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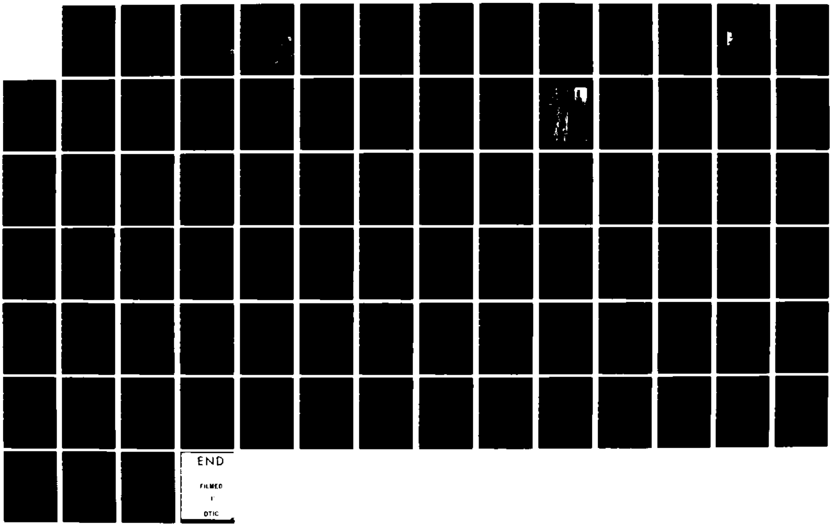
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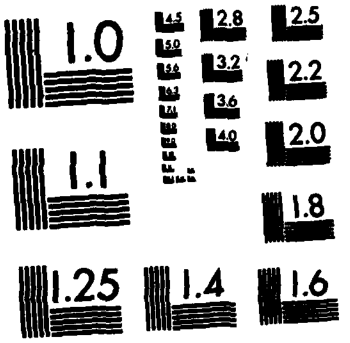

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CLASSIFICATION OF COASTAL ENVIRONMENTS

TECHNICAL REPORT 26

ANALYSIS OF SHOREZONE TOPOGRAPHY ALONG THE OUTER BANKS, NORTH CAROLINA

Nina Fisher
Robert Dolan
Bruce P. Hayden

DEPARTMENT OF ENVIRONMENTAL SCIENCES
UNIVERSITY OF VIRGINIA

DECEMBER 1982
OFFICE OF NAVAL RESEARCH
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N00014-81-K-0033 — TASK # NR389 170

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ANALYSIS OF SHOREZONE TOPOGRAPHY ALONG THE OUTER BANKS, NORTH CAROLINA

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Hatboro, Pennsylvania

B.S., Tufts University, 1979

A Thesis Presented to the Graduate
Faculty of the University of Virginia
in Candidacy for the Degree of
Masters of Science

Department of Environmental Science
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May, 1982

Approved
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ABSTRACT

↘Two beach profile data sets covering a 71 km reach of the Outer Banks, North Carolina, were examined in order to document large-scale topographic organization of the shorezone and relate this organization to other beach parameters. The earliest profiles (1937) were surveyed during the period of initial man-made dune stabilization by the Civilian Conservation Corps. A 1976 set comprises profiles that have been adjusting to the presence of these stabilized dunes for almost forty years. Four supplementary data sets - alongshore variations in active beach width, storm wave energy, sediment size and shoreline dynamics - document factors potentially related to shorezone topographic variation.

→Principal components analysis was used to reduce the topographic variation of the beach profiles into a few major definable and independent sources. The weightings for each principal component and the variables from the four supplementary data sets were further analyzed with spectral analysis so that significant alongshore periodicities could be identified. Cross-spectral analysis was then performed on pairs of variables to determine the amount of alongshore covariance.←

Three principal components for each profile data set were found to explain approximately 90% of the variance. This suggests a topographic organization of the shorezone. Comparison between the 1937 and 1976 data sets suggests that rhythmic forms of differing frequencies either migrate along the coast at different rates, or migrate at similar rates but are not synchronous due to their varying lengths. The dune stabilization has caused narrowing of the active beach width and steepening of the beach profile over a period of forty years, however, the intrinsic topographic organization has remained intact. The cross-spectral results indicated that the time-averaged, post-stabilization variables may not accurately reflect the constantly changing character of the 1930s beach system. However, these same variables more accurately depict conditions in the 1970s. The artificial dunes have decreased the variability of the system such that overwash is prevented at all but a few isolated points where dune breaching may take place.

Studies from the past ten years have verified the existence of rhythmic topography and the processes which may generate these forms. The results from this investigation have shown that large-scale topographic variation of the shorezone exists as well.

ACKNOWLEDGEMENTS

I would like to thank Dr. Robert Dolan and Dr. Bruce Hayden who directed my research throughout this project. I also wish to acknowledge William Smith, Paul May, Neal Grandy and Wilma Levan who assisted respectively with data management, graphics, drafting and the word processor.

Special thanks to Dr. Gerald Shideler and Dr. John Fisher who permitted use of their sediment size data and wave refraction data. This research was partially funded by the Office of Naval Research, contract #N00014-81-K-0033.

INTRODUCTION

Periodic overwashes, tidal inlet formation and closure, and seasonal erosion and accretion all result in gross configuration changes on barrier islands. More subtle changes, such as rhythmic and crescentic patterns in shorezone topography, have only recently been investigated by coastal researchers.

Rhythmic shorezone topography has been recognized and discussed by Hom-ma and Sonu, 1963; Komar, 1971; Sonu et al., 1966; Bowen and Inman, 1971; Dolan, 1971; and Bruun, 1954). They suggested that there is an organization of the beach system evidenced by the periodic repetition of crescentic forms along the shore. Dolan et al. (1974) proposed five major size categories of rhythmic forms: primary capes, secondary capes, sand waves, cusps and cusplets. These forms have been confirmed by field observations (Zenkovich, 1967; Hoyt and Henry, 1971; Komar, 1976).

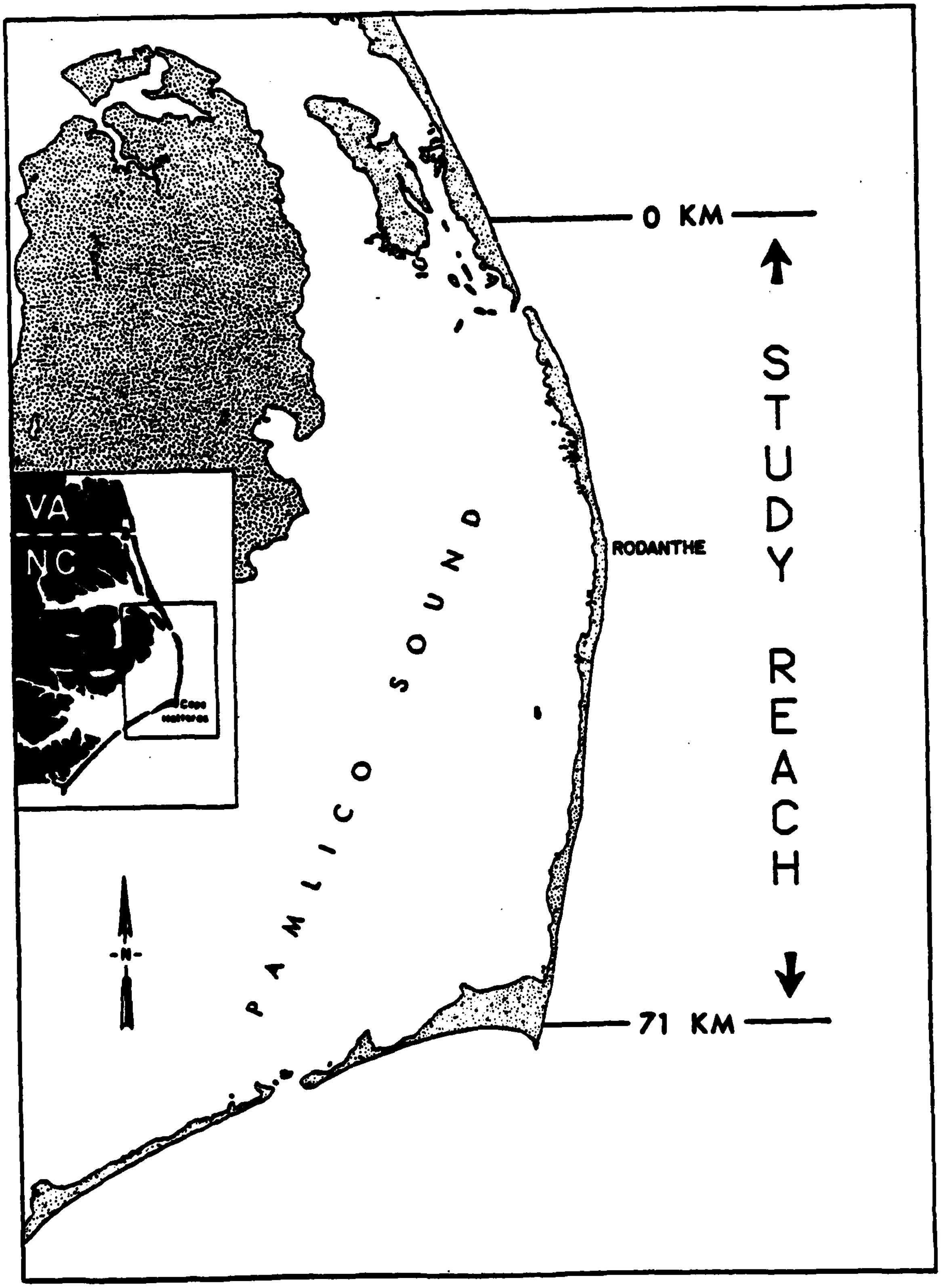
Previous studies of rhythmic topography have dealt primarily with the plan form of rhythmic features with little mention of elevational undulations along the shore. However, Sonu (1973) noted the existence of elevational periodicities and suggested that they are comparable to sand wave trains. Large-scale topographic organization of barrier island cross-sections was investigated by Vincent et al. (1975).

This study was designed to examine variation in the vertical components of the sub-aerial beach system over a 71 km stretch on the Outer Banks of North Carolina (figure 1) in order to determine whether rhythmic organization extends into the elevational aspects of this system. Confirmation of a spatially persistent vertical organization would substantiate the results from previous studies as well as add another dimension to the interpretation of these patterns. In addition, if elevational periodicities are observed, it is probable that they may function as both a process and response variable. As a process variable, these patterns may have important ramifications in the development of other beach forms.

The Outer Banks of North Carolina is an ideal location to study beach configuration because the three basic conditions necessary for rhythmic topography are common to the area. There is a high incidence of lateral wave approach, shallow offshore slopes, and large volumes of sediment (Sonu, 1973). In addition, a unique set of beach profile data was available from the National Park Service. These profiles were taken along a 75 mile (121 km) reach during the period of artificial dune stabilization in the 1930s, then again forty years later. This data set provides spatial and temporal information of the barrier island topography as well as superimposing a component of artificially induced environmental change.

The National Park Service data set permits examination

FIGURE 1



Map of Study Area

of a number of distinct questions on the spatial and temporal organization of the beach system.

1. Is there a spatial organization to the beach system along the coast with respect to elevation?
2. Does this organization (if present) persist through time? Is the spatial organization preserved on the same scale through time? Is there movement of the whole organizational unit down the coast through time?
3. What effect, if any, has beach dune stabilization had on these organizational patterns?
4. Does this organization correlate with any other spatially persistent beach processes or responses? What are the interrelationships amongst these processes and responses?
5. What are the possible causes of these organizational patterns?

PREVIOUS RESEARCH

Descriptions of crescentic and cuspate coastal landforms have long appeared in the geologic literature (Palmer, 1834; Johnson, 1919; Evans, 1938; Bruun, 1954; Hom-ma and Sonu, 1962; Zenkovich, 1967, Dolan, 1971 and Komar, 1976). The early work concentrated on the characterization of these landforms and hypotheses for their formation. In 1919, Johnson summarized the existing literature which dealt primarily with cusps and capes. Most of the explanations for cusp formation were based on observations of wave patterns, swash action, and the escape of water from behind a seaweed or sediment barrier. Johnson dismissed these hypotheses because of their failure to account for the regularity of the cusps. He proposed that existing depressions on the beach are selectively eroded by swash action until a spacing is developed which is in equilibrium with the height of the waves. This hypothesis, also, failed to explain the regularity of these forms.

Subsequent studies concentrated on the relationship of rhythmic forms to other coastal factors but did not offer explanations for the occurrence of the forms. Shepard (1935) observed that cusp formation at Santa Monica beach appeared to be closely related to the tidal cycle. During neap tides, well-developed cusps formed, but were subsequently obliterated during periods of spring tides.

Trask (1956) found that sediment size varied systematically with both cusp interval and position on the cusp form. Small spacings between cusps tended to be correlated with coarse grains, whereas large spacings were associated with fine grains. The horns of the cusps were generally composed of coarser sediment than the embayments between cusps. Longuet-Higgins and Parkin (1962) reaffirmed Johnson's (1919) proposal that normal incident wave approach is an important factor in cusp formation. Evans (1938), however, found no relation between the angle of incident wave approach and cusp development.

Evans (1938) was also one of the first researchers to suggest that there may be numerous origins for cuspate forms. He noted the existence of rhythmic forms on a larger scale than beach cusps which he called giant cusps. Bruun (1954) observed the migration of sand waves but offered no explanation for their existence. Dolan and Ferm (1968) created a hierarchical classification system of rhythmic forms which nested successively smaller forms ranging from capes down to cusplets.

In recent years there have been strong advances in quantitative explanations for the generation of crescentic shoreline forms (Komar, 1982). Controversy still occurs, however, due to the wide range over which rhythmic features may form and the existence of more than one mechanism for their formation. This situation led Guza and Inman (1975) to declare those classification systems based on size as unsatisfactory since different sized rhythmic features may have been generated by a similar process. Komar (1982) has suggested that a genetic classification of rhythmic forms should be developed. The size of a form may be related to the beach topography but it does not imply a singular relationship with one generating mechanism.

In summarizing the process-response models for rhythmic forms, Vincent (1973) suggested that they may be grouped into two categories:

1. Those which propose that the topography creates the nearshore circulation patterns.
2. Those suggesting that existing patterns of circulation induce rhythmic topography.

Many of the more recently proposed hypotheses evade such categorization and the feedback relationships between beach form and relevant processes are considered jointly. This line of thought necessarily reduces the import of landform scale and alternately stresses the process/form interaction. Each process may be responsible for forms of differing scales, but it is unlikely that one covers the entire range of crescentic forms.

The edge wave hypothesis has developed primarily in the past ten years (Bowen and Inman, 1971; Dolan et al., 1974; Guza and Inman, 1975; Holman and Bowen, 1982). It has gained progressively wider acceptance since Huntley and Bowen (1973) first measured edge waves in the field. Simply stated, the interaction of edge waves with incident waves may cause rearrangement of the beach material into cuspate or crescentic forms which recur periodically along the shoreline. Standing edge waves can be excited by reflection of incident waves having a normal shoreline approach (Guza and Davis, 1974) or by the joint effect of two incident waves having minimally different frequencies (Bowen and Guza, 1978).

Guza and Inman (1975) studied the development of cusps which resulted from the combination of surging incident waves and synchronous edge waves. Bowen and Inman (1971) suggested that rearrangement of sediment to form crescentic bars results from the combined effect of drift currents induced by standing edge waves and oscillations from incident waves. Rhythmic shoreline patterns have also been related to the interaction of two or more progressive edge waves by Holman and Bowen (1982). Komar (1982) has noted that the periods of measured edge waves may be as long as 300 seconds. He suggested that rhythmic features with spacings up to several kilometers may, therefore, result.

Cuspate forms may also be generated by nearshore cell circulation which is controlled by the occurrence of rip currents (Komar, 1971). Rip currents, in turn, are initiated by various processes. Dalrymple and Lanan (1976) experimented with intersecting wave trains of the same period and found that rip currents developed with subsequent cusp formation. Bowen (1969) suggested that incident waves combining with synchronous edge waves generate a series of rip currents. Rhythmic features created by rip currents may range in scale from a few meters up to hundreds of meters.

Investigations of rhythmic forms have focused on the occurrence and formation of cusps, sand waves, and capes, as these forms are easily perceived from ground-level observation or aerial photography. However, some of the same processes generating these forms may also produce a range of intermediate forms not readily observable. Dolan et al.'s (1978) study of the distribution of shoreline rate changes and storm surge penetration is one of the few investigations of these intermediate-scale periodic forms. They concluded that edge waves may play a role in the spatial variations of the shoreline on a scale of kilometers.

The objective of this study is to explore the variation of the subaerial beach in order to determine if topographic trends occur on a similar scale. Recent advances in the study of rhythmic forms suggest that the processes which may produce such trends do indeed exist.

DATA SETS

A beach profile data set and four supplementary data sets were used to quantify the topographic organization of the beach and to identify factors potentially related to this organization.

Beach Profile Data

From 1932 to 1937, the Civilian Conservation Corps established a survey baseline from South Nags Head to Ocracoke Inlet on the Outer Banks of North Carolina as part of a large-scale dune stabilization program (McGee, 1962; Shabica, 1978). The baseline was set up to document changes in the shoreline over periods of time. Therefore, profile surveys were conducted by the Civilian Conservation Corps and the National Park Service on four different occasions: 1937, 1961, 1963-1965, and 1976-1977 (Nnaji and Fisher, 1981). At the same time the first measurements were being taken, dune stabilization and rehabilitation were also being carried out by the Corps (McGee, 1962; Nash, 1964).

Subsequent profiles were surveyed from a second baseline (parallel to the first) which was established in 1961 because numerous portions of the original baseline had been eroded away (Fred Kelly, personal communication). Two investigators at East Carolina University (Johnson and Stephenson, 1977) later compiled and summarized the four sets of data from field notes into a set of two books of computer printouts. These books record both the beach profiles and changes in the shoreline.

The baseline was oriented essentially parallel to the coastline with benchmarks posted at approximately 1000 foot (305 meter) intervals. The data consists of a series of elevation measurements taken oceanward from each benchmark at 10 foot (3 meter) intervals down to sea level. All measures were taken without regard to season or tidal stage.

The data matrix was reduced in size both along and across the barrier island to create a more homogeneous data set designed to address the objectives of the study. In order to maintain a fairly consistent eastern orientation along the island, only 71 km of the coast, from South Nags Head to just north of Cape Hatteras point, were considered. South of Cape Hatteras, there is a distinct change in the orientation of the island to the southeast. Across the island, only those measurements taken from sea level to a distance of 65 meters landward from the sea were investigated. Additionally, this study was confined to the examination of the 1937 and 1976* beach profile data sets.

Aerial Photography

Two sets of aerial photographs were used to measure the active beach zone width, which is the distance between the

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*All of the data within the study area (figure 1) was taken in 1976. The data for the area south of the study area was measured in 1977.

high water line and the continuous vegetation line (Dolan, 1978). This was done by transferring the mapped position of each base station (figure 2) to its corresponding position on the barrier island (figure 3). The active beach zone width at each benchmark location could then be measured directly from the aerial photographs.

The first set of aerial photographs was composed of a mosaic of photographs taken in 1932, 1933 and 1934 since a continuous set for one year was not available. This set of photos includes only a portion of the study reach, from South Nags Head to Rodanthe. Photos beyond this point were also unavailable. The second set of photographs was taken in May, 1978.

Wave Refraction Data

Fisher et al. (1977) developed a wave refraction model to correlate shoreline erosion rates with the amount of storm wave energy impacting the shoreline. In 1981, Nnaji and Fisher applied this model to the section of coast beween South Nags Head and Cape Hatteras point. Using intervals of 3.5 nautical miles along the shore, they plotted the per cent of the total number of wave rays approaching each unit area. This procedure was carried out for five storm types.

Individual extratropical storm events from 1942 to 1972 were defined on the basis of three descriptors: fetch, duration, and direction (Nnaji and Fisher, 1981). Clustering of these events allowed distinction of the five

FIGURE 2

Sample Base Map Showing
Location of Stations

(Dots represent Base Stations)

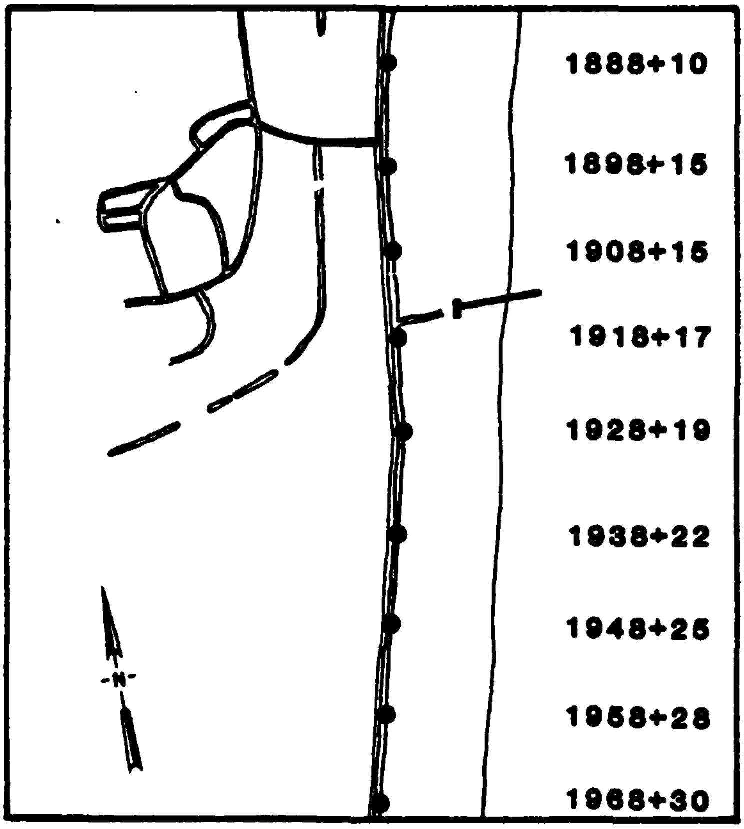


FIGURE 3

Sample Aerial Photograph Showing Location of Stations

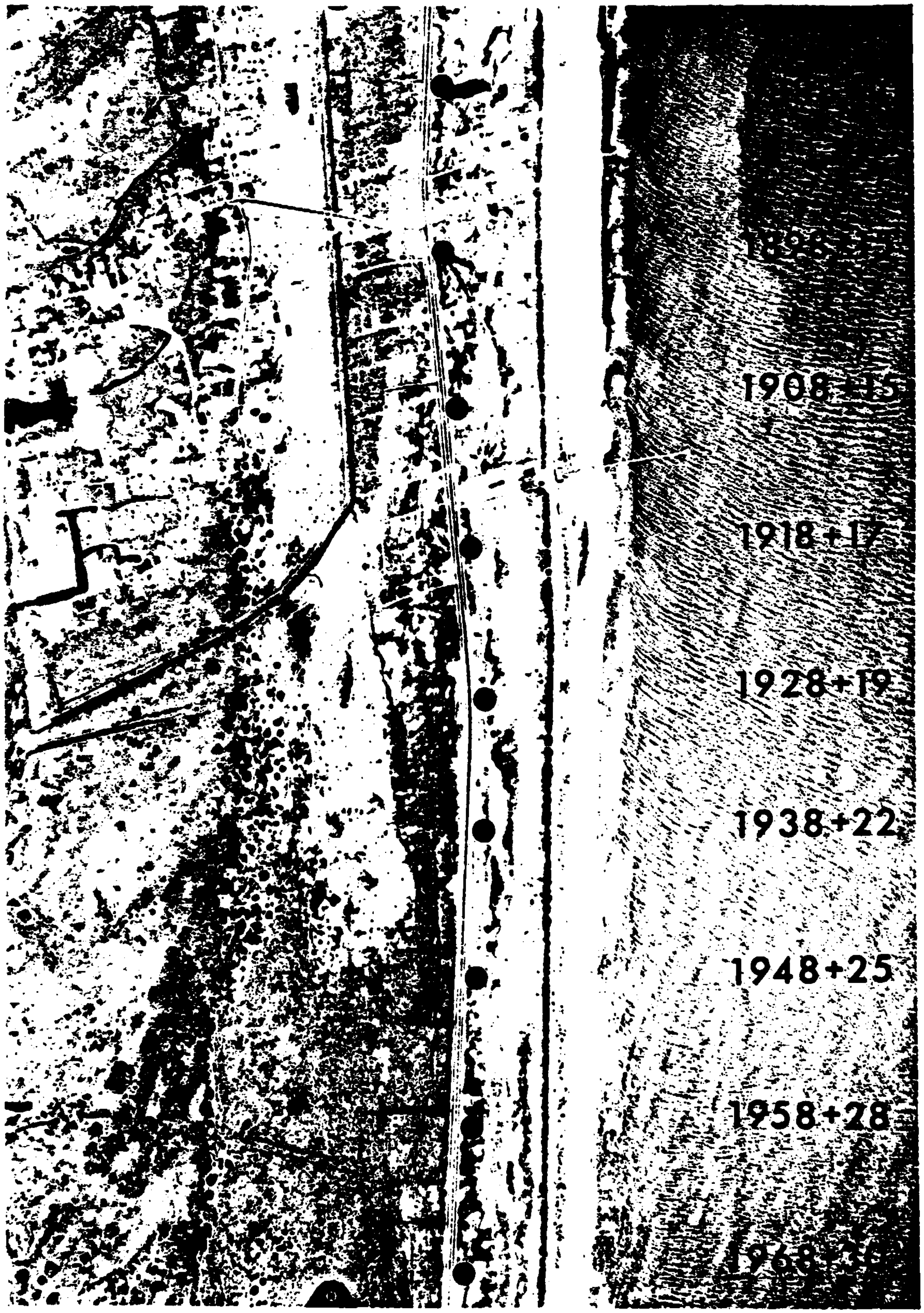


TABLE 1

Modal Values of Storm Descriptors

STORM TYPE	FETCH (Nautical Miles)	DURATION (Hours)	DIRECTION (Degrees)	RETURN PERIOD (Years)
1	110	18	0	2.1
2	200	12	22.5	3.7
3	130	12	0	6.5
4	400	12	45	14.7
5	500	24	0	41.5

From Nnaji and Fisher (1981)

storm types (table 1). Each type was assigned a characteristic orientation of wave approach determined by the mean fetch direction. Frequency distributions were plotted for each storm type so that the mean and standard deviation could be calculated. The wave height and period of the mean were entered into the model as well as one standard deviation of the distribution. Wave ray distribution plots were then generated based upon these parameters.

Analysis by Nnaji and Fisher (1981) of wave ray distributions along the shoreline indicates that the type of storm impacting an area is an important determinant in the alongshore response of the beach. Although an individual storm will not be indicative of shoreline response through time, Nnaji and Fisher found that areas with consistently high wave energies tend to erode while those with lower wave energies tend to accrete. Storm type, then, appears to be functionally related to shoreline change. The use of storm data may, therefore, indicate whether storms are additionally significant in the topographic arrangement of the beach.

Sediment Size Data

In 1973, Shideler investigated textural trends of sediments from the Virginia-North Carolina border to just north of Cape Hatteras. Stations were set up at 2 nautical mile intervals and samples were collected from the center of the berm and the center of the wetted intertidal zone. Mean and median grain size were then calculated for the berm and foreshore samples from each station.

Shideler's analysis of sediment size trends indicates that sediment size is variable both along the berm and the foreshore. Large-scale trends of sediment size were found within the study area for this project. These fluctuations of median sediment size along the shoreline may be directly compared to beach topography trends for the same coastal reach.

Shoreline Dynamics Data

In 1978, Dolan et al. developed a photogrammetric technique for documenting shoreline dynamics. Using this method, distance to the shoreline and the mean overwash penetration distance (OPDX) on aerial photographs were measured from a stationary baseline divided into 100 meter intervals. Repeating this through time with successive sets of aerial photographs for this same region, the mean rate of change in the overwash penetration distance (OPX) and the mean rate of shoreline change (SLX) were also calculated. The data record covers a time span of 29 years, documenting changes along this reach from 1945-1974.

Previous analyses of sections of this data set (Hayden et al., 1979; Dolan et al., 1979) have revealed spatial periodicities in all three shoreline variables along the coast. Their results suggest that these periodicities may persist for decades. By comparing the periodicities of these shoreline features with trends in beach topography, the temporal persistence of topographic periodicities from 1937 to 1976 may also be revealed.

Each of the variables within these supplementary data sets share the attribute of distinct variation along the coast. Analysis through the use of the following statistical methods should indicate whether these periodicities exist for each parameter and whether these periodicities (if present) covary with alongshore topographic variations as represented by the principal components. Additionally, covariation between the parameters may further facilitate the interpretation of beach organization.

STATISTICAL ANALYSES

Principal Components Analysis

The 1937 and 1976 beach profile data were analyzed using principal components analysis. This is an analytical method which transforms a series of correlated variables into a new set of statistically independent (orthogonal) factors known as principal components or eigenvectors (Kleinbaum and Kupper, 1978; Williamson, 1972). The first component explains the largest amount of variance with successively smaller amounts being accounted for by each additional component. In addition, the original data values are transformed into scores (weightings) with one unique set of scores associated with each principal component (Daultrey, 1976).

This statistical technique has been utilized by other researchers (Winant and Aubrey, 1976; Vincent et al., 1975; Resio et al., 1977) to explain the variance of the beach system. It is appropriate for use in this study for the following reasons:

1. The topographic variation of the beach system may be organized into a few major definable and independent sources.
2. Loadings for each principal component may be easily interpreted in terms of the physical beach environment and used to explain variation from the mean across the beach.
3. Weightings for each principal component may be studied in order to reveal

trends along the shoreline.

4. Direct comparisons may be made between the 1937 and 1976 beach profiles.

Spectral Analysis

Each of the variables (table 2) was examined by spectral analysis so that statistically significant periodicities could be ascertained. In spectral analysis, sinusoidal curves of differing frequencies are fitted to each series of data points using the least squares method (Rayner, 1971). Within a given data series, there may be numerous frequencies having power. Each of these frequencies explains a certain amount of the total variance. Frequencies that account for a significant portion ($p < .05$) of the total variance are of primary concern.

In order to use spectral analysis, it is necessary to have equally spaced observations. Variables with unequally spaced cases were adjusted by interpolating values between the experimentally derived data points at equally spaced intervals.

Cross-Spectral Analysis

Cross-spectral analysis is used to determine the amount of covariance between pairs of variables by examining the phase difference between the two cosine waves set up for each data series (Jenkins, 1965). The results show whether the series are in-phase or out-of-phase as well as which frequency band (or bands) contributes to the overall

Table 2

List of Variables

VARIABLE #	VARIABLE NAME	MEANING
1	E1-1937	Weightings for Eigenvector 1 - 1937
2	E2-1937	Weightings for Eigenvector 2 - 1937
3	E3-1937	Weightings for Eigenvector 3 - 1937
4	E1-1976	Weightings for Eigenvector 1 - 1976
5	E2-1976	Weightings for Eigenvector 2 - 1976
6	E3-1976	Weightings for Eigenvector 3 - 1976
7	BW-1932-1934	Active beach width - 1932-1934
8	BW-1978	Active beach width - 1978
9	GS-Foreshore	Median grain size - Foreshore
10	GS-Berm	Median grain size - Berm
11	STM1	Storm type 1
12	STM2	Storm type 2
13	STM3	Storm type 3
14	STM4	Storm type 4
15	STM5	Storm type 5
16	OPDX	Mean overwash penetration distance
17	OPX	Mean rate of change in overwash penetration distance
18	SLX	Mean rate of shoreline change

correlation between these series. This method provides the means of determining whether other beach attributes covary with beach topography and whether rhythmic beach landforms are migratory through time.

Cross-spectral analysis generally requires that the data be equally spaced and that each pair of variables have an equivalent number of cases. The data were equally spaced in the same manner as for the spectral analyses. The second requirement was achieved by using the number of cases (220) in the beach profile data as a standard. Data sets with less than the prerequisite number were then interpolated to provide intermediary values. In data sets having greater than this number of cases, only those values closely matching the alongshore position of values from the standard were retained.

RESULTS

Mean and Standard Deviation

The mean ($\bar{X}$) and standard deviation (SD) of the beach profiles from 1937 and 1976 are shown in figure 4. These graphs indicate that the mean beach profile in 1976 is steeper than the 1937 mean profile for the same reach of coast. The 1937 standard deviation is relatively constant across the entire beach profile. This implies that the variation in the height of the profile is essentially the same regardless of position on the beach. The 1976 plot of standard deviation, while constant across the first half of the profile, shows a sharp increase across the second half of the profile. Therefore, the back portion of the beach profile becomes progressively more variable in terms of height relative to the front of the 1976 beach and to the 1937 beach.

Principal Components Analysis

Twenty-one principal components (eigenvectors) for each data set were derived from the principal components analysis. Of these, only the first three components for each data set were included in the results since they account for a substantial portion of the total variance (table 3). The graphs for the three eigenvectors (figure 5) are distinctly interpretable in terms of the physical beach environment. Each graph describes systematic variation away

FIGURE 4

Mean and Standard Deviation of
Beach Profiles

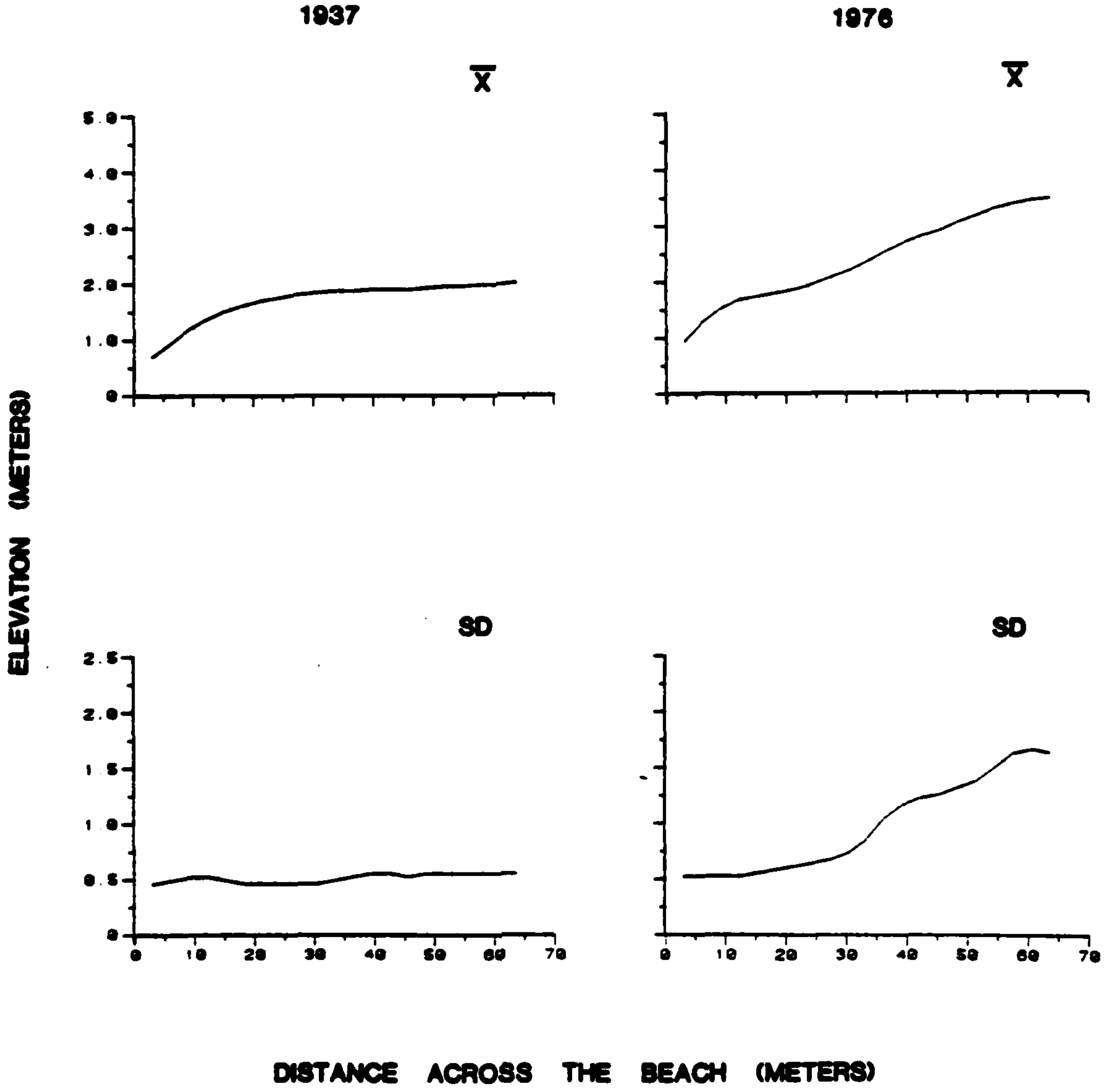


Table 3
Explanation of Eigenvectors

	EIGENVECTOR #	INDIVIDUAL AMOUNT OF VARIANCE EXPLAINED	CUMULATIVE AMOUNT OF VARIANCE EXPLAINED	TOPOGRAPHIC EXPRESSION* **
1937	1	60.89%	60.89%	-Large accumulation of sand across profile -Maximum amount of sand stored on front of backshore
	2	21.73%	82.62%	-Low accumulation of sand on foreshore and front of backshore -Large accumulation of sand on mid-backshore
	3	8.86%	91.48%	-Large accumulation of sand on foreshore -Low accumulation on front of backshore -Large accumulation on *mid-backshore*
1976	1	57.58%	57.58%	-Large accumulation of sand across profile -Maximum amount of sand stored on backshore
	2	21.19%	78.77%	-Low sand accumulation on foreshore and backshore -Large accumulation on dunes
	3	9.46%	88.23%	-Large accumulation of sand on foreshore and front of backshore -Low accumulation on rear backshore and dune front -Large accumulation on dunes

* As compared to the mean beach profile.
** The topographic expression for a positive weighting is given here.

from the mean profile (which is represented by the 0.0 horizontal line).

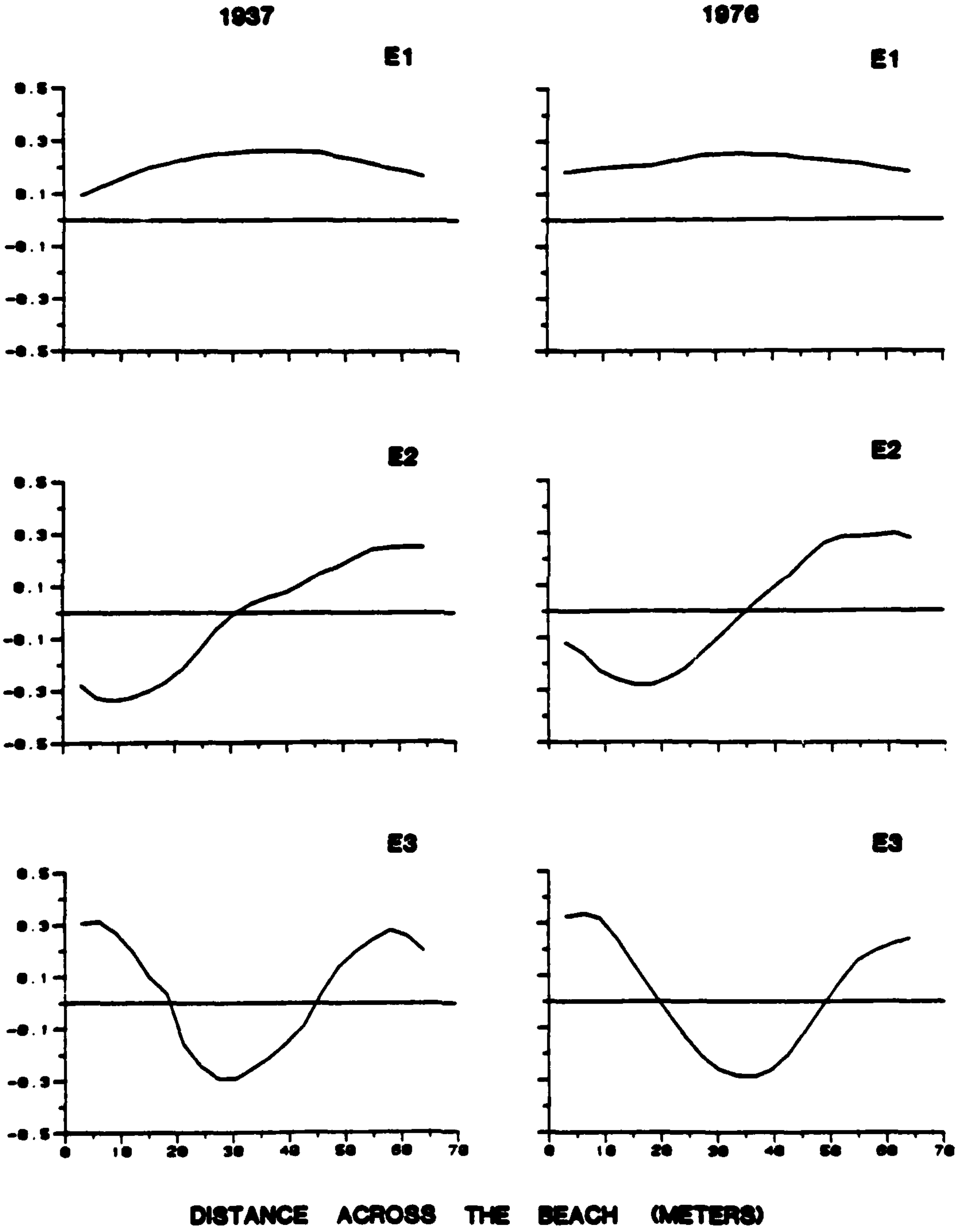
Eigenvector 1 (E1) represents a beach height function. A positive weighting indicates that there is a greater than average accumulation of sand across the beach profile. A profile with a positive weight would, therefore, be of greater than average height. In both 1937 and 1976, there is a larger storage of sand relative to the mean in the middle portion of the profile than at either extreme. This relative accumulation of sand is more accentuated in the 1937 eigenvector plot.

Eigenvector 2 (E2) represents a sand storage function which describes the distribution of sand across the beach profile. A positive weighting on E2 signifies that when the seaward half of the profile has a lower than average accumulation of sand, there is a concomitant surplus of sand in the landward half of the profile. A negative weighting denotes the opposite of this. The form of E2 for 1937 and 1976 is essentially the same. However, while form remains similar, there is a landward shift of the mean/E2 intersection point suggesting a slight change in the distribution of sand across the profile.

Eigenvector 3 (E3) further describes the distribution of sand across the beach. A positive weighting indicates that when there is a greater than average amount of sand contained within the extremes of the profile, there is a concurrent deficiency of sand in the center portion of the

FIGURE 5

Graphic Portrayal of Eigenvectors



profile. A negative weight represents the opposite condition. As in E2, there is a slight shift of the mean/E3 intersection points in 1976 relative to 1937, although the basic form of E3 for both years is similar.

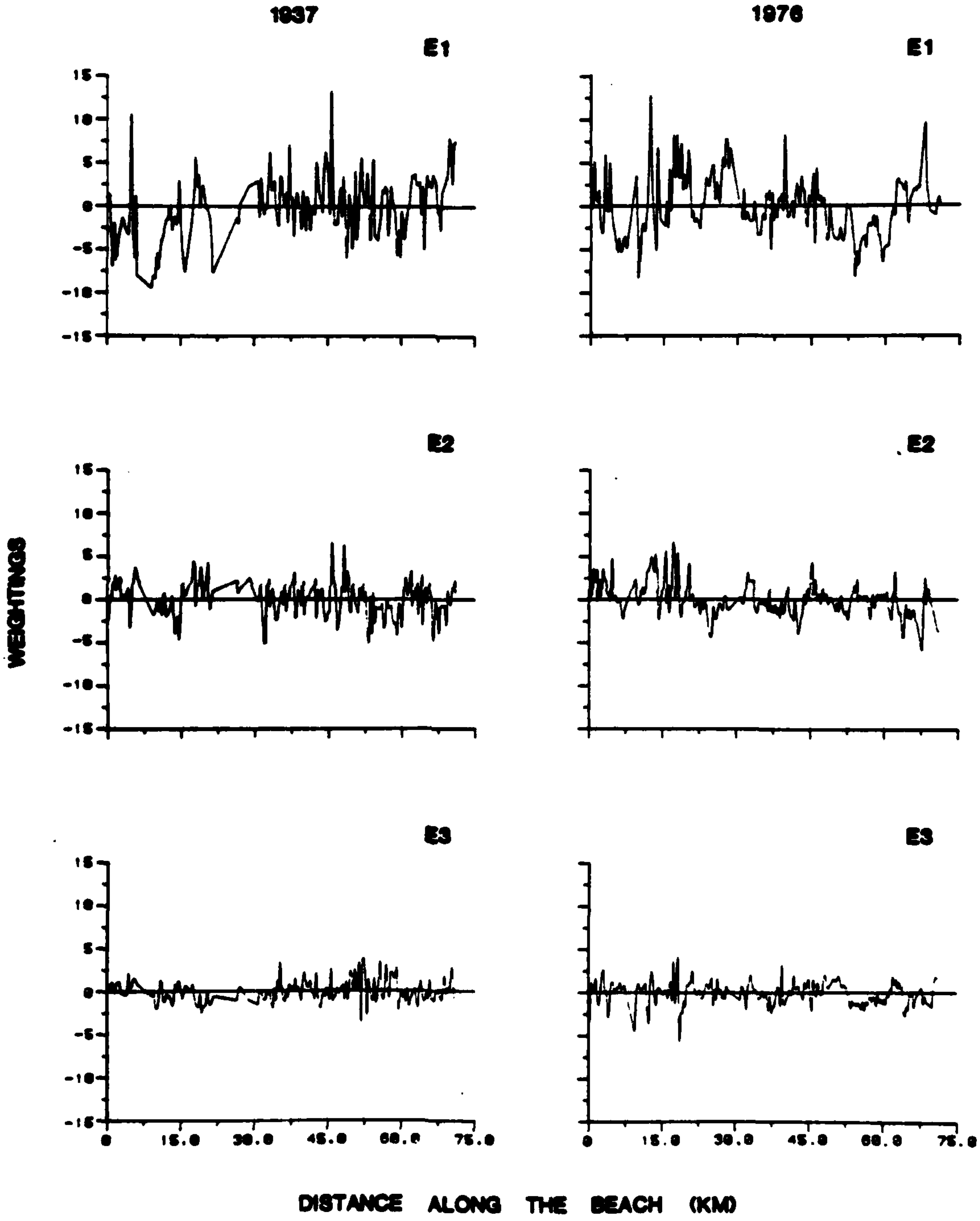
E1 accounts for the largest amount of the total variance with E2 and E3 explaining respectively lesser amounts (table 3). This suggests that in most of the profiles, E1 will describe the basic topographic form of the beach. E2 and E3 will modify this basic form. The remaining 18 eigenvectors for each data series account for only 8.5% of the variance in 1937 and 11.8% in 1976. Any modification of the basic beach profile accounted for by these remaining eigenvectors is minimal.

The weightings for the first three eigenvectors were plotted along the coast (figure 6). These weightings are the transformed data values measured in terms of the principal component axes (Daultrey, 1976). The variation of these scores along the island indicatesthat the importance of each eigenvector is not constant for each beach profile.

Although periodicities of these weightings will be examined mathematically by spectral analysis, some organization in the distribution of these scores may be visually observed as well. E1-1976 (figure 6) shows a distinct trend in variation on the order of tens of kilometers. The E1-1937 scores also appear to show a similar trend, although this is not as distinct due to missing data values. The E2-1937 and E2-1976 score

FIGURE 6

Eigenvector Weightings along the Coast



distributions both show a definite downward trend from north to south. The E3-1937 and E3-1976 scores are less variable, therefore, systematic deviation in their distributions are not readily discernible.

Supplementary Data Sets

The alongshore data distributions for variables 7 through 18 (table 2) are given in figures 7-9. These plots cover the same coastal reach as the beach profile data (figure 1) with the exception of the 1932-1934 beach width data and the sediment data. These two data sets have the same northerly endpoint as the beach profile data, but do not extend fully to the southern limit due to the unavailability of data.

Active Beach Width - Plots of the 1932-1934 and 1978 active beach width, measured directly from the aerial photographs, are shown in figure 7b. Comparison of the two plots indicates that a substantial decrease in the width of the active beach zone has occurred in the 44 year intervening period between photographs. The mean width of the active beach zone in 1932-1934 was 336 meters. By 1978, it had decreased to 112 meters. There was a simultaneous decrease in the standard deviation which declined from 167 meters to 68 meters. Therefore, the beach width by 1978 had generally decreased and become more homogeneous relative to the beach in the early 1930s.

FIGURE 7a

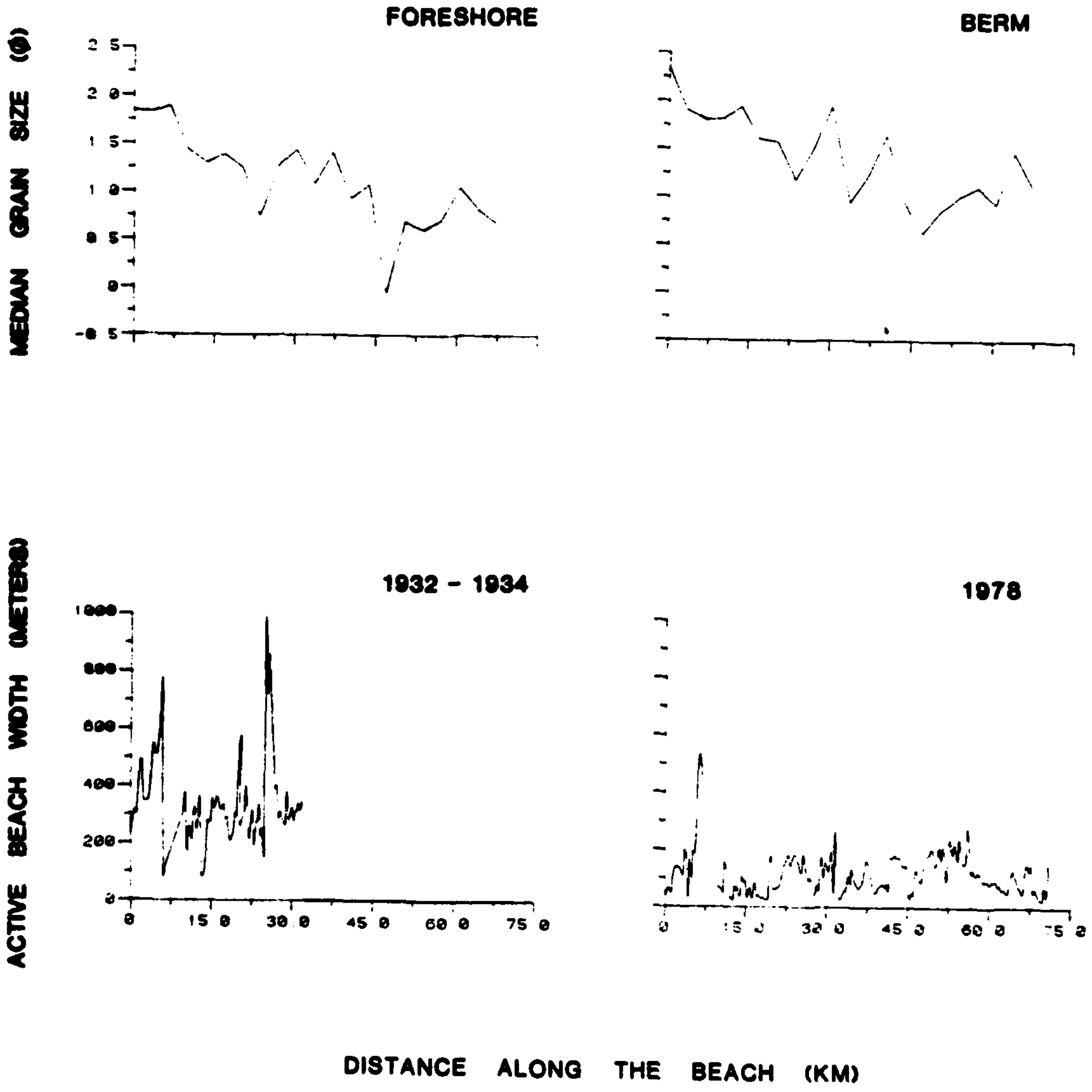

FORESHORE
BERM
MEDIAN GRAIN SIZE (ϕ)
2.5
2.0
1.5
1.0
0.5
0
-0.5
1932 - 1934
1978
ACTIVE BEACH WIDTH (METERS)
1000
800
600
400
200
0
0
15.0
30.0
45.0
60.0
75.0
DISTANCE ALONG THE BEACH (KM)

FIGURE 8

Concentration of Wave Energy

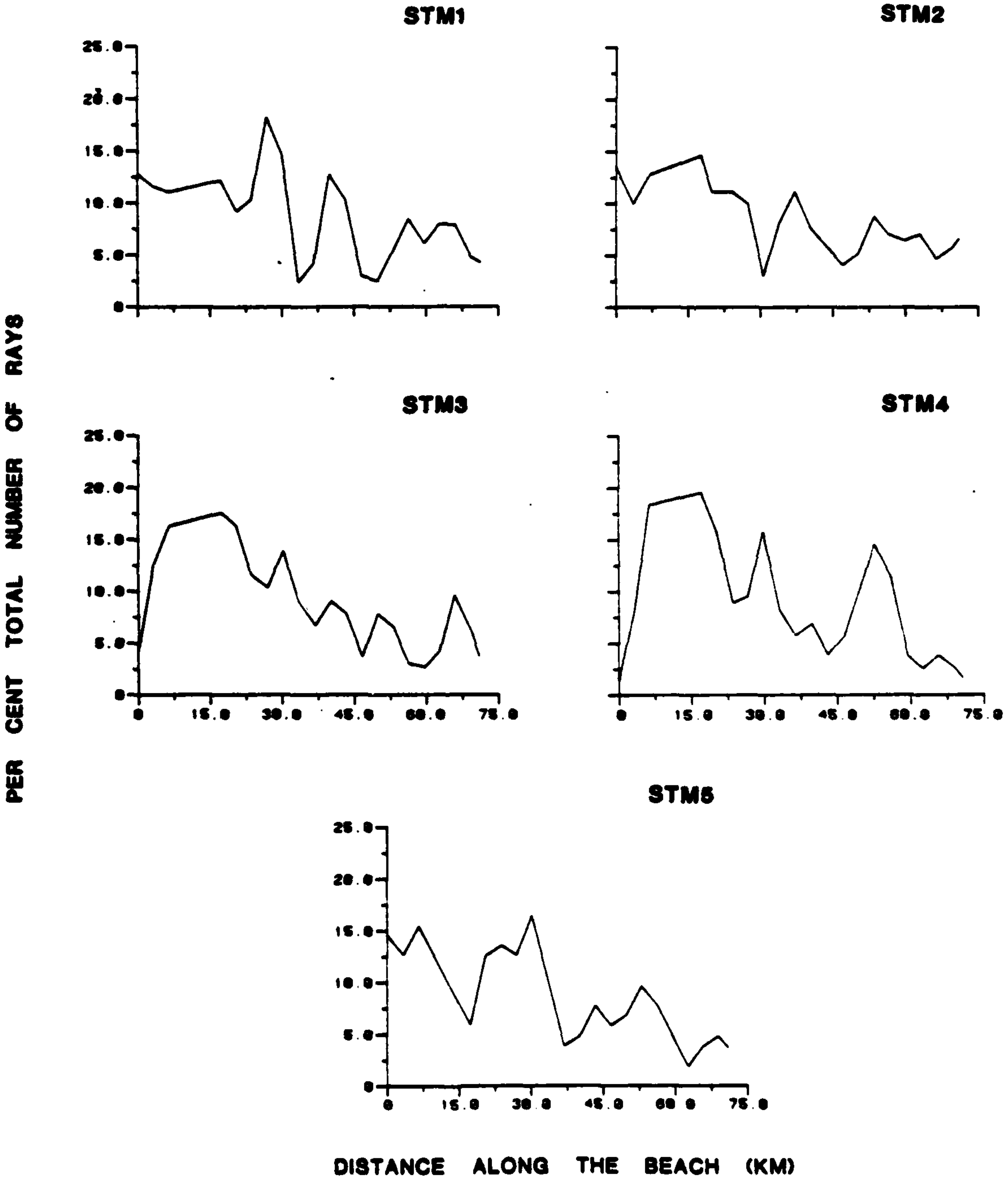
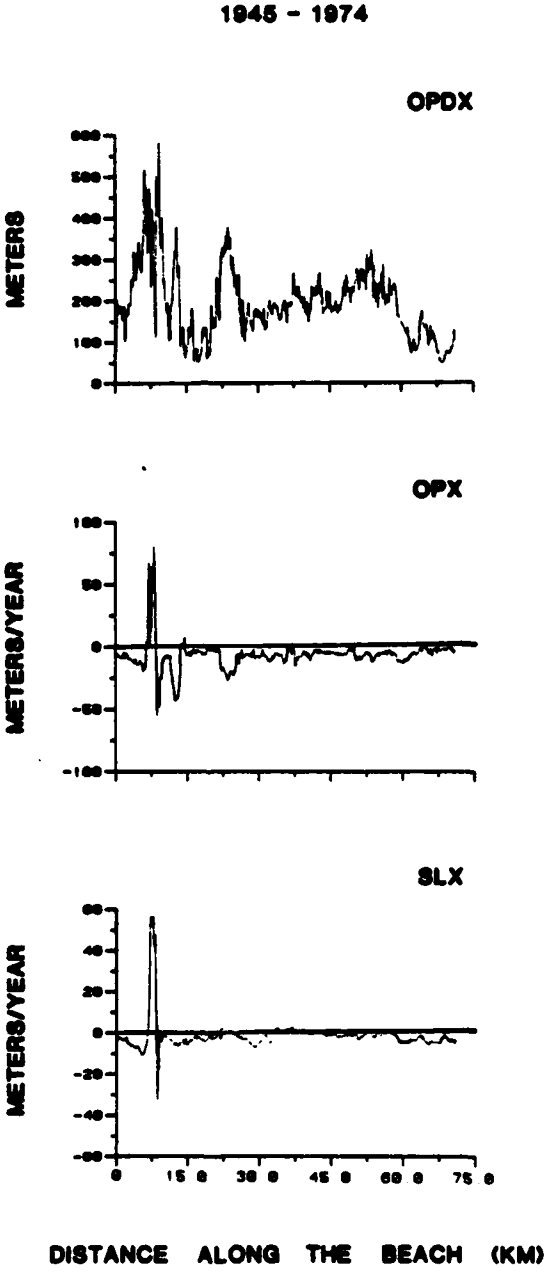


FIGURE 9


1945 - 1974
OPDX
METERS
600
500
400
300
200
100
0
OPX
METERS/YEAR
100
50
0
-50
-100
SLX
METERS/YEAR
60
40
20
0
-20
-40
-60
0
15.0
30.0
45.0
60.0
75.0
DISTANCE ALONG THE BEACH (KM)

Wave Energy Distribution - The distribution of wave rays impacting the shoreline (figure 8) indicates that the concentration of wave energy along the coast is highly variable. However, the alongshore placement of high and low amounts of wave convergence does not remain constant for differing storm types. This implies that storm type will be an important factor in determining shoreline response (Nnaji and Fisher, 1981). Generally, all five storm types do exhibit an overall decrease in wave energy from South Nags Head to Cape Hatteras.

Sediment Size Distribution - The alongshore distributions of median sediment size from South Nags Head to 5.5 km north of Cape Hatteras point are given in figure 7a. Median sediment size on the berm and foreshore generally increases from north to south. Shideler noted in his study of these sediments (1973a and 1973b) that the foreshore is a zone of comparatively high average wave energy whereas the berm has lower average conditions. In addition, he found that the foreshore often tends to be composed of a more homogeneous sediment population than the berm. Despite these differences, the plots for both areas tend to show similar changes in median grain size along the coast.

Shoreline Dynamics - The distributions of the OPDX, OPX and SLX variables from 1945 to 1974 are shown in figure 9. The position of the overwash penetration line as well as the rate-of-change of the shoreline and distance to the overwash penetration line are highly variable. There is an increased amount of variation for all three parameters in the vicinity of Oregon Inlet. This area has long been recognized as an unstable reach (Dolan and Glassen, 1972).

The mean distance to the overwash penetration line (OPDX) has a longshore distribution which displays a conspicuous large-scale sinusoidal trend. This suggests that overwash penetration is more severe on certain sections of the coast relative to other areas. The SLX distribution indicates that the shoreline is being eroded in most areas, while the OPX distribution shows that an overall narrowing of the overwash penetration zone has occurred from 1945-1974. Therefore, although the overwash penetration line (vegetation line) is also migrating landward, it is doing so at a lesser rate than the shoreline. Rates of retreat along the barrier island for both SLX and OPX are not spatially constant.

Spectral Analysis

Spectral plots for individual variables are given in figures 10-13. Table 4 summarizes the results of the spectral analysis for all variables. Numerous statistically significant periodicities were revealed. The majority of these were found to range in length from 1/4 to 1/2 the distance of the study reach. The predominance of these longer periodicities is partially due to the resolution of

FIGURE 10
Spectral Plots of Eigenvectors

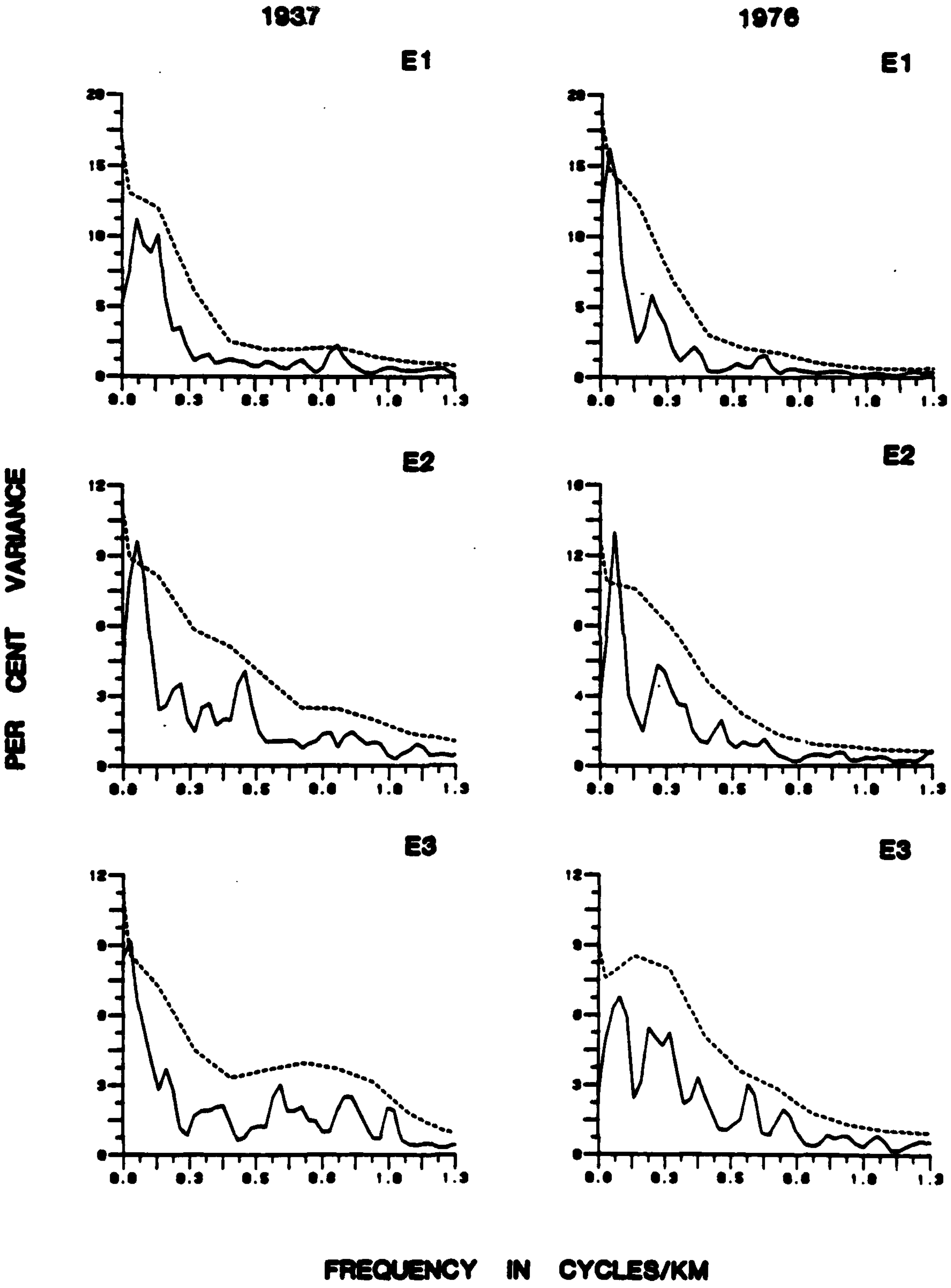


FIGURE 11a

Spectral Plots of Median Grain Size

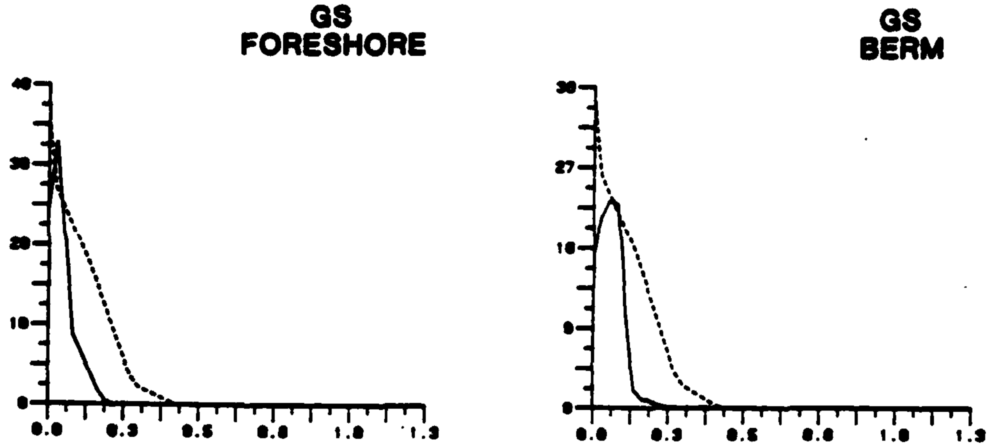
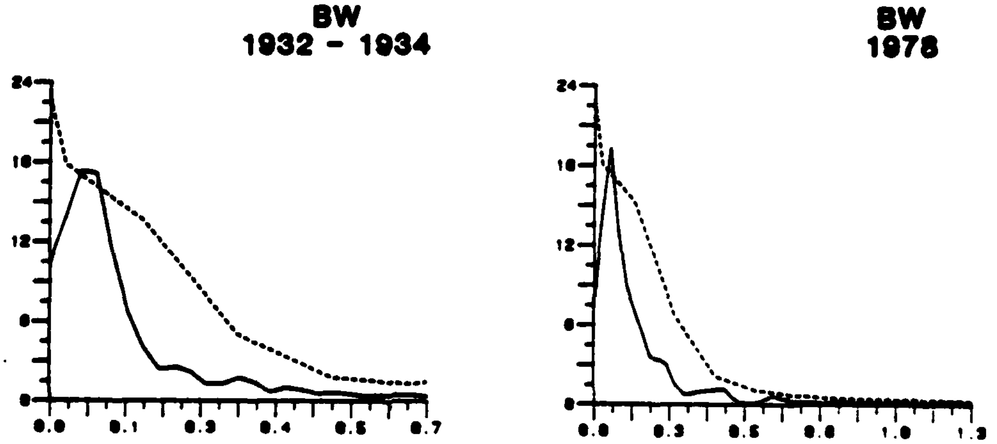


FIGURE 11b

Spectral Plots of Active Beach Width



PER CENT VARIANCE

FREQUENCY IN CYCLES/KM

FIGURE 13

Spectral Plots of Shoreline Dynamics Variables

1945 - 1974

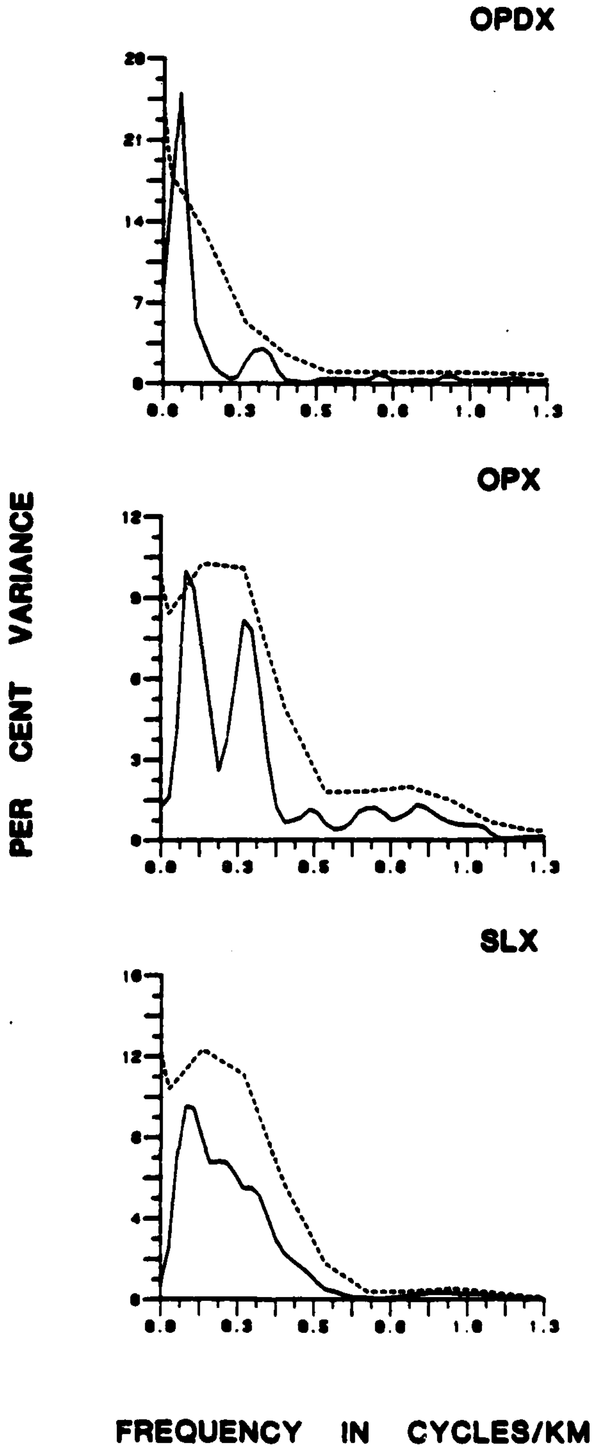


FIGURE 12

Spectral Plots of
Wave Energy Concentration

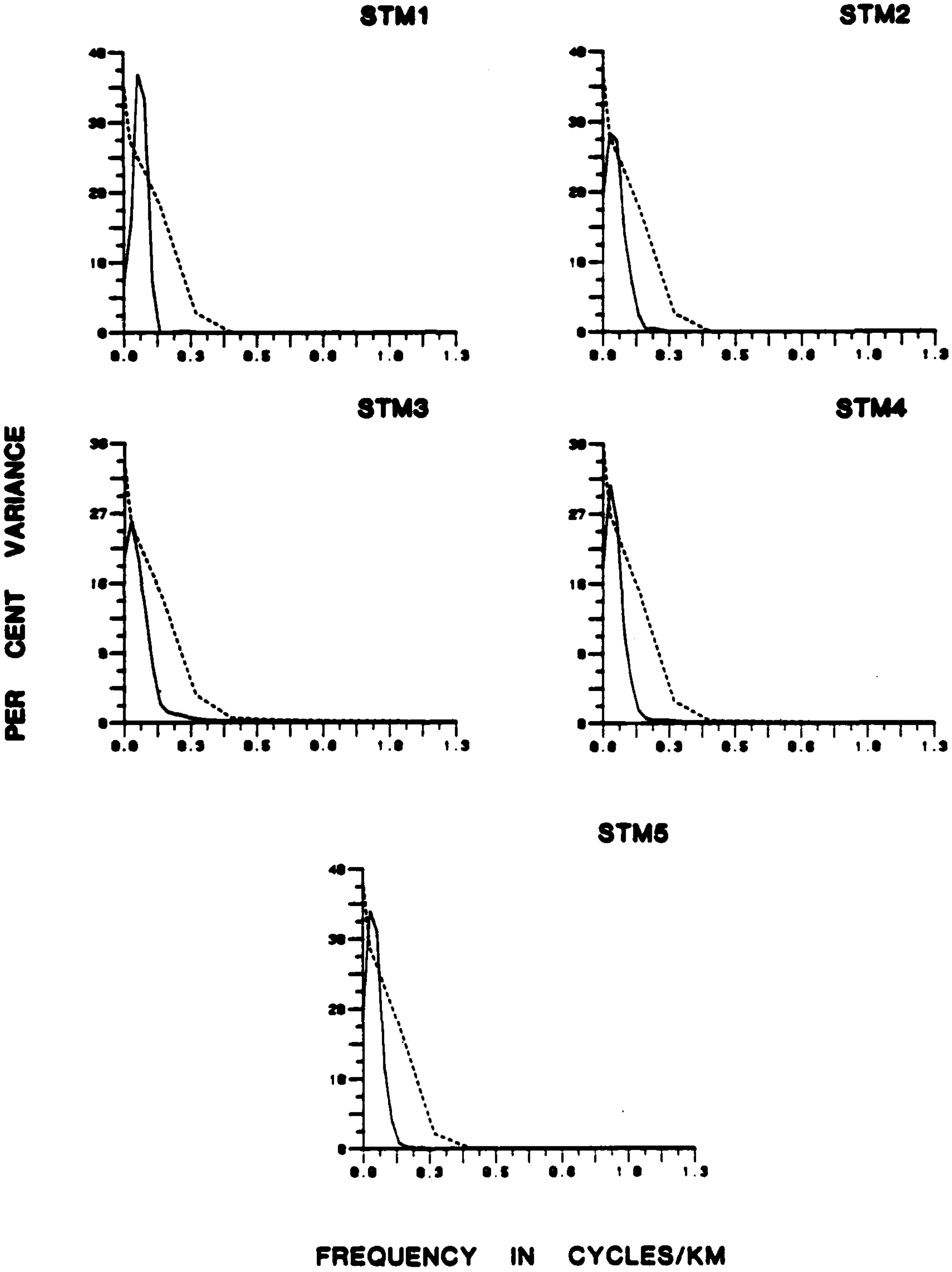


TABLE 4

Spectral Analysis Results

	Significant* Periods (in kilometers)			
E1-1937				1.2
E2-1937		17.8		
E3-1937	35.7			
E1-1976	35.7			
E2-1976		17.8		
E3-1976				
BW 1932-1934		17.5	11.7	
BW-1978		17.8		
GS-Foreshore	35.4			
GS-Berm			11.8	
STM1		17.8	11.9	
STM2	35.7	17.8		
STM3	35.7			
STM4	35.7	17.8		
STM5	35.7	17.8		
OPDX		17.8		
OPX			11.9	
SLX				

* $p < .05$

the sampling intervals. However, statistically insignificant peaks in the power spectra were found to exist at smaller periods as well. Filtering out of the larger scale periods failed to result in increased significance of the small periods.

The existence of these large-scale cyclic trends suggests that many of the variables associated with the beach system are organized on the order of 10's of kilometers. Additional substantiation for these trends is given by variables which do not have statistically significant periodicities, but do show peaks in the power spectra on this same scale. The prevalence of these periods indicates that different variables may be expressed on a similar scale. However, spectral analysis gives no information on the positioning of these periodic forms along the coast. In order to determine relationships between periodicities, the next step was the cross-spectral analyses.

Cross-Spectral Analysis

The results of the cross-spectral analyses are summarized in tables 5 through 10. These tables give only the statistically significant ($p < .01$) correlation coefficients. However, lack of significance does not necessarily imply that the series are unrelated. There are three explanations for low correlations:

1. There is no significant relationship

between the two data series at any cosine frequency.

2. There is a correlation between the data series at specific cosine frequencies but the waves are 90 or 270° out-of-phase. This means that the individual correlation coefficients between the cosine waves will be low.

3. A correlation exists between the series but positive and negative individual correlation coefficients for cosine curves of different frequencies negate each other. This causes the overall correlation coefficient to be low.

The relationships between the eigenvector weightings for 1937 and those for 1976 are shown in table 5. The only significant correlation is between the first eigenvector for 1937 and 1976. This indicates that the data series for the 1937 and 1976 weightings demonstrate a tendency to have similar deviations in beach height along the coast. However, examination of the individual coefficients and the phase angles indicates that these trends are not synchronous for all cosine periods. The 35.6 and 23.7 km periodicities both have small phase lags. Thus, the two data series at these periods are almost in-phase. The cosine waves set up for the two series at 71.1 km are out-of-phase by 132.5°. The resulting negative correlation coefficient for the two curves reduces the positive summed coefficient. This causes the overall relation between the eigenvector weightings to appear less strong.

Another effect, not represented by the overall cosine waves for different frequencies. In the E1-1937 weightings, there are a number of smaller scale periodicities (17.8, 14.2, 7.9 and 6.5 km) with high amplitudes. These same periodicities are absent in the E1-1976 weightings. Therefore, the covariance of the two variables at these higher frequencies is minimal, suggesting that smaller scale topographic variations may have been reduced during the 39-year intervening period.

The cross-spectral analyses between E2-1937 and E2-1976 as well as E3 for the same years yield insignificant results (table 5). Examination of the individual coefficients for the E2 weightings suggests that the phase lags partially account for the low values. If these data series were in-phase, there would be an increase in the value of the individual coefficients. However, this increase would not be sufficient for the overall coefficient to be significant at the .01 level. The E3 weightings for both years show no apparent association.

Many of the beach variables show a strong association with the eigenvector weightings from 1937 and 1976 (table 6). Significant correlations imply that as one of the paired variables changes in value along the coast, there is a tendency for the other variable to vary systematically as well. Therefore, a given profile may be typified by certain characteristics dependent upon its weighting for each eigenvector (table 7).

Table 8 summarizes the relationships between pairs of beach variables. Interrelationships add another dimension to the interpretation of the beach topography.*

The active beach width in 1932-1934 shows a correlation with three storm types. The positive correlation with STM1 implies that wider beach widths in the early 1930's tend to be associated with areas of high wave energy. More severe storms (STM3 and STM4), however, display a negative relationship with the beach width. As beach width increases, there tends to be a simultaneous decrease in the wave energy delivered from these two storm types. These same relationships are not applicable to the 1978 beach width. However, in 1978, a wide beach is likely to occur in conjunction with high wave energy from STM4 and STM5.

The 1932-1934 active beach width is negatively correlated with SLX. Thus, wider beaches are likely to be associated with areas of shoreline erosion. Again, this relationship does not hold for the 1978 beach. Wide beach widths in 1978 tend to coincide with areas of low erosion or slight accretion of the shoreline. In addition, there is likely to be a large distance to the overwash penetration line and low rates of erosion or accretion of this line.

Storm wave energy is directly related to the grain size

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* For all the relationships listed below, the inverse relationship is true as well.

on both the berm and foreshore. The correlation coefficients suggest that as wave energy for all storm types increases there is likely to be a concurrent decrease in the grain size on both the berm and foreshore. This result contradicts Shideler's (1973a) conclusion that the trend of decreasing grain size from north to south is accompanied by decreasing wave energy.

OPDX is also positively correlated with STM2-STM5. This relationship means that regions along the coast receiving high wave energy from these storms are likely to have larger distances to the overwash penetration line.

Comparisons among the shoreline dynamics variables yield two important relationships. The OPDX/SLX correlation indicates that large distances to the overwash penetration line are often associated with low rates of erosion or slight accretion of the shoreline. Additionally, when an area is undergoing only minimal shoreline erosion, then there also tends to be a low rate of change in the overwash penetration zone (OPX). However, when shoreline erosion is high, there is a concurrent increase in the rate of overwash penetration zone narrowing. These interactions suggest that the narrowing of the active beach zone is due primarily to shoreline erosion.

Tables 9 and 10 give the spatial periods which are most important in contributing to the overall correlation between pairs of variables. Concentration of the correlation on one period suggests that the relationship between the two variables is based primarily on that scale. Spreading of the correlation over several periods implies that the variables are covarying on numerous scales. Very few of the pairs covary on a scale less that 10 km and larger scale periods from 23 to 71 km are most common. This is partially due to the resolution of the data series. However, the lower limit of possible covariance is more than a degree of magnitude lower than the smallest period of correlation for any of the variable pairs. Therefore, these tables indicate that many parameters describing the beach system are operating on scales that have commonly been bypassed in much of the past coastal literature.

TABLE 5

Cross-Spectral Analysis Results: Comparison of Eigenvectors*

	Overall Correlation Coefficient	Individual Correlation Coefficient (r)	Period Corresponding to Individual (r) Values (in km)	Phase Lag (in degrees)
E1-1937 and E1-1976	.21*	-.09	71.1	132.5
		.07	35.8	9.9
		.10	23.7	8.1
E2-1937 and E2-1976	-.07	.04	71.1	51.9
		.05	23.7	153.6
E3-1937 and E3-1976	.00	—	—	—

*$p < .01$

TABLE 6

Cross-Spectral Analysis Results:

Overall Correlation Coefficients between the Eigenvectors and the Beach Variables

	(1937)			(1976)		
	E1	E2	E3	E1	E2	E3
BW 1932-1934		.34**		***	***	***
BW-1978	***	***	***	-.39**	-.26**	
GS-Foreshore	***				.27**	
GS-Berm	***			.26**	.31**	
STM1	.29**	.23**	-.19*	.39**		
STM2	.50**				.36**	
STM3	.40**		-.23**	.21*	.27**	
STM4	-.41**				.35**	
STM5	-.40**				.23**	
OPDX	-.45**			-.33**		
OPX					-.20*	
SLX	-.27**			-.18*		

* $p < .01$
** $p < .001$
*** Comparison not made.

Table 7

Beach Profile Characterizations

Characteristics of profiles having a (+) weighting* on:

E1-1937

(1) Area of high wave energy for moderate storms
(2) Area of low wave energy for more severe storms
(3) Short distance from shoreline to overwash penetration line
(4) High rates of shoreline erosion

E2-1937

(1) Large active beach width
(2) High wave energy for least severe storm type

E3-1937

(1) Low wave energy for least severe storm type
(2) Low wave energy for moderate storm type

E1-1976

(1) Narrow active beach width
(2) Small grain size on berm
(3) High wave energy for moderate storms
(4) Short distance from shoreline to overwash penetration line
(5) High rates of shoreline erosion

E2-1976

(1) Narrow active beach width
(2) Small grain size on berm and foreshore
(3) High wave energy for STM2 - STM5
(4) High rate of retreat of overwash penetration line

E3-1976

No consistent beach characteristics

* Profiles having a (-) weighting will be characterized by conditions opposite to those given here.

note - Graphical depictions of each eigenvector are shown in figure 5.

TABLE 8

Cross-Spectral Analysis Results: Overall Correlation Coefficients between Beach Variables

	BW 1932-1934	BW 1978	GS Foreshore	GS Berm	STM1	STM2	STM3	STM4	STM5	OPDX	OPX	SLX
BW 1932-1934	—		***	***	.28*		-.30*	-.35**				
BW-1978	--	—						.23**	.35**	.61**	.31**	
GS-Foreshore	—	—	—	.90**	.61**	.66**	.61**	.36**	.57**			
GS-Berm	—	—	—	—	.77**	.68**	.69**	.49**	.58**			
OPDX	—	—	—	—		.22*	.17*	.32**	.46**	—		.27**
OPX	—	—	—	—							—	.74**
SLX	—	—	—	—								—

*p < .01
**p < .001
***Comparison not made

TABLE 9

Cross-Spectral Analysis Results:

Periods Contributing to Overall Correlation between the Eigenvectors and the Beach Variables*

	(1937)			(1976)		
	E1	E2	E3	E1	E2	E3
BW 1932-1934		31.7 10.6				
BW-1978				23.7	35.6 14.2	
GS-Foreshore					67.3	
GS-Berm				67.3 13.5	67.3	
STM1	71.1 17.8 14.2	71.1 17.8 14.2 11.9	71.1	71.1 14.2 10.2		
STM2	71.1 35.6				71.1 35.6	
STM3	71.1 35.6		71.1 35.6	71.1 35.6	71.1 35.6	
STM4	71.1 35.6 23.7				71.1 35.6 23.7	
STM5	71.1 23.7				71.1	
OPDX	35.6 23.7 17.8 14.2			35.6 23.7		
OPX					**	
SLX	35.6 23.7 17.8 14.2			23.7		

* All periods are in kilometers

** The distribution of the overall correlation is over numerous periods.

TABLE 10

Cross-Spectral Analysis Results:

Periods Contributing to Overall Correlation between the Beach Variables*

	BW 1932-1934	BW 1978	GS Fore-shore	GS Berm	STM1	STM2	STM3	STM4	STM5	OPDX	OPX	SLX
BW 1932-1934	—				31.7 15.9 10.6 7.9		31.7	31.7				7.9 5.3
BW-1978	—	—						35.6 23.7	23.7	35.6 23.7 17.8 14.2	11.9 7.1	23.7 17.8 14.2
GS-Foreshore	—	—	—		67.3 16.8 11.2	67.3	67.3	67.3 33.7	67.3			
GS-Berm	—	—	—	—	67.3 13.5	67.3	67.3	67.3 33.7	67.3			
OPDX	—	—	—	—		35.6	71.1 35.6	35.6 23.7	23.7	—		23.7 17.8 14.2
OPX	—	—	—	—							—	**
SLX	—	—	—	—								—

* All periods are in kilometers

** The distribution of the overall correlation is over numerous periods.

DISCUSSION

Topographic Organization

Principal components analysis shows that the beach topography on the Outer Banks demonstrates strong spatial organization. Three eigenvectors explain 90% of the variance indicating the concentration of this organization on a relatively small number of beach descriptors. Although changes have taken place on the Outer Banks since the 1930s (Nash, 1964; McGee, 1962; Godfrey, 1973; Dolan, 1972), the configuration of the beach, as shown by the three eigenvectors from 1937 to 1976, has remained almost constant. This suggests that despite modifying influences, such as the construction of stabilized dunes and increased development, the overall organization of the system has remained largely intact.

The high percentage of variance explained by the first eigenvector in both 1937 and 1976 indicates that the data points describing the beach profile are highly intercorrelated (Daultrey, 1976). This means that when one portion of the beach profile is modified by either natural or man-made disturbances the effect of this disturbance is felt over the entire profile. Thus, any attempt to modify beach behavior must consider the ramifications of this change over the whole beach profile, not only over the portion being modified.

Spectral analysis of the eigenvector weightings yields a periodic element of beach topography along the coast in the range of 17.8 - 35.6 km. This suggests that large-scale elevational rhythms are present within the beach system. Although these undulations are not significant at the .05 level for El-1937, there is power in the 17.8 km periodicity. Lack of significance may be due to numerous missing values in the original data set.

Temporal Persistence

The positive correlation between the two eigenvectors which explain the largest amount of variance (El-1937 and El-1976) is the strongest indication of temporal persistence of large-scale topographic forms. Although the overall correlation coefficient is low, this is partially due to the differing signs of the individual coefficients. Missing values in the 1937 data set may also cause a low coefficient.

The second eigenvector for both data sets displays a 17.8 km periodicity along the coast. However, the overall correlation is not significant at the .01 level. Examination of the spectral plots (figure 10) shows numerous peaks in the spectra. It may be that the spreading of the overall correlation over such a wide range of frequencies diminishes the individual correlation in the 17-18 km scale. There is little or no temporal persistence of forms for the third eigenvector.

The overall relationship between the two data sets suggests that rhythmic forms of each frequency either migrate at different rates along the coast or migrate at similar rates but are out-of-phase with previous forms due to their differing lengths.

Effects of Dune Stabilization

One of the most predominant man-made alterations of the Outer Banks is the line of stabilized dunes established in the 1930s (Nash, 1964). Barrier island response to stabilized dunes has been studied by a number of investigators (Dolan, 1972; Godfrey, 1973; Leatherman, 1979). Dolan's (1972) hypothesis proposed that the stabilized dunes have caused winnowing of fine sand material and have also resulted in narrowing of the beach. Godfrey (1973) concurred with this interpretation and also suggested that dune stabilization hindered the process of barrier island retreat. Stauble (1979) conducted a laboratory investigation to study the effects of uprush and backrush on an inclined dune and a vertical dune scarp. He found that wave reflection from the inclined dune caused bed erosion during backwash. Uprush striking the vertical dune scarp resulted in a reflected bore that eroded the base of the scarp and provided additional sediment to the backshore.

Leatherman (1979) has speculated that stabilized dunes do not increase erosion rates and may even serve as sources of sediment. However, his hypothesis fails to consider the fact that there has been a considerable decrease in the width of the active sand zone since stabilization was initiated. Although beach narrowing does not necessarily imply increased erosion rates, it does suggest that the stabilized dunes are interfering with the dynamics of barrier island migration in response to sea level rise. Unstabilized areas, such as Cape Lookout, have maintained their wide beaches despite recent rises in sea level (Dolan et al., 1973).

In addition to beach narrowing, there has also been a decrease in the standard deviation of the beach width from the 1930s to the 1970s. The ratio of the standard deviation to the mean is .50 for the 1930s and .61 for the 1970s. These ratios suggest that despite changes in active beach width, the fluctuation about the mean remains approximately one-half of the mean beach width. As the dunes have apparently caused a decrease in the beach width, they have also forced a concurrent decrease in the standard deviation. Stabilization of the dunes prevents overwash at all but a few isolated points where dune breaching can take place, thus decreasing the standard deviation.

Past investigations have documented beach narrowing in response to dune stabilization (Hayden et al., 1980; Godfrey, 1973). The change in the mean beach profile ($\bar{X}$) from 1937 to 1976 supports Dolan's (1972) contention that there has been a compression in the zone available for energy dissipation and that sediment winnowing has led to steepening of the beach profile. This situation may also be analogous to Hayden et al.'s (1980) study of Assateague Island. This barrier island is generally eroding and has a stabilized dune system. They found that both the overwash penetration line and "topographic maximum" of sediments have relatively moved seaward in recent years due to the dunes. Associated with these trends is an increase in profile steepness.

The increase in the standard deviation (SD) over the landward half of the beach profile from 1937 to 1976 (figure 4) may be due to two factors. In 1937, the 65 meter mean profile is composed of the nearshore and backshore; in the 1976 profile, beach narrowing may have allowed expression of the dune field at the back half of the profile. Dunes are variable in elevation which would account for the increase in the standard deviation.

Secondly, if the stabilized dunes have a vertical scarp on the oceanward side, as is frequently the case (Leatherman, 1979; Dolan et al., 1973), then Stauble's (1979) laboratory investigations may be applicable. These suggest that as the uprush strikes the dune face, undercutting of the scarp by the reflected bore takes place. This eroded material is added to the backshore. Unequal distribution of the additional material due to differing amounts of wave attack should increase the standard deviation. Thus, in this sense, Leatherman's (1979) proposal that stabilized dunes act as a sediment source for the beach may be accurate.

Interrelationships of Beach Variables and Beach Topography

Prior to dune stabilization, the Outer Banks were relatively free of man-made disturbances (Kaufman and Pilkey, 1979, p.94; Godfrey, 1976). Natural processes on the islands were allowed to proceed without restraint. With the construction of stabilized dunes, the dynamics of the islands were necessarily altered. Thus, study of the barrier island response requires that the 1930s beach and the post-stabilization beach be regarded as two distinctly separate systems.

On unstabilized barrier islands overwash occurs regularly during storms (Godfrey, 1976). Examination of aerial photographs of the Outer Banks from the 1930s shows sparse development of vegetation due to the frequency of overwash. Although parameters describing the active beach may correlate with any particular storm event, the recurrence of overwash as well as the relatively slow rate of vegetative recovery suggests that time-averaged, post-stabilization measures such as STM or OPDX, OPX and SLX may not always accurately reflect the constantly changing character of the beach system. Since the 1930s, however, the artificial dune system has caused overwash to become a much less frequently occurring process. Therefore, these time-averaged, post-stabilization variables are able to more accurately depict the beach conditions in the 1970s.

This discrepancy between beach systems is represented by the results of the cross-spectral analyses. Although some of the relationships for the 1930s are reasonable in light of previously documented beach processes and responses, a number of others appear tenuous.

The results of the 1930s analyses suggest that areas receiving high wave energy from the less severe storms also tend to have higher, wider beaches. In contrast, areas impacted by high wave energy from the more severe storms tend to be associated with narrower, lower beaches. Regions of high wave energy and low topography are considered to be most susceptible to overwash (Dolan et al., 1981; Godfrey, 1976). Overwashed areas have relatively wide active beach widths; therefore, contradiction between the experimental and observed relationships suggests that the storm and overwash data are unable to accurately account for variation in beach width and height.

These 1930 relationships do not corroborate with the STM/OPDX results which are comparisons of two time-averaged parameters. These correlations suggest that through time, areas receiving high wave energy from STM2-STM5 will generally have a large distance to the overwash penetration line. This relationship is a reflection of post-stabilization conditions. These relationships do not agree with the interaction between the 1930s beach variables and the post-1930s time-averaged variables, suggesting that shorezone response to the driving processes has changed since stabilization was initiated. Additionally, because these comparisons are untenable, the interrelationships of the 1930s data with any of the beach variables must be considered suspect due to temporal discrepancies.

The cross-spectral results for the 1970s generally support one another and also corroborate with past research on beach behavior for stabilized systems. In this case, the time-averaged variables are within the time constraints of post-stabilization.

The composite relationship between storm waves and the height and width of the 1970s beach may represent a threshold phenomenon associated with increasing storm severity. Areas of higher wave energy for less severe storms tend to have higher beaches. This may be due to the situation that Bascom (1954) first observed in which storm waves scarp the beach face but also tend to build up the berm. A high berm may persist until a larger storm removes it (Komar, 1976). Therefore, the larger wave energies of STM4 and STM5 could account for the lack of BW/STM correlations for more severe storms. Additionally, these higher waves may be responsible for breaching of the dune system in the form of an overwash deposit which would account for wide active beach widths as implied in the BW-1932-1934/STM4 and 5 relationships.

Interrelationships between the shoreline dynamics variables, storm wave energies and the 1970s beach complement the above relationships. Wide beaches in the 1970s are often associated with low rates of erosion or slight accretion of the shoreline, as well as a large distance to the overwash penetration line. This implies that regions which are subject to overwash tend to have fairly stable shorelines. Hayden et al. (1980) have found that on areas of Assateague which are stabilized and have reduced storm-surge penetration, there is a high rate of shoreline erosion.

Further, the OPX/SLX relationship indicates that high rates of shoreline erosion are associated with high rates of narrowing of the overwash penetration zone; whereas low rates of shoreline erosion are associated with low rates of narrowing (or widening) of the overwash penetration zone. As noted previously, these relationships suggest that the narrowing of the overwash penetration zone (the active beach) is due primarily to shoreline erosion. Dune stabilization essentially fixes the position of the overwash penetration line until the dune is breached. Thus, landward retreat of the overwash penetration line has been inhibited by dune stabilization. This change means that island response to the driving processes is virtually limited to fluxes in shoreline position until the capacity of the dunes to withstand wave attack is exceeded.

Areas of high, concentrated wave energy have generally been considered the most likely regions for overwash to occur (Fisher et al., 1974; Pierce, 1970). Hosier and Cleary (1977) have found that washover often destroys the vegetation behind the dunes. This would effectively increase the active beach zone width. Through association, those areas receiving high storm wave energy (and thus are more susceptible to the overwash process) should tend to have a wide distance to the overwash penetration line. This has been substantiated by the STM/OPDX cross-spectral results. Relating this further to the beach topography, it is found that a beach profile with a greater than average height often is associated with a low distance to the overwash penetration line. This suggests that the dunes are very well developed in these areas and thus prevent waves from breaching them, which keeps the overwash penetration distance low. It is possible that wave erosion, in these situations, takes place by scarping of the dune face since overtopping of the dune is inhibited.

One cross-spectral relationship that does not fit into this composite portrayal of shorezone interactions is the relationship between E2-1976 and STM1-5. Given the interrelationships of the other variables, a positive correlation was not expected. The positive coefficient obtained may be due to a chance association between the two data sets or may reflect some process or response which has not been taken into account.

Another series of correlations which do not pertain directly to the preceding relationships, but are interesting nonetheless, may be seen in the GS/STM cross-spectral results. Generally, it is considered that an increase in wave height will cause a coincident increase in grain size

(Shideler, 1973) due to winnowing of the smaller grains. In this study, increases in wave energy for all five storm types were strongly correlated with a decrease in grain size on both the berm and foreshore. There are two possible explanations for this. It is feasibile that both variables covary with a third, undocumented variable which is creating this apparently anomalous relationship. It is also possible that the sediment response to wave energy dissipation across the beach (the phenomenon that most studies have examined) is not applicable to the mechanism of along-the-coast distribution.

The preceding discussion of beach variable interrelationships is somewhat speculative in nature. This is partially due to the utilization of different data sets which were not collected at the same time or with the same interval spacing along the coast. However, further principal components analysis of all variables has confirmed that despite these limitations, a significant amount of covariance resides among these variables such that beach profile charcterizations (table 7) may be reasonably constructed. This suggests that as future multivariate data sets are collected which are both spatially and temporally consistent, beach profile characterizations may become more definitive. For reaches of the coast found to have a high degree of covariance between numerous beach parameters, these characterizations may prove to be a potentially invaluable tool in land use management.

Potential Causes of Organizational Patterns

Recent investigations have suggested the existence of distinct coastal processes responsible for the generation of shorezone rhythmic forms (Bowen, 1972; Huntley and Bowen, 1975; Sonu, 1972; Dolan et al., 1979; Guza and Inman, 1975). Although these studies have dealt primarily with the horizontal character of cuspate and crescentic forms, it is likely that the same processes, such as edge waves, may also be responsible for large-scale systematic variation in the beach topography. Bowen (1972) has proposed that the presence of "observable longshore features" suggests that edge waves must be operating. In addition, Komar (1982) has speculated that long period edge waves may be capable of producing rhythmic forms on a scale of up to tens of kilometers.

This study does not provide conclusive evidence that edge waves are causing large-scale rhythms in the topography. However, the documentation of strong spatial organization of shorezone topography combined with the evidence for the effect of edge waves on the beach suggests that these two are related. It also appears likely that other beach variables are related to the incidence of edge waves as well. However, the potential existence of a whole range of edge waves increases the complexity of the beach system (Bowen, 1972) and makes interpretation more difficult. Due to this situation, it is necessary to have more spatially and temporally consistent data before further inference is possible.

There is a considerable amount of spatial variation in the shorezone. Despite this, the results of this study have shown that this shorezone variation is often systematic and occurs as a result of organized processes. An understanding of the dynamics of this organization is needed in order to guide any further development of barrier islands. The relationship of beach topography to overwash penetration provides just one example of how this understanding may be applied. This relationship suggests that a few feet of difference in elevation may make an important difference in whether a building located near the shorezone will be subject to overwash. The results of studies investigating the interaction between barrier islands and the sea should provide a future guide for more intelligent use of these natural resources.

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Two beach profile data sets covering a 71 km reach of the Outer Banks, North Carolina, were examined in order to document large-scale topographic organization of the shorezone and relate this organization to other beach parameters. The earliest profiles (1937) were surveyed during the period of initial man-made dune stabilization by the Civilian Conservation Corps. A 1976 set comprises

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profiles that have been adjusting to the presence of these stabilized dunes for almost forty years. Four supplementary data sets - alongshore variations in active beach width, storm wave energy, sediment size and shoreline dynamics - document factors potentially related to shorezone topographic variation.

Principal components analysis was used to reduce the topographic variation of the beach profiles into a few major definable and independent sources. The weightings for each principal component and the variables from the four supplementary data sets were further analyzed with spectral analysis so that significant alongshore periodicities could be identified. Cross-spectral analysis was then performed on pairs of variables to determine the amount of alongshore covariance.

Three principal components for each profile data set were found to explain approximately 90% of the variance. This suggests a topographic organization of the shorezone. Comparison between the 1937 and 1976 data sets suggests that rhythmic forms of differing frequencies either migrate along the coast at different rates, or migrate at similar rates but are not synchronous due to their varying lengths. The dune stabilization has caused narrowing of the active beach width and steepening of the beach profile over a period of forty years, however, the intrinsic topographic organization has remained intact. The cross-spectral results indicated that the time-averaged, post-stabilization variables may not accurately reflect the constantly changing character of the 1930s beach system. However, these same variables more accurately depict conditions in the 1970s. The artificial dunes have decreased the variability of the system such that overwash is prevented at all but a few isolated points where dune breaching may take place.

Studies from the past ten years have verified the existence of rhythmic topography and the processes which may generate these forms. The results from this investigation have shown that large-scale topographic variation of the shorezone exists as well.

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