions of the barrier ever since, possibly resulting in an increased resistance to longitudinal retreat. Reduced barrier erosion may also indicate that the adjacent inlet has reached a state of equilibrium after 3 years of rapid development.

Distal-Spit Accretion

Distal accretion occurred both as elongation and as widening. Spit growth is often defined as elongation or axial growth, and this occurred in almost all non-breaching intervals, both stormy and mild. No obvious correlation exists between an interval's rate of axial growth and its barrier erosion rate, storm frequency, or storm intensity. However, when storms were severe enough to cause pervasive overwashing (intervals 4, 6, and 14), the spits simply translated bayward and elongation was slowed or did not occur. Climate was also qualitatively reflected in the orientation of the axial accretion, which was oriented to the west during stormier intervals and to the north during milder intervals. Axial growth of the spit narrows the bay entrance between the distal spit and the mainland. There is no clear evidence that axial growth rates were more constrained as the spits grew longer despite the potential for increased tidal velocities through this entrance. Adding to the complexity, the erosion and migration of the detached distal ends caused a progressive shoaling of the bay entrance during the course of this study. Though a shallower bathymetry could enhance spit elongation, a deep tidal channel was continually scoured directly ahead of the distal spit (Fig. 3) and much of the pre-existing bathymetry was reworked before distal deposition took place. Widening of the distal spit or neap-berm building in the manner described by Hine (1979) was common during mild intervals and absent during the stormy intervals.

Overwash Progradation

Progradation of the spit's bayside shoreline was accomplished by overwash processes during storms. The proximal and mid-section of the inlet-spits were the regions narrow enough to allow overwash to traverse the spit. The bathymetry adjacent to the bay side of the spit determined the configuration of the overwash-derived sediment volume. The shallow tidal-flat opposite the proximal section (within 100 m of the base) allowed overwashed sediments to prograde more rapidly than did the deeper regions opposite the mid-section (150-250 m beyond the base).

Breaching

Breaching occurred when all or most of the following conditions existed: 1) storms with onshore winds (probably all cycles, but the circumstances of the fourth breach are uncertain); 2) spring tides (perhaps four out of five cycles, but again the circumstances of the fourth breach are uncertain); 3) a spit length in excess of 400 m (four out of five cycles); 4) a minimum spit width of 60 m (all cycles); this location was usually the mid-section 150-250 m beyond the base of the spit.

Model

Based on these observations, a conceptual model has been constructed of the

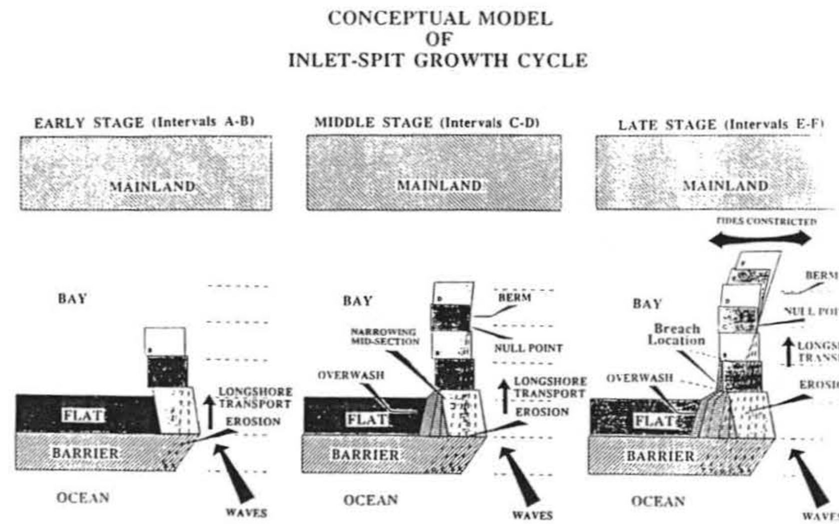


Figure 10. A conceptual model of inlet-spit evolution is illustrated in three stages of development. Breaching of the spit in the late stage terminates one cycle and begins the early stage of a new cycle. Not shown above is that following breaching (during the early stage of the new cycle) the detached distal section erodes and its sediments move bayward and towards the mainland. The remnant spit's axis rotates counterclockwise from its previous orientation and spit growth resumes.

morphological evolution of the South Beach inlet-spit. This model is illustrated in three stages of inlet-spit evolution for one cycle (Fig. 10).

Early Stage (Intervals A-B)

Waves and tidal currents erode the narrow end of the barrier adjacent to the inlet. The short spit elongates as longshore transport supplies sediments derived from the eroding barrier and spit-beachface. The proximal section narrows as the spit-beachface erodes.

Middle Stage (Intervals C-D)

Erosion of the barrier and the spit's proximal beachface decreases downspit, reflecting a bayward decrease in wave energy. Overwash crosses the spit as the proximal section is critically narrowed forming a prograding washover fan on the adjacent back-barrier tidal flat. In this way, the proximal section is able to maintain its sub-aerial width despite beachface losses. Progradation of the bay side shoreline is retarded in the deeper water beyond the tidal-flat and so the mid-section narrows. Elongation extends the distal portion of the spit beyond the null point where net erosion yields to net accretion.

Late Stage (Intervals E-F)

The spit's mid-section becomes critically narrow as the spit's beachface continues to erode. Distal beachface accretion occurs beyond the null point in the form of successive berms, and the distal spit widens as a result. As the spit elongates, the separation between it and the mainland narrows which causes an increasing constriction of the tidal flow into and out of the bay. This tidal constriction causes a decreasing tidal amplitude in the bay and an increasing lag in the bay's tidal phase relative to the ocean tide. This results in an increasing hydraulic head across the spit. The hydraulic head gradient (hydraulic head/ width of spit) will be greatest at the location where the spit is narrowest — the mid-section. The morphology of the inlet-spit is now conducive to breaching under suitable tidal and meteorological conditions. Following breaching, the model reverts back to the early stage and the cycle repeats. The remnant spit is reoriented counterclockwise owing to the dominant wave conditions on the inlet side of the spit and the new tidal entrance's closer proximity to the ocean. The detached distal section erodes as its sediment supply is interrupted by the formation of the breach channel, and this island/shoal migrates bayward in response to the dominant wave conditions on its oceanward side.

The main aspects of the conceptual model are supported by comparing it (Fig. 10) with the composite time series of inlet-spit growth cycles (Fig. 9). During most of the growth cycles, the spit's axis appears to rotate clockwise around a node located in its mid-section, about 200 m beyond its base. This apparent rotation is caused by the increasing erosion oceanward of the node and the increasing beachface accretion bayward of the node. The proximal section maintains its width, whereas the mid-section generally narrows, with the breaches occurring in the mid-section of the inlet-spit.

Climatic Imprint on Inlet-Spit Morphology

The variation in spit morphology between one cycle and the next can largely be explained by each cycle's climatic history. The small scale, rapid growth, and short duration of the inlet-spit cycles on South Beach allow synoptic and seasonal changes in storm climate to be strongly correlated with the morphology of the spit. Surprisingly, there is no evidence from the field data that sediment supply or inlet-spit growth (elongation or areal growth) is related to energy conditions. This may be because northeast storms, while effective agents of erosion of the north end of South Beach and the proximal sections of the spit, are also effective at depositing this eroded material elsewhere besides the inlet-spit. This material may be deposited farther into the bay, on the other shoals within the lagoon and inlet, or may be moved south along the outside of South Beach. Fairweather conditions at Chatham, have a dominant southerly component (Weidman, 1988) and may move sediment northward along the outside of South Beach, into the inlet, and along the inlet-spit. Also, the reduced energy conditions may tend to inhibit the transport of sediment off the inlet-spit. In this way, compensating processes appear to provide a more or less steady supply of sediment to the inlet-spit under contrasting energy conditions. However, different wave energy conditions (stormy vs. mild) do cause characteristic erosion and accretion, producing spits with different orientations and shapes (Fig. 11). This can be demonstrated by comparing the morphologies and climates of each of the five cycles .

Cycle I

The strong recurve of the inlet-spit's distal end is explained by increasing wave energy conditions as the spit grew. This is consistent with a cycle that began in early summer and ended in mid-winter. The earlier mild conditions

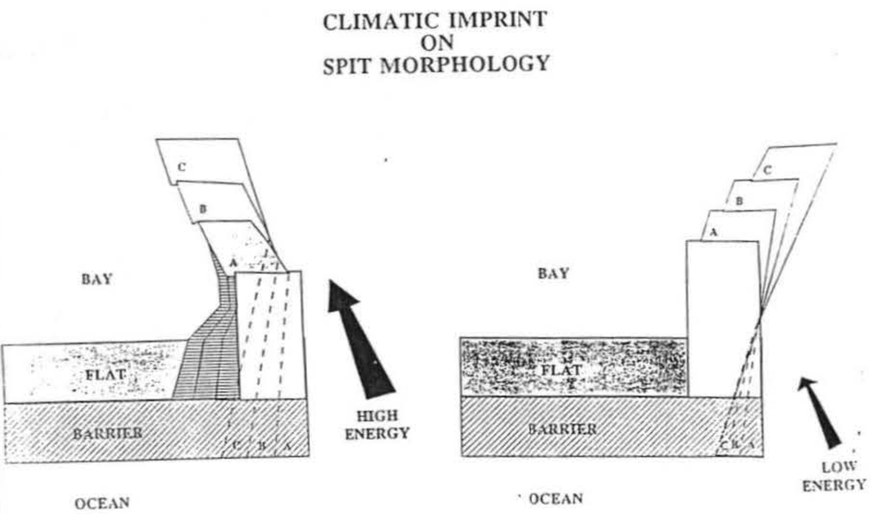


Figure 11. The influence of climate on inlet-spit morphology is most apparent in the orientation of its distal accretion.

resulted in a rather straight, nearly northward-oriented proximal section and mid-section (indicating some lateral beachface accretion). The later stormier conditions caused the sediment to be deposited farther westward around the spit's distal end, causing the recurve.

Cycle II

The westward orientation of the inlet-spit, the narrowness of its distal portion, and the brief duration of its cycle are all evidence of stormy conditions, consistent with a cycle entirely within a winter climate. The greater energy conditions erode the spit-beachface and cause frequent overwashing, resulting in a narrow spit that is subject to early breaching.

Cycle III

The spit's wide distal end and narrow mid-section reflect distal beachface (lateral) accretion and proximal beachface erosion. This was a product of increasingly mild conditions characteristic of a passage from spring to summer. Except for a lack of overwash deposition after the first interval of the cycle, this cycle is most similar to the model "type".

Cycle IV

The spit's narrowness throughout its length is evidence of stormy conditions throughout its cycle, consistent with a fall to late winter climate. The early intervals of this cycle are reminscent of cycle II, another winter cycle, when beachface erosion and overwash caused the bayward migration of the entire spit. The spit attained a long length despite a narrow mid-section and persistent storminess for most of its cycle. The meteorological and tidal record explain this by a lack of coincident storms and peak tidal conditions, so that a breach was not triggered for many weeks despite the inlet-spit's morphological "ripeness" for breaching.

Cycle V

An anomolously wide spit without a narrow mid-section was produced during a cycle characterized by little erosion of the barrier and proximal spit-beachface, and steady distal spit-beachface accretion. The extreme westward orientation of the initial spit was a product of stormy (late winter) conditions which existed at the beginning of the cycle. This was followed by 5 months of mild conditions (spring and summer). This sequence of energy conditions allowed for a relatively large clockwise rotation of the spit axis and a wide mid-section. The narrow distal portion in the later intervals reflects increasing storminess.

Inlet-Spit as Scale Model

The short period cyclicity of the South Beach inlet-spits provides an opportunity to understand better the evolution of spit systems that are larger in spatial and temporal scale. As a precaution, it should be recognized that the inlet-spit on South Beach exists within the unique environment of a developing tidal inlet. However, some previous investigations of larger scale spit accretion and breaching cycles reveal that these cycles conform to a number of aspects of inlet-spit morphology and behavior.

DeBoer's study (1967) of the morphological history of Spurn Head in Yorkshire, U.K., documents four cycles of spit growth and breaching from almost a thousand years of historical record. He offers a model in which the eroding mainland supplies sediment for spit elongation and simultaneously erodes the proximal parts of the spit. This leads to a reorientation of the spit's shoreline towards the dominant storm wave direction which in turn allows for more frequent overwashing of the spit during storms. The mid-section narrows through continued erosion and is eventually breached. This ends one cycle and another begins.

The cyclic growth and breaching of Nauset Beach, the parent body of the South Beach inlet-spits, is thought to be controlled by increased constriction of the tides caused by the southward growth of the spit (Giese, 1978, 1988; McClennen, 1979). According to Giese, elongation of the Nauset Beach spit produces an increasing tidal phase lag and amplitude difference between the Atlantic Ocean and Pleasant Bay. These tidal differences eventually reach a critical stage, where a breach of the spit north of the extant inlet results in the formation of a new permanent inlet, and the cycle repeats itself.

The morphological evolution of these systems is similar to that of the inlet-spit on South Beach. All these spit systems evolve to where breaching becomes inevitable. Their behavior supports a generalized concept of cyclic spit morphology in which spit growth is characterized by elongation, reorientation, and thinning. Elongation constricts lagoonal tides and raises a hydraulic head across the spit. Reorientation may increase the spit's exposure to wave energy leading to more frequent overwash and beachface erosion. The local storm climate and surrounding hydrodynamics determine the

critical width necessary for the spit to breach. A similar concept of critical barrier width as a prerequisite for washover fan progradation has been previously discussed by Leatherman (1979). The location of a breach is strongly influenced by the bay side bathymetry. Pierce (1970) argued that the barrier sections most susceptible to breaching are narrow and lack shallow tidal flats on their lagoon sides. Finally, storms whose effects may be enhanced by extreme tides provide the necessary conditions for triggering a breach. Wood (1976) has correlated significant coastal changes with coincident storms and extreme spring tides.

Conclusions

The South Beach inlet-spit displays a cyclic morphology of accretion and breaching. Five cycles have been documented in two years. This cycle is characterized by: 1) a 3-7 month period of spit elongation from a minimum length of 100 m to maximum length of 500 m; 2) a clockwise rotation of the spit axis reflecting a combination of distal spit-beachface accretion and proximal spit-beachface erosion; 3) gradual narrowing and the eventual breaching of the spit's mid-section 100-200 m from the spit's base, resulting in the formation of a small tidal channel between former spit-sections; and 4) evolution of the detached distal section from a supratidal island to subtidal shoals.

A conceptual model has been offered which explains the cyclic behavior of the inlet-spits as a consequence of interrelated of morphological, tidal, and meteorological factors. 1) The erosion of South Beach's northern end is forced by wave and tidal conditions related to the developing New Inlet system. 2) This erosion plays a dual role by supplying sediments for the construction of inlet-spits and simultaneously causing their destruction by narrowing their proximal- and mid-sections. 3) The bathymetry on the bay side of the spit constrains the width of the spit by influencing the rate of bay side progradation from overwash. The shallow regions adjacent to the proximal spit help to maintain the spit's width, while the deeper regions adjacent to the spit's mid-section allow it to narrow. 4) As the spit elongates, the distance between the spit and the mainland shortens, possibly constricting the tidal flow between the bay and the inlet. This would be reflected by increasing tidal phase and amplitude differences between the bay and inlet side. 5) The morphology of the spit is "ripe" for breaching when the spit is long (400-500 m), the mid-section is narrow (< 60 m), and consequently the hydraulic head gradient is greatest. 6) At this point, a sufficient combination of storm waves, storm surge, and spring tides will trigger a breach of the spit and initiate a small tidal channel, thus ending the cycle.

Differences between cycle morphologies are largely governed by their climatic histories. Cycle periods are measured in months, and so inlet-spits can complete their entire growth cycles within one or two seasons. The sequence of changes in storm frequency and intensity (and resulting wave energies) on a seasonal basis, causes characteristic patterns of erosion and accretion during spit growth. Mild weather favors beachface accretion and stormy weather favors beachface erosion and overwash. In this way, the inlet-spits retain a signature of their cycle's climatic history in their resultant shape and orientation.

Some aspects of inlet-spit morphology might be applied towards understanding the evolution of barrier and spit systems in general. The concept of a critical barrier width for breaching, as determined by the surrounding hydrodynamic conditions (both wind-wave- and tide-related), could be instrumental in assessing a system's stability. Lagoon bathymetry can play an important role in determining breach locations by affecting the rate of back-barrier migration. Seasonal or climatic changes may be reflected in the changing orientation of spits and barriers along their length and could be useful in reconstructing a climatic history of a region. Finally, it is important to emphasize that although storms trigger barrier breaching, the evolution of a system incorporates somewhat predictable hydrodynamic and morphological changes that can eventually produce a morphology that is "ripe" for breaching.

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