UPDRIFT MIGRATION OF TIDAL INLETS[1]

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ABSTRACT

Three mechanisms are responsible for tidal inlet migration in an updrift direction (counter to net longshore transport): (1) attachment of distal ebb tide delta bars to the downdrift barrier spit; (2) storm-induced breaching and subsequent stabilization to form a new inlet; and (3) ebb tide discharge around a channel bend creating a three-dimensional flow pattern which erodes the outer channel bank and accretes on the inner channel bank. The last two mechanisms can result in either updrift or downdrift inlet migration, depending on channel geometry in the bay and barrier beach configuration. The last mechanism is discussed here for the first time. Analysis of historical charts and aerial photographs, combined with an historical storm synthesis, shows that all three mechanisms are active at a natural tidal inlet along a sandy coast (Nauset Inlet, Cape Cod, MA). On a time scale of 10 years, these mechanisms were effective in producing an updrift migration of more than 2 km. Initiation of updrift migration coincided with a marked increase in storm frequency perturbing the historically stable inlet position. Subsequent updrift migration resulted from ebb-delta bypassing and channel bend flows.

INTRODUCTION

Migration of tidal inlets and the associated changes in adjacent barrier beaches have profound implications on both the geological evolution of inlet/estuary systems and the short-term stability of these features. Past studies have documented many instances of inlets migrating in the direction of net littoral drift along sandy shores but have uncovered few cases (e.g., Indian River Inlet, Delaware, and Thorsminde Inlet, Denmark) where inlets appear to migrate in directions opposed to the dominant longshore transport direction (Bruun 1978). Migration of tidal inlets in any direction accelerates inlet-induced changes in the estuary. The estuary may fill in with littoral sands derived from updrift sources, as flood tide delta growth accompanies the migration of the inlet, and marsh development (colonization and plant emergence) becomes more variable and less permanent.

Previous attempts to explain a reversal in direction of inlet migration suggest a change in direction of net littoral drift, causing a change in migration direction. This explanation is not realistic for some inlets where wave forcing and nearshore bathymetry have remained constant through time. This study presents three alternatives to explain the tendency of some inlets to migrate updrift, each supported by historical observations at a site with a large-volume, directionally-biased littoral drift.

The study site is located on the Atlantic coast of Cape Cod, Massachusetts (fig. 1), exposed to open ocean waves from the east and a 2-m ocean tide. Offshore bathymetry and sediments are described elsewhere (Aubrey et al. 1982). Longshore transport rates and directions were studied by Zeigler (1954, 1960), and net littoral drift has been estimated at 250,000 m^3 per year towards the south (U.S. Army Corps of Engineers 1969). Sediment is derived from erosion of sea cliffs bordering Nauset Inlet to the north. Overwash processes along Nauset barrier beaches are described in Zaremba and Leatherman (1979). Aubrey and Speer (1983, 1984) discuss tidal flows and sediment transport in the bay and inlet. Other sedimentologic studies of the region are found in a summary volume by Leatherman (1979).

Sea level has risen over the past 50 years an average of about 3.5 mm/year (based on tidal data from Woods Hole and Boston, MA; Aubrey and Emery 1983). This rate is three times greater than the mean sea level rise of 1 mm/year over the past 2100 years established from measurements of salt marsh peat accumulation at Barnstable Harbor, Cape Cod (Redfield and Rubin 1962). As discussed by

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[1] Manuscript received January 31, 1984; revised May 11, 1984.

[2] Woods Hole Oceanographic Institution Contribution Number 5205.

[JOURNAL OF GEOLOGY, 1984, vol. 92, p. 531–545]

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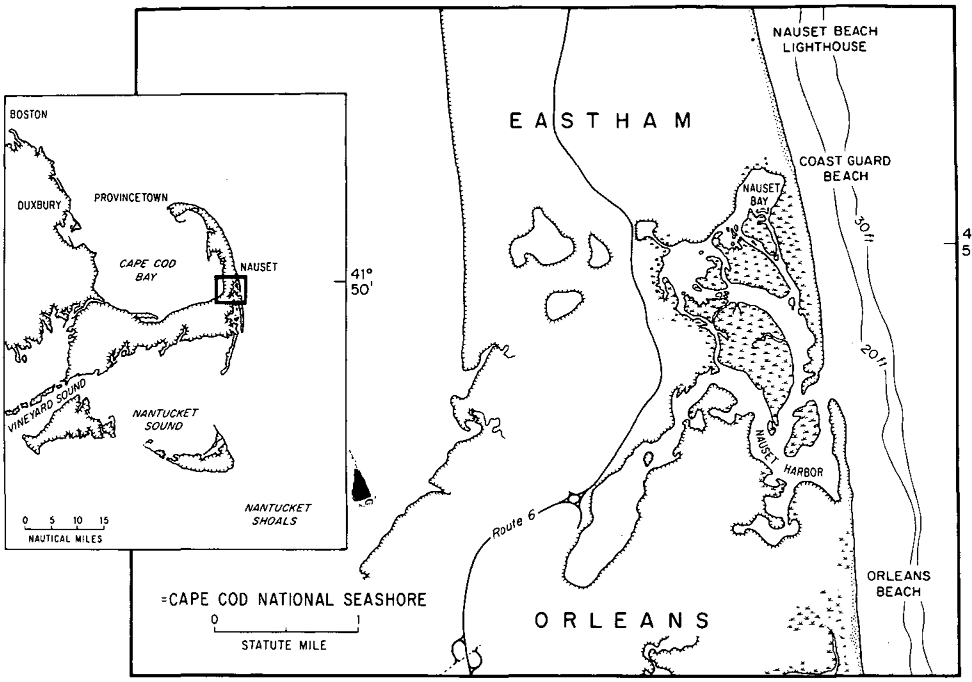

FIG. 1.—Location map for study.

Aubrey and Emery (1983) and others, although short-term mean sea level records exhibit considerable oscillations about a mean trend, the mean rate over the past 50 years has not changed significantly. Sea-level rise favors landward migration of evolving barrier beaches.

METHODS

Historical charts and aerial photographs of the Nauset Inlet area dating from 1670 and 1938, respectively, were examined to define and (where possible) quantify changes in inlet position and morphology. Historical data (fig. 2) were obtained from a variety of sources including government agencies, the National Archives, the Library of Congress, the Woods Hole Oceanographic Institution, and private industry (Speer et al. 1982, Appendices 1 and 2). Chart coverage is dense from 1790 to present (coverage was sparse before 1790), and good aerial photographic coverage exists from 1951 to present (only one aerial photo sequence was available prior to 1951, taken in 1938). Small scale and uncertain mapping techniques used in pre-1846 historical charts make it difficult to quantify changes in inlet morphology during this period, but these charts were valuable in depicting general trends in inlet morphology. Care was required in interpreting the charts because several of the charts from the 1800's did not specify survey dates, and were merely reproductions of earlier and perhaps outdated surveys. Also, in the case of U.S. Coast and Geodetic Survey (USC&GS) charts, only limited shoreline segments were updated between editions.

Aerial photographs provide more detailed information than the charts because they are generally larger in scale (allowing resolution of shoreline features such as bars and marshes). They also provide more comprehensive temporal coverage for a limited period (1951 to 1981) than do the charts, and the dates of coverage are unambiguous. Fifty vertical sets of the 125 photographs available were analyzed to quantify inlet and spit migration at Nauset. The remaining photographs were not analyzed because they were taken at oblique angles, were poorly fitted mosaic series, or lacked sufficient ground control to assure measurement accuracy. However, they were instrumental in provid-

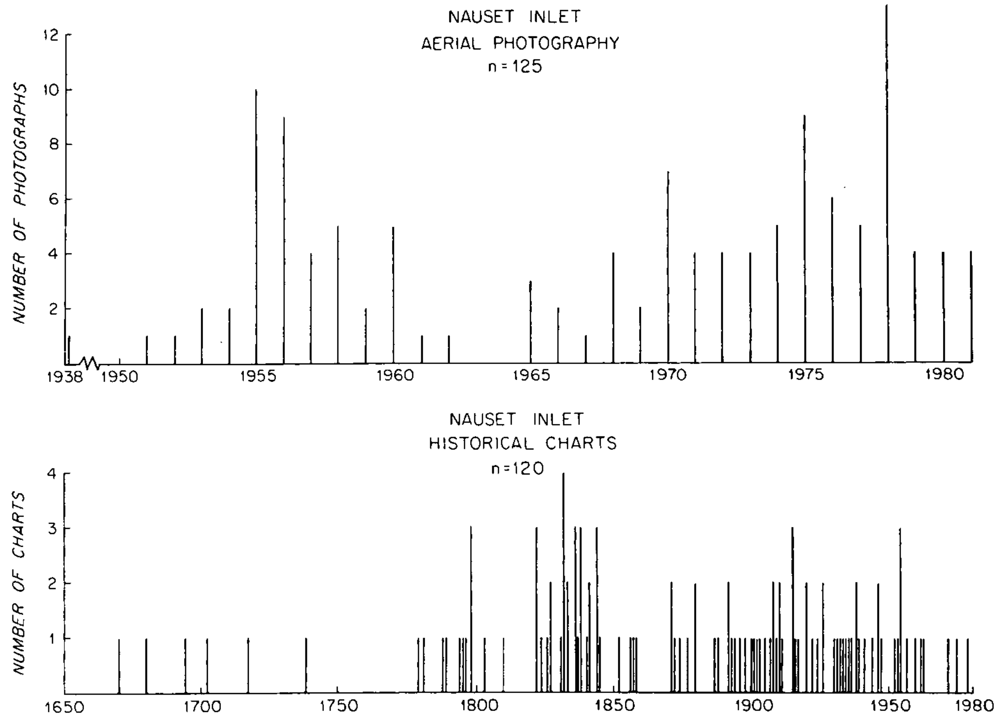

FIG. 2.—Summary of Nauset Inlet aerial photography (125 sets since 1938) and historical charts (120 sets since 1670).

ing a continuous record of relative changes in inlet and spit locations during the past 30 years.

Measurements of spit and inlet locations are relative to a baseline, sub-parallel to the shoreline, established between well-defined, permanent features identified on each set of aerial photographs (fig. 3). The known length of this baseline provided a consistent determination of scale for all photos. Uncertainty in some measurements resulted when one of the two primary reference points was absent from a particular photo mosaic. In these cases, secondary landmarks were used, along with geometrical relations to define the baseline from the one available endpoint. As a result of such variations in the photographs, overall accuracy of measurements is estimated to be ± 15 m, despite a measurement resolution of 5 m.

RESULTS

Analysis of historical charts and photographs reveals patterns of inlet migration and barrier beach elongation/shortening at Nauset. Nauset Inlet has migrated extensively over the past 30 years, related in part to an increase in storm frequency, as discussed below.

Inlet/Barrier Beach Migration.—Historical charts (dating from 1779) and aerial photography (dating from 1938) show the preferred inlet location to have been just north of Nauset Heights, at the southern (downdrift) extremity of the bay drainage system (fig. 4). None of the charts (up to 1946) depict a significant south spit. Although aperiodic historical coverage might have undersampled previous episodes of inlet migration, the persistence of a southern location suggests this was an historically stable inlet configuration.

Aerial photographs from 1938 and a 1946 USGS chart confirm an inlet location just north of Nauset Heights, with no south barrier apparent (figs. 5 and 6). From the 1950's into the early 1980's the inlet has been active, with three distinct cycles of northward (updrift) movement. The first two of these (fig. 5, 1952–1957 and 1965–1972) resulted in a pattern of overlapping spits. In both cases, the

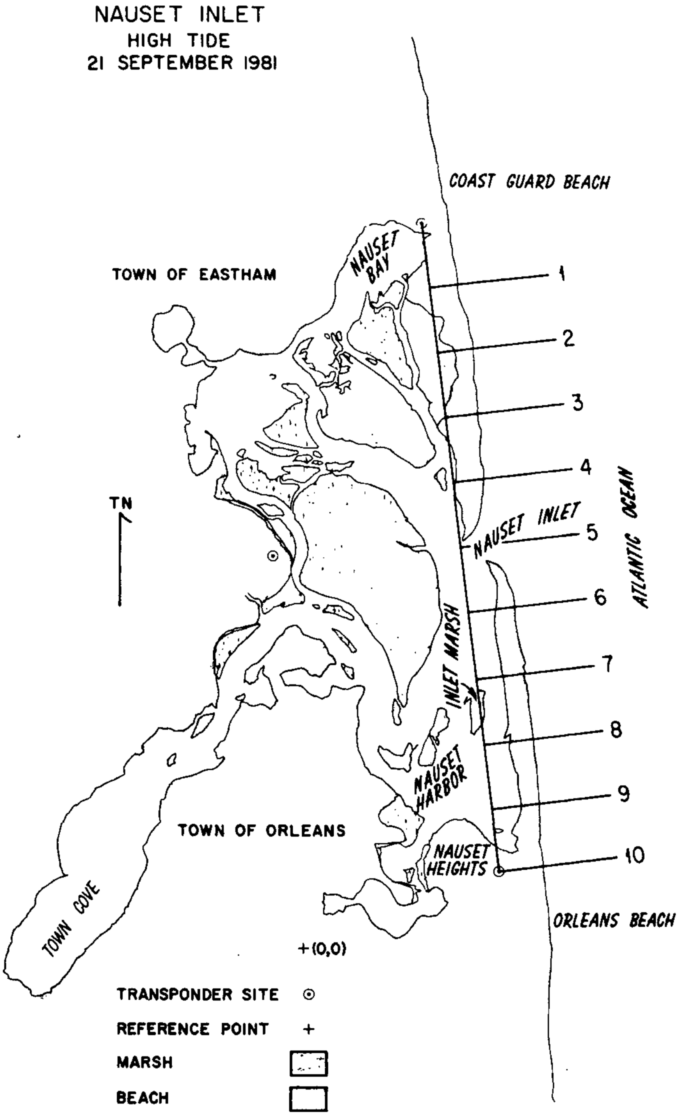

FIG. 3.—Baseline location for inlet migration measurements. The northern reference point adjacent to Coast Guard beach is Coast Guard Station. Distance between adjacent reference lines (1–10) is 535 m.

length of the north spit remained approximately stable while the south spit continually grew north. The third cycle (fig. 5, 1972–1984) has involved substantial erosion of the north spit along with northward growth of the south spit.

The first cycle of northward growth was initiated by storm activity. The north barrier was breached, and a remnant of the barrier located south of the new breach attached to the south barrier. Subsequent southward growth of the north barrier through attachment to an island in the marsh (Inlet Marsh), and northward growth of the south spit, resulted in the overlapping pattern of the mid-1950's (fig. 6). During this period of barrier growth, the elongated inlet channel extended to the north from its original southern location. A series of storms in the late 1950's and early 1960's re-established the inlet to its southernmost position immediately adjacent to Nauset Heights (figs. 6*f*, 7*a*). By April 1965, the inlet/barrier beach configuration was similar to that in 1938, with the sole ma-

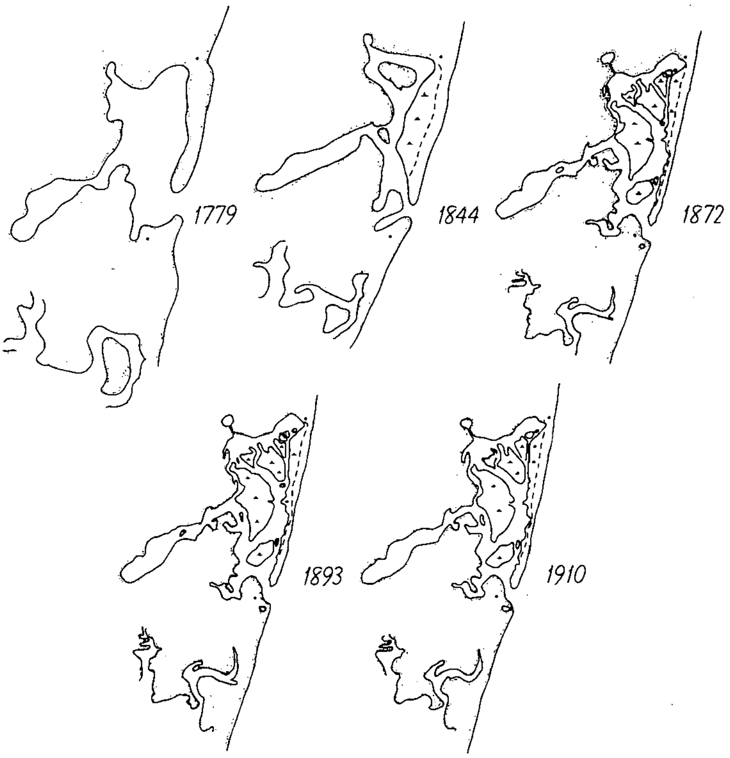

FIG. 4.—Five representative historical charts depicting variability of Nauset Inlet from 1779–1910.

jor difference being landward migration of the north spit due to repeated storm overwashes (Zaremba and Leatherman 1979). The second cycle of northward migration was characterized by extension of the south barrier while the north barrier remained in approximately the same location. Between 1965 and 1972, the south spit extended nearly 900 m to the north (fig. 7*b*, 7*c*). As in the mid-1950's, the inlet channel also extended north, accompanying this barrier growth.

The final cycle of northward movement was initiated by a storm breach in the north spit in the spring of 1972 (fig. 7*c*). This re-

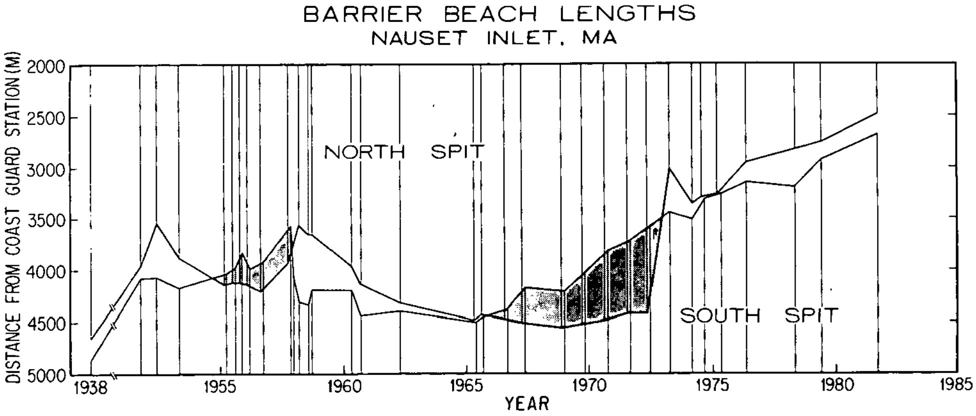

FIG. 5.—Location of North Spit and South Spit termini, measured along the baseline from Coast Guard Station (see fig. 3 caption). Stippled patterns indicate periods when South Spit overlapped North Spit, and extended farther north. Vertical lines indicate periods for which measurements were made.

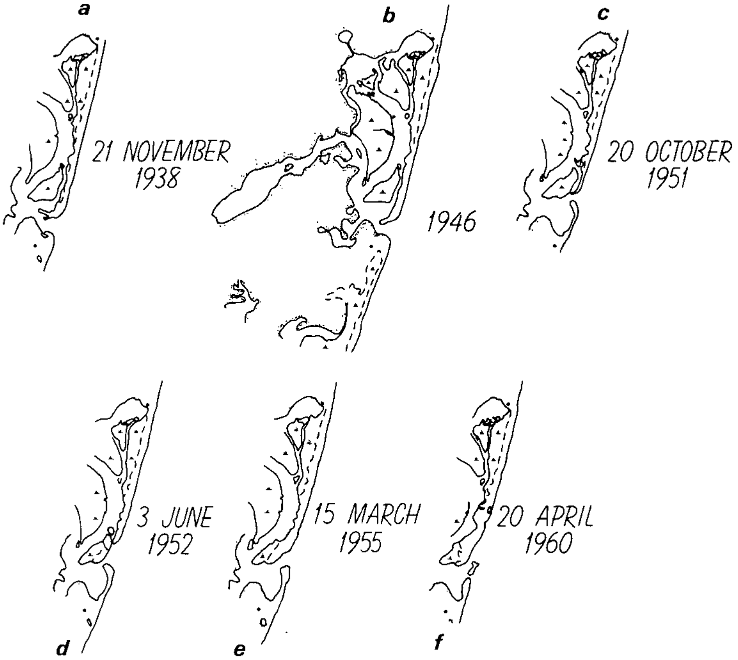

FIG. 6.—Tracings of vertical aerial photographs of Nauset Inlet between 1938 and 1960.

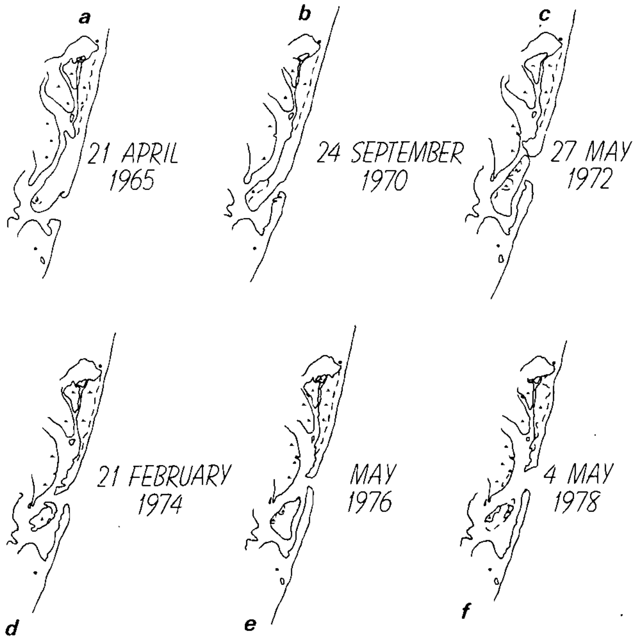

FIG. 7.—Tracings of vertical aerial photographs of Nauset Inlet between 1965 and 1978.

sulted in the present phase of northward migration which is qualitatively different from the previous two episodes. In this third instance, the main inlet channel stabilized in the location of the newly formed breach with the former inlet closing off. Since 1972, the inlet channel and the south barrier have been growing northward at a rate of approximately 100 m/yr. Unlike previous cycles, the north spit is steadily eroding and the main inlet channel is actually moving north, instead of simply extending to the north from a southern location (fig. 7*d*–7*f*). No major breaches affecting the stability of the south spit have occurred during this latest period. A large overwash occurred at the northernmost part of the north spit during the 6 February 1978 blizzard. Since this overwash emptied into a shallow (<1 m deep), broad bay (Nauset Bay), the overwash did not evolve into a permanent breach. Such an overwash occurring on the south spit would probably result in a new inlet position.

Storm Analysis.—The Atlantic shore of Cape Cod is frequently buffeted by storms which have the potential to cause dramatic changes in shoreline configuration. A U.S. Army Corps of Engineers report (1979) cites 160 gales with wind speeds greater than 15 m sec^{-1} between 1870–1975. Half of these were northeasters. Both tropical and extra-tropical (including northeasters) cyclones produce dramatic changes at Nauset Inlet because of the geographical orientation of the outer Cape.

Three types of storm data were collected for comparison with large-scale morphologic changes at Nauset Inlet:

a) Hayden and Smith (1982) compiled a monthly list of cyclone occurrences off the east coast between 1885 and 1982, using as a data base the "Tracks of the Centers of Cyclones at Sea Level" published by *Monthly Weather Review* and in recent years by *Mariners Weather Log.* Cyclone statistics (both tropical and extra-tropical) are available on 2.5° latitude by 5° longitude grid cells. The four grid cells bordering the Cape Cod region to the east and southeast (total area covered is 60°W to 70°W, 37½°N to 42½°N) are used as the region of storm influence for the study area. For generation of year-by-year and monthly mean statistics, storm values for the four grid cells are summed. Although this yields an overestimate of the number of storms (the same storm may pass more than one grid cell), it will still provide a qualitative indication of storm duration and persistence, since on the average a storm tracking through two grid cells generates waves in the study area for a longer period of time than one passing a single grid cell.

Cyclone statistics resulting from the averaging serve as a crude indicator of wave activity. Large cyclone counts suggest high wave activity; a small cyclone count represents low wave activity. Persistence and frequency of storms are our criteria for wave intensity. Clearly, storm intensity or magnitude would be a useful weighting factor for linking waves and storms; unfortunately, this information is not available.

The period from 1885 through 1949 experienced a relatively low incidence of storm activity (fig. 8). Within this low background level, the periods from 1885–1893, 1921–1924, and 1930–1941 have local maxima in cyclone frequency. The last 30 years of the record show consistently higher cyclone frequency, with local maxima at 1950–1954, 1961–1962, 1972, and 1974. Although the absolute number of storms may be sensitive to the quality and quantity of weather observation stations, local trends (minima and maxima) are valid indicators of relative storm occurrence.

b) Another source of storm incidence data was the U.S. Army Waterways Experiment Station (WES) wave hindcast program (data provided by W. Birkemeier). This program computes nearshore wave height statistics based on weather observations and local bathymetry. The study identified the 157 largest storm events from 1956 to 1976 (inclusive). These storms were assigned recurrence intervals according to their rankings, allowing for weighting of storms by severity. The WES compilation correlates well with cyclone data. WES data show high storm activity in 1956, 1962, and 1972; however, it also indicates a high level of storm activity in 1969 which does not appear in cyclone data. Differences between the two data sets are the result both of weighting procedures and different representations of the data base.

c) Finally, a list of major storms affecting the outer Cape was compiled from newspapers, historical descriptions, and published

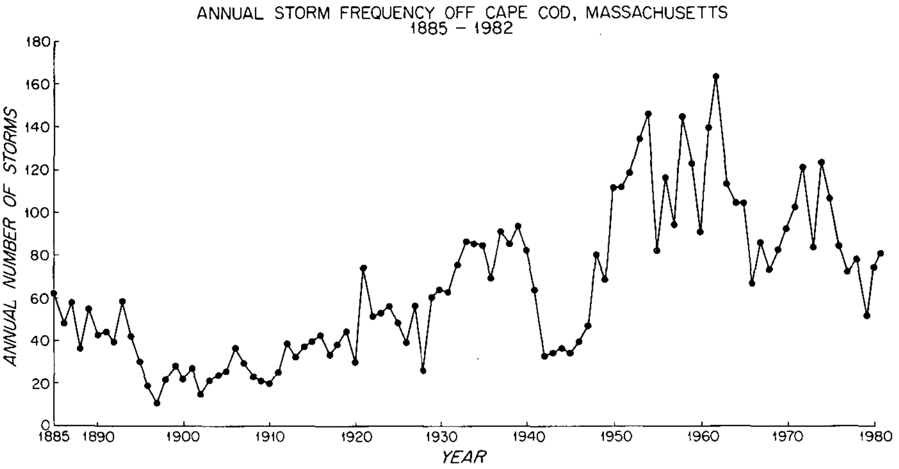

FIG. 8.—Number of cyclones affecting Cape Cod, Massachusetts (including area 60°W to 70°W, 37½°N to 42½°N) from 1885 to 1981. Storm count is indicative of storm duration, and not individual cyclone events. Data derived from Hayden and Smith (1982).

tropical storm tracks (fig. 9). This list is incomplete since prior to 1948 it only includes hurricanes and storms of historical significance. It is possible to identify specific storms which are likely to cause changes at Nauset Inlet, although irregular sampling afforded by aerial photography (fig. 2) makes direct correlation difficult. Through this method, 10 significant storms were found that were not hindcast in WES study.

DISCUSSION

Aerial photographs and historical charts reveal patterns of inlet/barrier beach change with which conceptual models must be consistent. The important features of Nauset Inlet's migration patterns are: the historical stability of the southernmost inlet entrance; the role of storms in initiating major changes in the inlet/barrier beach system; and the recent tendency for the inlet to move in a direction opposite the predominant longshore drift. Migration of the inlet with accompanying changes in the barrier beaches takes place on essentially two different time scales. Major relocations of the inlet, involving longshore movements of hundreds of meters in several days, occur episodically during large storms and have a recurrence on the order of a decade. The other important time scale is asso-

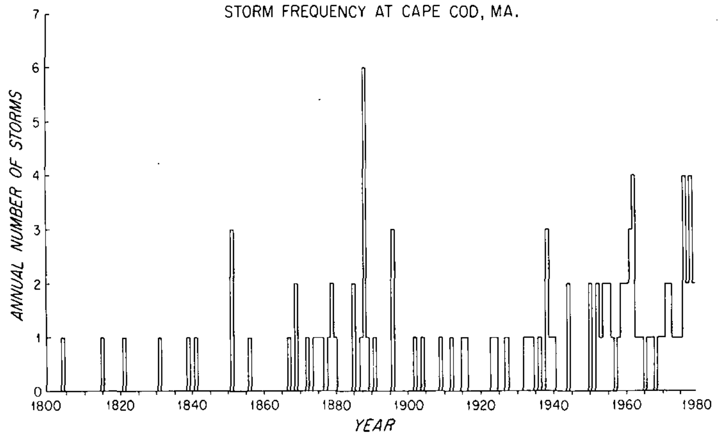

FIG. 9.—Compilation of storm events on an annual basis from 1800 through 1980. Sources are newspapers, historical descriptions, and published tropical storm tracks.

ciated with the recent steady migration of the inlet in a general northward direction, responding to the combined effects of wave activity, tidal flows, and longshore sand transport. The magnitude of this movement is on the order of 100 m/yr. Northward migration of the inlet is accompanied by extension of the southern barrier and generally by shortening of the northern barrier (especially from 1973–1983).

The general stability of a southern inlet location in this system is not surprising. Most of the tidal prism passes through the deeper southernmost channels of the marsh; therefore a southern inlet provides the most direct link to the ocean. Frictional dominance in this shallow inlet/estuary system (Aubrey and Speer submitted; Speer and Aubrey submitted) makes this an energetically favorable location for the inlet. The 1983 location of the inlet requires that long (~2 km) shallow channels carry most of the tidal prism to the south. A large fraction of the total tidal energy is dissipated in these channels; consequently development of an energetically more favorable inlet location further south is probable in the near future (order of a decade).

The southernmost location places constraints on barrier beach configuration. In general, the northern barrier is not strongly eroded by the ebb tidal flows when the inlet is in a southerly location as compared to a more northerly one (reasons for this are presented later). A short, slowly-growing southern spit can develop without catastrophic storm influence. However, large-scale growth of a southern barrier spit is dependent on storm activity and breaching of the northern barrier.

Three mechanisms appear responsible for observed updrift tidal inlet migration at Nauset (fig. 10): (a) attachment of distal ebb tide delta bars to the downdrift barrier spit; (b) storm-induced breaching and subsequent stabilization to form a new inlet; and (c) ebb tide discharge around the inlet channel bend. The last two mechanisms can result in either updrift or downdrift migration. The first two mechanisms have been observed widely at other inlets; the third mechanism is described here for the first time.

a) Any model of Nauset Inlet's migration must include mechanisms for longshore bypassing of sediment past the inlet, since the volume rate of longshore sand transport is a primary factor controlling inlet stability (e.g., Bruun and Gerritsen 1959; Bruun 1978). Average net longshore transport rate is estimated to be about 250,000 m^3/yr to the south (U.S. Army Corps of Engineers 1969) at Nauset Inlet, with considerable year-to-year variability. Consequently, shallow overwashes are filled quickly, and the tidal prism seems capable of supporting only a single stable inlet.

A common mode for sediment bypassing of tidal inlets is through formation and migration of distal ebb delta bars, which are predominantly wave-driven. For many wave-influenced tidal inlets throughout the world, ebb delta bar migration is the dominant bypassing mode (Bruun 1978; Fitzgerald 1983; Nummedal 1983), while bypassing through the inlet proper (Galvin 1983) appears less important. Bar bypassing results in episodic accretion of sand on the downdrift barrier, often increasing encroachment of the downdrift barrier into the inlet throat.

Bar bypassing has been documented several times at Nauset Inlet, increasing the length of the southern (downdrift) barrier. The existence of active bar bypassing at Nauset causes south spit to grow to the north, *against* the influence of predominant longshore transport, since the migrating bars weld to the spit terminus instead of escaping the inlet influence (fig. 10). The accreted sand remains on the downdrift spit, increasing its length and forcing the inlet to migrate northwards. Contrary to the observations of Fitzgerald (1983), these accretionary episodes occur on time scales of months, not years.

b) The importance of storm activity to major changes in inlet/barrier beach configuration is illustrated by comparison of inlet migration rates with storm frequency. Historical data (figs. 8 and 9) show three periods of high storm activity since 1933, preceded by a 48 year period of relative quiescence. The first period of intense activity lasted from 1933 until 1939. Unfortunately, inadequate chart and photo coverage prevents full documentation of inlet response to this stormy period. The second stormy period covered the years 1950 to 1962. Large scale inlet migration, together with overwash and breaching of the barrier beaches, occurred during this

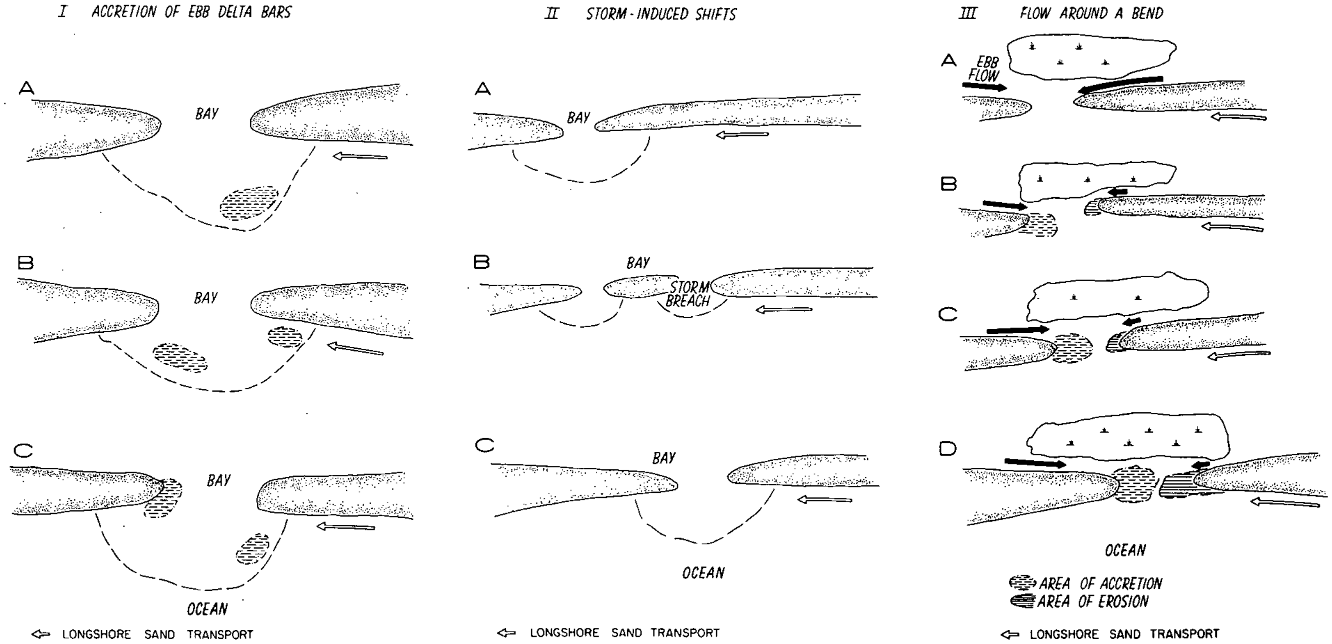

FIG. 10.—Three modes of updrift inlet migration responding to different combinations of waves, tides and storms. All three modes have been observed at Nauset Inlet, Cape Cod, Massachusetts.

time. The north barrier breached in May 1953 and January 1956, while the south barrier breached in December 1957 and early spring 1960. Storm-induced changes in barrier beach length of as much as 780 m have been observed. A third period of intense storm activity existed in the early 1970's. One of the peak years, 1972, coincides with a breach in the north spit, which initiated the current phase of steady northward inlet migration.

c) Casual observation of tidal inlet and estuarine flows shows that these channels often are not straight, but rather have pronounced curvature. This curvature has dramatic effects on flow through these channels, affecting near-bed shear stress distribution and resultant sediment transport. Complexity of channel geometry ranges from long, straight channels with occasional bends to nearly continuous, sinuous geometry reminiscent of river channel meanders. Channel curvature within an inlet mouth provides a mechanism for inlet migration, as discussed below. An extensive literature discusses the effects of channel curvature on flow structure and sediment transport, largely resulting from an interest in river channel meanders and open channel flow. Much of the work to date has been done by engineers interested in channel scour and deposition (e.g., Nouh and Townsend 1979), or by geologists studying riverine processes (e.g., Dietrich et al. 1979). Recently, more complete numerical models have quantified aspects of channel bend flow which had been described qualitatively by previous researchers (e.g., Smith and McLean in prep.).

Since the inlet mouth at Nauset has considerable curvature (fig. 11), sediment transport patterns are modified by resulting bed shear stress gradients. To examine the magnitude of flow curvature at Nauset Inlet and evaluate its effect on sediment transport, a simple theory was developed and tested by field observations (Aubrey and Speer 1983). Since flow curvature induces gradients in water level through a channel bend and water level is relatively easy to monitor compared to velocity or shear-stress distribution, modeling and measurement efforts concentrated on surface gradients across the inlet mouth.

For simple geometry and quasi-steady channel flows, the along-channel (n) momentum equation reduces to a simple balance be-

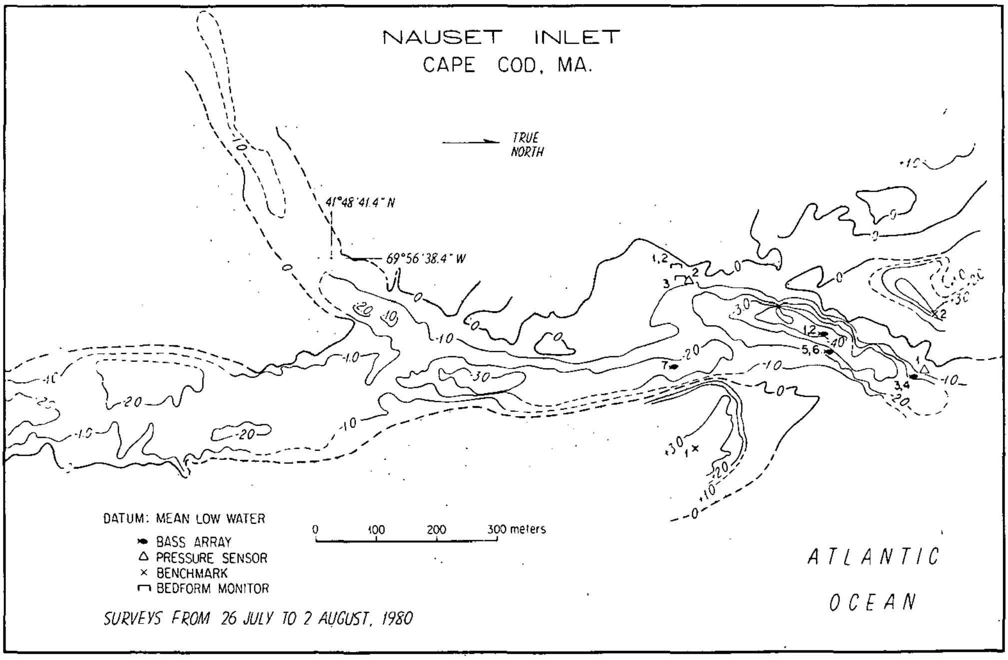

FIG. 11.—Nauset Inlet in summer of 1980 shows the strong channel curvature responsible for "river-bend" flow structure. Primary tidal channels in the estuary are to the south (left), causing this curved flow.

tween the bottom stress (τ_b) and the sea surface gradient ($\partial\eta/\partial n$):

$$\tau_b = -\rho g h\, \partial\eta/\partial n \qquad (1)$$

where h = mean water depth, ρ is density of water, and g is gravitational acceleration. If the downstream set-down is measured, an estimate of total bottom friction is obtained. The lowest order equation for cross-stream flow reduces to:

$$\frac{U^2}{gR} = \frac{\partial}{\partial r}(\eta) \qquad (2)$$

for the case of small channel half-width (b) compared to radius of curvature (R). U is the depth-averaged velocity. For a sinusoidal channel, the cross-stream gradient reduces to:

$$(\eta_b - \eta_{-b}) = \frac{2b}{gR_o} U^2 \qquad (3)$$

The depth-averaged velocity required for solving for cross-channel gradient is obtained from equation (1) and

$$\tau_b = \rho C_f U^2, \qquad (4)$$

where C_f is a friction coefficient. Then the cross-channel set-up is given by

$$(\eta_b - \eta_{-b}) = \frac{2bh}{R_o C_f} \partial\eta/\partial n \qquad (5)$$

This simple depth-averaged model can be improved using a complete perturbation solution (similar to that used by Smith and McLean in prep.), but the difficulty of obtaining high quality field data within a tidal inlet with which to evaluate such theory caused us to use the simple theory outlined above.

Field experiments covering 5 days (described in detail by Aubrey and Speer 1983) examined the magnitude of sea surface gradients, and checked their consistency with channel bend theory. Maximum instantaneous down-channel gradient over the 5-day period during ebb tide was 0.0007 (30 cm over the channel length separating the two sensors), while maximum flood tide gradients were 0.0005 (20 cm over the same separation). Average maximum gradients over the 5-day period are the same for flood and ebb tide (18.5 cm over the instrument separation). From these gradients, a maximum shear stress of approximately 140 dynes/cm^2 was calculated, where these shear stress estimates include not only near-bed friction but also form drag, wave/current interaction, and sediment transport effects (e.g., Grant and Madsen 1982). Bed shear stress is not easily separated from this total shear stress. Maximum cross-channel set-up of approximately 5 cm was calculated from the down-channel gradients using equation (5), which represents a slope of 0.0009, similar to the down-channel gradient. Field measurements show a cross-channel set-up of complicated structure, with a magnitude of 5–8 cm, most of which is consistent with the simple model presented above. The remainder of the observed set-up is of unknown hydrodynamic origin and not explained by our simple theory.

Theory and observation are consistent with the analogy between Nauset Inlet flow structure and river-bend flows, although neither the measurements nor theory allow for in-depth comparison of the flow fields. Resulting inlet morphology is also consistent with the hypothesis that channel bends are responsible for inlet migration. Nauset Inlet has both a steep outer (northern) channel bank, and an accreting point bar on the inner (southern) bank, similar to sedimentation patterns in river bends. The sediment source for the point bar is longshore transport, with sediment reworked in the flood tide delta. Observation of Nauset Inlet since 1972 shows a migration pattern consistent with the river bend analogy, with the south spit elongating and the north spit shortening due to erosion. Although analogies between inlet bends and river bends based on simple theory and observations of flow patterns and sedimentation are incomplete, they indicate the potential importance of curvature in inlet geometry on migration history of tidal inlets.

A conceptual model of inlet migration (fig. 10) based on the three mechanisms described above explains the unusual northward movement of Nauset Inlet, opposite the longshore transport direction. When the inlet is at its southernmost location, the estuary channels empty directly into the ocean. There is no curvature to the flow (which could result in complex flow non-uniformity), and the north barrier is not preferentially eroded. Tidal flows are strong enough, however, to prevent material transported past the north spit from filling in the inlet channel. Bar bypassing of littoral drift leads to accretion along the downdrift split. If storms do not halt this growth, the south spit can extend to the north and eventually overlap the north spit, as occurred in the late 1960's and early 1970's. The base of the inlet channel retains its southerly location, and the channel simply elongates to the north. In this configuration, the north barrier remains essentially unchanged. This particular pattern has been observed once in the last 30 years.

A different mechanism was responsible for the barrier overlap pattern observed in the 1950's. In this instance, the northern barrier was breached during a storm. The barrier remnant south of the breach attached to Nauset Heights to form a relatively long southern spit. The base of the inlet channel retained its southern location and extended through the breach. Subsequently, the northern barrier lengthened by attachment to a marshy island in the bay. The south spit further elongated through bar bypassing, resulting in a pattern of overlapping spits. As in the 1965–1972 pattern, the inlet channel lengthened as the south spit grew to the north. The north spit remained relatively stable after attachment to the bay island. Neither of these patterns is representative of the present migration phase. The past ten years of movement have been characterized by actual northward migration of the inlet channel and shortening of the north spit, with no barrier overlap.

A storm breaching the north spit in 1972 caused this new migration pattern to develop. The main inlet channel stabilized further north than in previous storm breaches. As a result, the dominant ebb tidal flow was constrained to flow to the north, and then east through the inlet channel, setting up a channel bend flow pattern with erosion on the outer part of the bend (north), and accretion on the inside of the bend (south). The north wall of the inlet channel is presently eroding while a large sand deposit is forming on the south bank of the channel. This "flow around a bend" has existed for approximately 10 years, leading to nearly 1 km of northward inlet movement. This migration will probably continue until either the inlet encounters an erosion-resistant substrate or a major storm changes the inlet location. In the case of Nauset, the former is unlikely (see Aubrey et al. 1982) since inlet tidal flows are currently eroding peat deposits underneath the sandy barrier spits. Nothing more erosion-resistant is likely to be encountered. Storm-induced inlet relocation is a strong possibility. The long, frictionally dominated channels presently carrying the tidal prism would probably be abandoned if a more southerly breach were created by a storm. In that case, the large long-shore transport could quickly close off the present inlet, which is nearly clogged by the extensive ebb-tide delta. A more northerly breach created by storm overwash is not likely to persist (as the February, 1978 blizzard demonstrated) because the northern depths and tidal prism are too small. An additional factor increasing the likelihood of breaching near Nauset Harbor is the narrow width of the barrier at this point. This narrowing is caused by erosion on the bay side of the barrier during ebb tide, as the easterly-flowing tide is redirected northwards towards the present inlet (resulting in another complex, channel-bend flow pattern).

The long-term fate of this estuary is affected by two dominant trends: inlet migration (which contributes sediment to the estuary via flood tide delta growth) and westward spit migration. Both of these factors reduce the tidal prism, and consequently reduce the equilibrium cross-sectional area of the inlet. The first factor has been discussed in detail. The second factor, net onshore migration of the Nauset barrier beach, is apparent in spite of large, higher frequency fluctuations (Speer et al. 1982). The steady shoreward migration is a result of sea level rise combined with overwash and inlet processes (barrier roll-over). Higher frequency oscillations superimposed on this steady retreat result from inlet migration episodes, seasonal beach changes, bar bypassing events, and large, nearshore bedform generation (Aubrey 1980). The effect of the onshore migration is a reduction in tidal prism (specifically by reduction of the area of the back bay). Tidal prism is also reduced by deposition of sand as a flood tide delta, an important factor since 1972, as the inlet has steadily migrated northwards approximately 1 km. Vestiges of the former flood tidal deltas are visible on recent aerial photographs of the area. As a result of overwash and bay infilling, the stable inlet configuration will become narrower and shallower with time (reduced equilibrium cross-sectional area). This filling trend currently exceeds back-barrier deepening attributable to sea-level rise, but anticipated increased rates of sea-level rise (Aubrey and Emery 1983) may reverse this trend.

SUMMARY

Three distinct patterns of natural inlet migration have been identified from historical data (fig. 10), and their underlying causes hypothesized. These mechanisms explain the rare case where an inlet migrates in a direction opposite the dominant longshore sand transport, such as at Nauset Inlet. Large variability in barrier spit length across a baymouth can also be a reflection of these mechanisms. This rapid, spatially variable, inlet migration contributes to infilling of some inlet/estuary complexes on a geological time scale, as the continually enlarging flood tide delta evolves at each inlet location. The result is an accelerated shrinkage of some estuaries, with consequent reduction in inlet channel depth and width (the decreased channel area responding to a reduced tidal prism). Whether or not this flood tide delta growth significantly alters the fate of the estuary depends on the hydraulic characteristics of the inlet and estuary (flood tide delta growth is a function of flood/ebb flow dominance), as well as long-term trends in sea-level rise.

The three distinct patterns of inlet migration are (fig. 10):

1) Growth of the downdrift spit by addition of sediment from ebb tide delta distal bars: some of these distal bars weld onto the downdrift spit without escaping the inlet environment. The time scale of these growth episodes is months, with an associated spit growth on a scale of 100 m. Resultant spit changes are relatively small compared to the other two growth mechanisms. This mechanism can cause only updrift inlet migration.

2) Storm-induced shifts in inlet position associated with superelevated water levels: these changes are rare but significant, with time scales of tens of years and spatial scales of hundreds of meters. Storm breaches will remain stable and replace previous inlets if they are hydraulically more efficient than alternative breaches. These major inlet relocations have played an important role at Nauset Inlet, by shifting the inlet position to the north (against the sense of net littoral drift) and allowing the flow characteristics to set up a stable, steady northward inlet migration independent of storm influences.

Storm effects in the future are expected to influence the Nauset barriers significantly, and shift the inlet to the south. Since the southernmost limit of the estuary/inlet system has historically been the preferred position (because it is the most efficient location for tidal exchanges between the ocean and bay), a breach at this narrow part of the barrier will likely become the preferred inlet position. At present, a stable dune-line is inhibiting storm overwash and breaching at this location.

3) Steady northward migration characterized by flow around a bend (erosion on outside of bend, accretion on inside of bend) during ebb tides: this migration has occurred since 1972 when a storm breach rapidly shifted the inlet location, setting up a long, confined southern barrier-parallel channel through which most tidal exchange takes place. Ebb flow through this barrier-parallel channel must make a sharp bend through the inlet to exit into the ocean. This bend creates a distinctive three-dimensional flow pattern similar to river bend flows, eroding the north spit and accreting to the south. The result is a steady northward migration which will cease when a storm opens a breach further south of the present inlet; this new breach will likely become the preferred inlet position. Flow curvature resulting from complex inlet/tide channel geometry may be responsible for both updrift and downdrift inlet migration at other locations, playing an important role in barrier beach evolution.

ACKNOWLEDGMENTS.—The authors wish to thank Drs. K. O. Emery, J. Karson, B. Tucholke, and E. Uchupi for their constructive comments on the manuscript. The work was supported by NOAA, Office of Sea Grant under Grant No. NA80-AA-D-00077 (R/B-21), by the U.S. Army Research Office under Grant DAAG29-81-K-0004, and by the Woods Hole Oceanographic Institution Coastal Research Center. Personnel from the Woods Hole Oceanographic Institution Archives, the U.S. National Archives, and the U.S. Library of Congress, were particularly helpful in making available historical data for our study. Mr. Eric Ruder performed the storm survey and made measurements from the photographs.

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