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BEACH CHANGES ON COASTS WITH DIFFERENT WAVE CLIMATES

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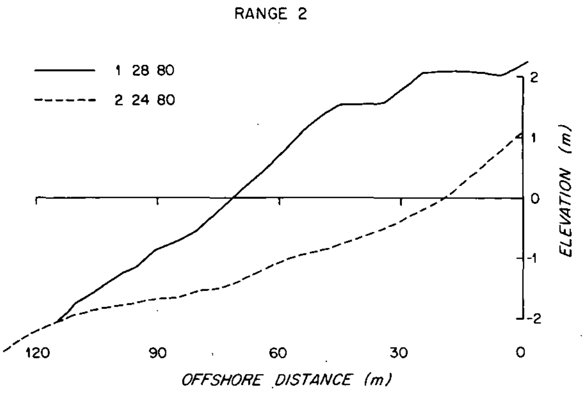
SYNOPSIS

Seasonal and longer-term beach variability is quantified for seven U.S. beaches exposed to widely varying wave climates. One U.S. west coast location (southern California) and six U.S. east coast locations (from North Carolina to Massachusetts) form the basis of this study. Wave exposure varies from complete exposure to open ocean waves, to partly sheltered locations, and finally to nearly complete sheltering where locally-generated waves dominate. Beach response was documented with beach profiles distributed along each of the seven coastal locations, spanning a minimum of five years of observation. Frequency of measurement was at least once per month, with periods of more intense weekly sampling lasting for up to two years (southern California location). Wave climate was either measured directly or estimated from hindcast and/or compilations of ship observations. Consequently, wave information varies in detail from joint statistics of wave height, frequency, and direction, to compilations of local storm history (and hence inferred wave behaviour). Magnitude of annual beach variability ranged from 3.3 m^3 per metre of beach to 0.2 m^3 per metre of beach, with the greatest variability in regions exposed to open ocean waves (most severe wave climate) and the lowest variability along protected coasts (least severe wave climate). All open coast locations studied had a seasonal variability which accounted for at least 50% of the beach variability. Protected coastal locations had less pronounced seasonal signatures. These seasonal and aseasonal beach responses mirror corresponding seasonality (or lack thereof) in wave and storm climates. The study re-emphasizes the need for careful measurement or estimation of coastal wave climate to enable predictive modelling of shoreline behaviour, and discusses different analysis techniques for analyzing changes in beach profiles through time.

INTRODUCTION

Quantification of spatial and temporal scales of beach change is vital to a wide variety of scientific and engineering investigations of nearshore environments. Vertical elevation changes of 2.5 metres, mean shoreline transgressions on the order of 50 metres, and volume changes on the order of 10^2 m^3/m of beach length can occur on time scales of hours, drastically altering the physical and biological characteristics of beaches (Fig. 1). Intertidal benthic communities must be able to respond quickly and efficiently to these profile readjustments, since habitat, oxygen levels, nutrient retention, and other environmental factors can be significantly



1) Beach erosion resulting from a series of storms battering Santa Barbara, California, in February, 1980, causing vertical cuts in the beach of up to 2.5 metres, and horizontal beach retreat of up to 60 metres.

altered in a short time (Steele, Munro and Giese, 1970; Parr, Diener, and Lacy, 1978). The degree of seasonality in these changes similarly may affect the viability of nearshore benthic communities, since the timing of beach changes interacts with the developmental stage of the benthic community. The seasonality and magnitude of beach changes also play a direct role in retention of hydrocarbons in beach sands with subsequent impact on biota, a consideration in many beaches exposed to naturally-occurring or man-induced hydrocarbons in the shallow nearshore. Rapid beach changes of large magnitude will help rid the beaches of oil naturally; longer-lived beach hydrocarbons may limit benthic diversity or density. An example of this longer time scale for hydrocarbon residence was observed along beaches in Santa Barbara, California, by the author (unpublished data). A series of major storms in February, 1980, caused marked erosion along the beaches in Santa Barbara, exposing underlying beach material which had not been disturbed in the preceding decade (Fig. 1). During the later stages of the storm, an oil-impregnated horizon which had been deposited during February, 1969 was exposed, and eroded from the beachface. In this instance, the residence time of the oil was of the order of 10 years, in contrast to the residence time of months for oil in beach sands emanating from local, natural oil seeps in the Santa Barbara Channel. Presence of a persistent hydrocarbon horizon limits the vertical mobility of biota, and affects the transport of nutrients and oxygen through normally permeable beach sands.

The importance of beach variability in engineering studies is well-known. Seasonal and aseasonal beach changes can affect the lifetime of coastal structures, and the design of beach protection devices. Proper set-back requirements for near-shoreline development is dependent on long-term trends in coastal change as well as natural seasonal fluctuations in beach level. Finally, quantification of beach variability and its statistical relationship to driving forces can serve as useful input to nearshore sediment transport models, particularly as a test of variation in beach response as a function of different sediment types (grain size, sorting). Empirical guidance for modellers can also be provided through well-constructed statistical studies of driving force/beach response, when constructed using insight gleaned from dynamical considerations (e.g., Aubrey et al., 1980).

The basic problem addressed here is the quantification of seasonal and aseasonal patterns of beach change along coasts with different wave climates, and for beaches with different sediment characteristics. Rigorous statistical techniques for quantifying these changes must be developed to allow for meaningful comparison of beach response at different sites, providing a statistical basis for defining differences in beach behaviour. The ultimate goal is to develop a capability for predicting beach changes on many spatial and time scales, but this goal is to be achieved only with careful statistical methods combined with dynamical (both analytical and numerical) modelling.

Observation of changes in beach planform have been made for the past century, and relations between these beach changes and the driving forces postulated. For instance, Davies (1964) related beach characteristics to global patterns of waves (swell coasts, storm coasts, and protected coasts), using not direct measurement but compilations of winds and wave behaviour observed from ships and shore. Davies (1964) pointed out that the major drawback in obtaining statistical relationships between beach behaviour and driving forces is lack of knowledge of the driving forces, specifically wave activity. This is still true at the present, although progress has been made in the last couple of decades in measuring nearshore wave characteristics (e.g., Pawka et al., 1976; Seymour and Sessions, 1976; Thompson, 1977; Seymour, 1979).

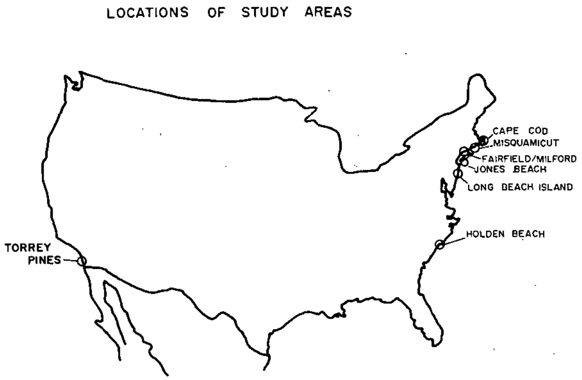
Beach profile monitoring programmes generally have had the following characteristics: limited duration of sampling; inadequate sample frequency; inadequate spatial coverage, particularly for beaches with much longshore variability; inadequate spatial density of sampling; and poor documentation of the driving forces. Analysis procedures for most of these studies have varied considerably, with little uniformity in treatment of the data. Consequently we are left with many observations of beach change, of highly variable quality, and no capability for readily comparing changes at one location with changes at another location. The resulting lack of comparison leaves us with a disturbing inability to synthesize these data into a meaningful set of observations, which might provide valuable insight into causes and patterns of beach variability.

Work reported in this paper represents an attempt to take data from different coasts of the United States, exposed to widely different wave climates, with different sediment types, and synthesize it in a rigorous fashion to allow quantitative intercomparison of magnitude of seasonal and aseasonal beach changes at these different locations. The work represents a plea for some uniformity in analyzing beach data to provide results useful to a variety of disciplines studying this active nearshore environment.

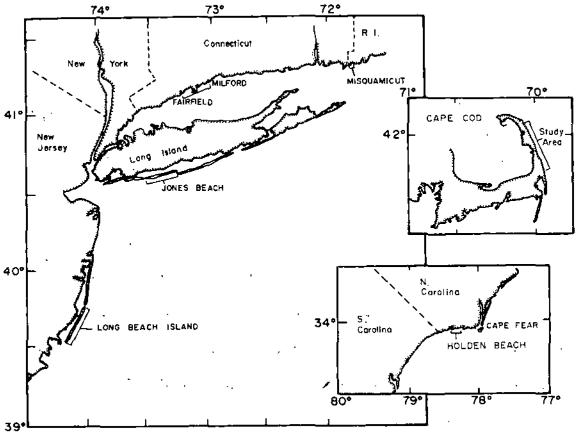
STUDY SITES

Seven locations were selected for this study (Fig. 2), six along the U.S. east coast (Fig. 3) and one on the U.S. west coast (Fig. 4). The beaches span a spectrum of grain sizes, and range from open ocean beaches, to those partly sheltered by offshore shoals and islands, to completely sheltered beaches. A brief description of each study site follows.

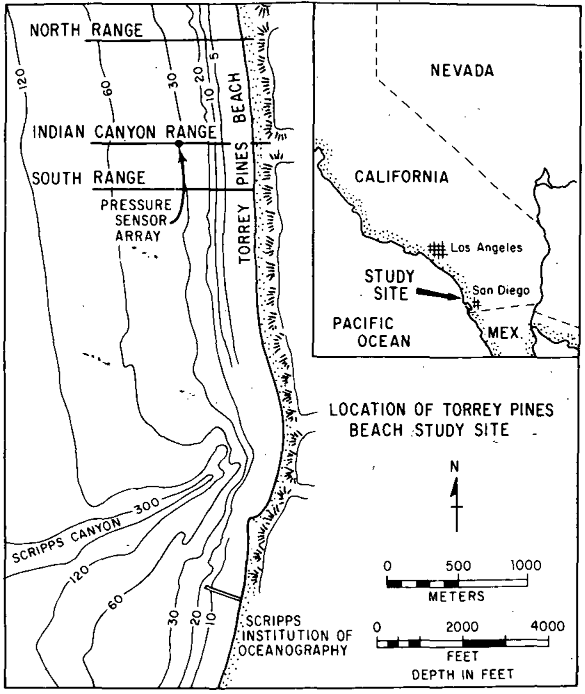
Torrey Pines, California: This southern California site (Fig. 4) is a long sandy beach, extending for more than 40 km with no man-made structures to impede longshore sand transport. The beach profile locations are backed by 100 m high sea cliffs, composed of



2) Location map for seven beach study sites distributed along the U.S. east coast (6) and the U.S. west coast (1).



3) Location map for six U.S. east coast study sites, showing beaches in relation to water bodies over which surface gravity waves are generated.



4) Location map for Torrey Pines, California, with profile line locations.

well-indurated deposits which add sediment to the nearshore zone upon collapse. Mean beach width varies from 40 m to 100 m, composed of sand with a median grain size of about 0.20 mm. Tide range is approximately 2.0 m on the average, and 2.5 during spring tides. The site was described in detail by Nordstrom and Inman (1975), Aubrey et al. (1976), and Aubrey et al. (1980).

The beach is exposed to a wave field which is partly sheltered by the islands offshore on the continental borderland (Pawka et al., 1976). The nearshore wave field is dominated by long-period swell from all offshore quadrants.

Holden Beach, North Carolina: Holden Beach is a 13 km-long barrier island located west of Point Fear along an east-west stretch of coastline (Fig. 3). It is bordered on the west by Shallotte Inlet, and on the east by Lockwoods Folly Inlet. Average beach width is about 250 metres, with the beach generally narrower near the ends of the barrier, broader near the centre. Beach material is a moderately well-sorted medium sand. Frying Pan Shoals, the southerly extension of Cape Fear, partly shelters Holden Beach from waves propagating from the east and southeast. These waves often break on Frying Pan Shoals, losing much of their energy, reducing the impact of northeasters which are so damaging to the remainder of the barrier beaches along the North Carolina shoreline. This site was described in detail by Miller (1982).

Long Beach Island, NJ: This site (Fig. 3) is a barrier island along the south shore of New Jersey, separating the Atlantic Ocean to the east from salt marshes to the west. The study area is bounded to the north by Barnegat Inlet, and to the south by Beach Haven Inlet, both active inlets. The island, with its east-southeast exposure, has a median sand diameter of 0.35 mm (Ramsey and Galvin, 1977), and stretches about 32 kilometres. Tides are semidiurnal with a spring/neap range of 1.5/0.9 metres. The beach itself is heavily structured, with 110 groins, 83 of which have been built or rebuilt over the period 1962-1975. The island is narrow (mean width of about 400-500 m), with a nearly continuous dune of height 5 to 8 m, MLW. Complex offshore topography (ridges and swales) imparts considerable alongshore variability to the wave field. Peahala Ridge is one ridge which is presently shore-attached. Except for the effect of the ridges and swales, Long Beach Island has an open exposure to Atlantic Ocean waves. Miller et al. (1980) describe the study site in more detail.

Jones Beach, Long Island, NY: Jones Beach is a 24-km long barrier beach separating the Atlantic from Great South Bay (Fig. 3). It is bounded on the east by Fire Island Inlet, and on the west by Jones Inlet. Mean beach width is approximately 150 m, with considerable variability (225 m near Jones Inlet jetty, to 35 metres on the eastern third of the study area). Beach sand is medium to fine grained. Tides are semidiurnal, with a mean range of 1.3 metres, and spring range of 1.5 metres. Offshore bathymetry is complicated by ridges and swales, which (unlike Long Beach Island, NJ) have no subaerial expression. No structures interrupt the longshore transport of sand, with the exception of the jetties protecting the entrances to Jones and Fire Island Inlets. The beach with its southerly exposure is not sheltered from Atlantic wave conditions. A more detailed description of the study site is available from Morton et al. (1982c).

Fairfield/Milford Beaches, CT: Both of these study sites are located along the northern shore of Long Island Sound, and are exposed to the locally-generated waves of the Sound (Fig. 3). Beach behaviour along Milford Beach is dominated by the impact of the Charles Island Bar, a submerged tombolo or bar. To the east, a sandy beach (Silver Beach) extends for about half a kilometre, with no structures in the surf zone, but backed by a seawall. Beach material ranges from sand through boulders. To the west of Charles Island Bar, a series of small beaches is disrupted by a number of shoreline structures, segmenting the beach. The beach is backed by a seawall here, also. Beach material ranges from medium sands to boulders. Fairfield Beach is located about 16 km west of Milford beaches, and stretches

1.8 km from Shoal Point to the entrance to Ash Creek. Along this length, there are no shoreline structures to interrupt longshore sand transport. Beach sand here is medium to coarse in texture.

Tidal range at both these locations, for spring/mean conditions, is 2.4 m/2.1 m. The site is described in greater detail in Morton et al. (1982b).

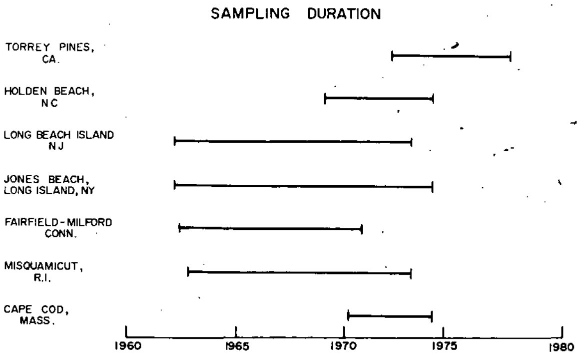
Misquamicut Beach, RI: Misquamicut Beach is a low-lying barrier beach located near the western limit of Rhode Island (Fig. 3). The beach, extending approximately 8.5 km from Watch Hill Point to Weekapaug Point on the east, is approximately 125 m in width, varying from about 100 m to 150 m. Beach material is composed primarily of fine-to-medium sands, interspersed with occasional areas of coarser sands and gravel. Offshore bathymetry is relatively complicated. Far offshore, a submarine ridge focuses waves propagating shoreward from the Atlantic. Nearer shore, a number of scales of bottom roughness are displayed which influence, and are in turn influenced by, nearshore waves. Tides in the area are semi-diurnal, with a spring/mean range variation of 0.96/0.78 m. Incident waves progagate shorewards from the southerly quadrant from the continental shelf, and are also locally generated within a restricted fetch to the western and eastern quadrants. The eastern part of the study area is bounded by a tidal inlet (structured). Other than this inlet, no significant shoreline structures inhibit the longshore exchange of sediment. This study site is described in more detail in Morton et al. (1982a).

Cape Cod, MA: The Cape Cod study area (Fig. 3) represents an eroding glacial feature, backed in the north by sea cliffs up to 30 m in height, and to the south by a marsh (the two southern-most lines are on a barrier beach). Beach material is composed of unconsolidated drift material derived from eroding sea cliffs. Grain size ranges from about 1.0 mm in the north, down to 0.25 mm in the south. No structures exist along the shore, so longshore exchange of material takes place unimpeded. Although the range varies a little along the study area, spring/mean ranges for this semi-diurnal tide are 2.5 m/2.0 m. The northern part of the study area commonly exhibits a longshore periodic shoreline feature, called a hooked bar by Aubrey (1980), with length scales of hundreds of metres. Migration of these shore-attached features can affect beach behaviour. The study area is completely exposed to open ocean waves progagating in from the Atlantic. This study area is described in more detail by Miller and Aubrey (1982).

Summary: These seven study sites represent a range of beach conditions and driving forces which can be expected to provide some insight into different modes and magnitude of beach change. In particular, these seven beaches have different grain sizes; they are exposed to varying wave climates, ranging from locally generated seas to distantly-generated swell conditions; they have variable degrees of structural development in the surf zone, ranging from highly developed along Long Beach Island, NJ, to completely undeveloped as in Torrey Pines, CA, and Cape Cod, MA; and they are exposed to different tidal regimes, with different tidal ranges (although all have semi-diurnal tides). This range of conditions makes a semi-quantitative comparison of beach changes a useful exercise, since this has not been done previously.

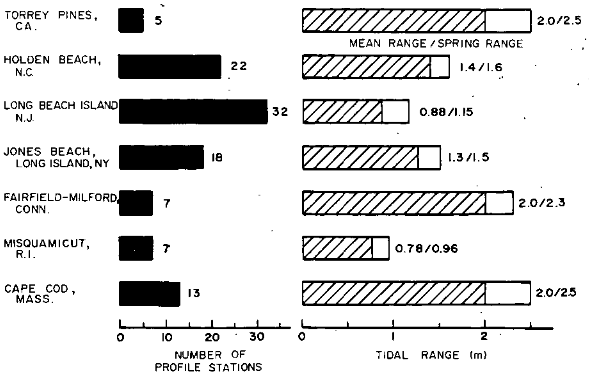
DATA SETS

Profiles of the beachface from the backshore out to approximately mean water level were made on each of these beaches for variable lengths of time (Fig. 5), and for a variable number of survey lines (Fig. 6). Consequently, the total number of beach profiles analyzed for each site is variable (Fig. 7), with a maximum of 2158 profiles analyzed from 32 lines on Long Beach Island, NJ, to a minimum of 378 profiles analyzed from 7 lines at Fairfield/Milford, CT. Duration of sampling ranged from about thirteen years at Long Beach Island (NJ), Jones Beach (Long Island, NY), and Misquamicut Beach (RI), to a short length of five years at Cape Cod (MA), with other sample lengths intermediate to these extremes.

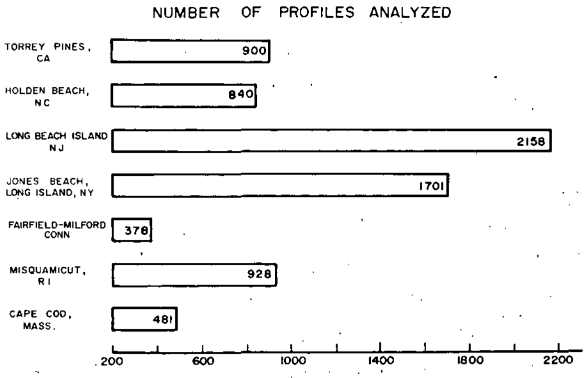


5) Duration of beach profile sampling at each of the seven study sites. Sampling was on approximately a monthly basis for most of the beaches.

All profiles examined were wading profiles, taken with engineer's level and survey rod, extending from an onshore benchmark along a profile line to the water line. The different data sets were obtained with different degrees of accuracy, reflecting in part climate extremes, wave activity, and vested interest of the survey parties. A more complete description of survey procedure can be found in Aubrey (1979). All survey notes were carefully



6) The number of survey lines (left) and approximate tidal range (right) for each of the seven survey locations making up this study. Lines were surveyed over the period shown in Fig. 11.



7) The number of beach profiles used in the analysis described in this study varied, ranging from a low of 378 at the Fairfield/Milford beaches, to a high of 2158 profiles on Long Beach Island, NJ.

checked for errors, both in the field and later in the laboratory, to assure high data standards. The data were checked as part of this study as well, to minimize outlying points of dubious validity. Profiles for all sites except Torrey Pines, CA, were obtained as part of the Beach Erosion Programme of the Coastal Engineering Research Center (USA Corps of Engineers). The Torrey Pines data set was collected initially under the aegis of CERC through Scripps Institution of Oceanography (D.L. Inman, principal investigator), and later funded through the Office of Naval Research. For all profiles, accurate benchmarks were established to provide both vertical and horizontal control for repeatability of surveys.

METHODOLOGY

Analysis of beach profile data sets in the past has taken a number of different forms, ranging from heuristic approaches to much more dynamical approaches. Common measures of net profile change which have been used are volume changes on the beach foreshore, migration of Mean Sea Level (MSL) intercept or other vertical datum, or beach stage models. Each of these techniques provides insight into the behaviour of beaches at a particular locality; however, comparison of beach change at different locations is difficult using these methods of analysis. Synthesis of changes at beaches with different characteristics exposed to different driving forces is difficult without some common analysis technique. This paper utilizes a method for quantifying beach change in a manner amenable to synthesis at a later time. Although the author feels this methodology is useful and provides insight into patterns of beach change, others may prefer alternate methods for intercomparison. One thrust of this paper is a plea to consider the need for later synthesis in any analysis scheme, so concepts of beach change can be determined not just for a single beach, but rather for many beaches.

The beach profiles are analyzed here by empirical eigenfunction analysis (also known as principal component analysis, empirical orthogonal function analysis, eigenanalysis, or factor analysis, a close relative). The empirical eigenfunction technique has been used by other investigators to determine the modes of variability of periodic beach profile measurements. The method can be useful in showing the spatial location at which the major amount of beach variability occurs along the profile line. Temporal eigenfunctions also show seasonal or other periodic trends in the data that may be less obvious from other methods of analysis. Properly used in conjunction with other, more conventional methods of analysis, the empirical eigenfunction technique provides a useful tool for understanding beach variability. Noble and Daniel (1977) provide a general explanation of the techniques. Specific applications to the coastal zone and beaches are provided by Winant, Inman, and Nordstrom (1975); Vincent, et al. (1976); Resio, et al. (1977); Aubrey (1978, 1979); and Bowman (1981).

The objective of eigenfunction analysis is to separate the temporal and spatial dependence of the data set so that it can be represented as a linear combination of corresponding functions of time and space:

$$h(x,t) = \sum_{k=1}^{n} c_k(t) e_k(x) \quad (\lambda_k n_x n_t)^{\frac{1}{2}} \qquad (1)$$

where

$h(x,t)$ = a profile sample at any point x and time t, n = the lesser of n_x and n_t (the number of points along each profile line and the number of times the profile was measured, respectively), $c_k(t)$ = temporal beach eigenfunctions, $e_k(x)$ = spatial beach eigenfunctions (BEF), λ_k = eigenvalues associated with each eigenfunction pair (c_k,e_k).

This representation helps identify processes responsible for profile changes, assists in evaluation of their relative importance, and aids the identification of specific events. The following properties of empirical eigenfunction make it a desirable tool for analysis of beach profile data (Aubrey, 1978):

(1) Empirical eigenfunctions provide the most efficient method of compressing the data; i.e., the most dense representation of a data set in the sense that the first n terms in the expansion represent more of the data variability than the first n terms of any other orthogonal expansion.

(2) Since both the spatial and temporal eigenfunctions are orthogonal sets, each corresponding set $(\lambda_k, e_k(x), c_k(t))$ may be regarded as representing a mode of variability which is uncorrelated with any other mode.

(3) The eigenfunction representation is convenient when using the method of minimum mean square error estimation. The eigenfunctions provide a useful _a priori_ method for reducing the number of variables in this estimation theory, and also provide a means of removing the noise (or less predictable part of the data) from the data set.

Empirical eigenfunctions, then, objectively represent the variation in the beach profile configuration in terms of distance from fixed data points, and in terms of temporal changes in the profile over the period of the study. Comparison of the variability of eigenfunctions from a series of profiles taken along the beach may show differences due to the presence of structures or change in shoreline orientation.

Since the empirical eigenfunctions form an orthogonal set, they are similar in some respects to the more familiar Fourier analysis. In Fourier analysis, a sinusoidal variation in the data set is assumed, and one best fits the data to a series of sines and cosines. This method assumes beforehand some given form for the orthogonal functions; in empirical eigenfunction analysis, the data themselves determine the form of orthogonal functions which are used in the analysis.

Applied to systematic measurements of beach elevation, the eigenfunction representation is a concise means of representing beach profile variability. The eigenfunction modes can be used to distinguish between variability on different time scales. Though a large number of eigenvalues are determined, Aubrey (1978) found that more than 99.75 per cent of the mean square value of his data set could be accounted for by the three eigenfunctions associated with the three largest eigenvalues. The second through fourth eigenvalues accounted for approximately 90 per cent of the variability in 4-year data sets of beach profiles in southern California. This concise representation of beach profile variability is desirable when trying to compare different locations, especially for data sets spanning long periods of time.

In the empirical eigenfunction technique, eigenvalues, λ_k, provide information on weights of the eigenfunctions. Each eigenvalue gives the mean square value of the data (the variance if the mean has been removed) accounted for by the eigenfunctions. This provides a convenient means for ranking eigenfunctions and assessing the importance of each. This also provides a convenient means of removing noise from the data, if it is assumed that a function accounting for only a small part of the mean square value of the data is not an important variable in the data. Eigenfunctions whose eigenvalues are below a certain value can be neglected in estimation problems. These screening techniques are discussed in detail by Preisendorfer et al. (1981).

Since some of the data considered in this study is non-uniformly sampled in both space and time, consideration must be given to the utility of this somewhat complex analysis technique for this data. The primary information derived from the profiles in this study is magnitude of beach variability, and seasonality of that variability. This information will not be as readily interpretable for a non-uniformly sampled profile sequence as for a uniformly sampled beach. However, if the frequency of sampling is high compared to the time scales examined, and the beach is observed for a long period of time, then the statistics derived from eigenfunction analysis will approach those derived from uniform sampling. In order to illustrate this conclusion, a beach with five years of relatively uniform and high-frequency sampling (Torrey Pines, CA) was artificially resampled at irregular intervals for the same period, and eigenanalysis results intercompared. The magnitude of beach variability (normalized as described below) was within 10% for the uniformly sampled and non-uniformly sampled cases, even when large seasonal sampling discrepancies were artificially induced. Seasonal beach signals likewise were apparent in both cases, with a clear seasonal signature dominating for the non-uniform sampling as well. This numerical exercise illustrates the attraction of using eigenanalysis for beach profile data, even for non-uniform sampling. Certain degrees of non-uniformity in sampling are not going to conform to this rule; clearly each season must be represented in the sampling, and sample intervals must not exceed one or two months, on the average, if seasonal information is derived. If the beach is undersampled, aliasing can be a major problem.

Eigenanalysis determines vectors such that the maximum variance of observed variables is described (as opposed to factor analysis, which optimizes the intercorrelations of all variables, yielding a correlation-weighted analysis instead of a variance-weighted analysis; see for example Joreskog et al., 1976). Since we are interested in describing beach variability, eigenanalysis is an obvious choice. As defined in the equation 1, we have represented the data by a complete set of orthonormal functions (λ_k, c_k, e_k). The mean square value of the data is given as:

$$\mathrm{MSV} = \sum_{k=1}^{n} \lambda_k \qquad (2)$$

where the mean is taken in both space and time, because of normalization by n_x and n_t in the governing equation. These eigenfunctions are referred to as 'mean eigenfunctions,' since they retain information about the mean state of the beach. For each profile line, the arithmetic time mean can be calculated, and subtracted from the data prior to analysis, yielding a new data set h'(x,t), as follows:

$$h'(x,t) = h(x,t) - \bar{h}(x) \qquad (3)$$

where h represents the mean (in time) value of the elevation at a point x. The eigenvectors of covariance matrices formed from h'(x,t) are termed 'de-meaned' eigenvectors. In this case, the sum of the eigenvalues represents the variance of the data set, instead of the mean square value:

$$\sigma_1^2 = \sum_{k=1}^{m} \lambda_k \qquad (4)$$

This variance estimate provides information on the variability in the data per spatial sampling point and per time sample. This type of normalization is not always amenable to comparison of one beach with another beach which has been sampled differently (in space and/or through time). Because of the normalization, and desire to compare results regardless of sampling strategy, a correction has been introduced into the analysis. The active beach correction is a factor multiplying the variance, σ^2 to adjust the results so they reflect only variance along the active part of the beach. If a long segment of a beach profile comprises inactive parts of the backshore, the variance as defined in equation (4) would be artificially low. The empirical correction for active beach width minimizes this problem:

$$\sigma_1^2 = \sigma_1^2 \cdot W \qquad (5)$$

where W = total length of profile/total length of active beach. The new variance provides a more consistent basis for comparison, even though it involves some definition or assessment of the active beach. For our work, this definition has been based on the degree of variability of the beach at any point along it. After eigenfunctions have been derived for a given beach, the first few are summed as in (1) (to account for a large fraction of the beach variability), and the weighting for all points along the beach profile compared. The segment defining the active beach is selected as that portion of the profile which excludes those points accounting for less than some fraction of the total variability along the profile. In applying this correction, we have taken care not to include backshore areas with dunes or seacliffs, since this section of the beach responds to different forcing than the foreshore. This was necessary, in particular, along the Cape Cod (MA) profiles.

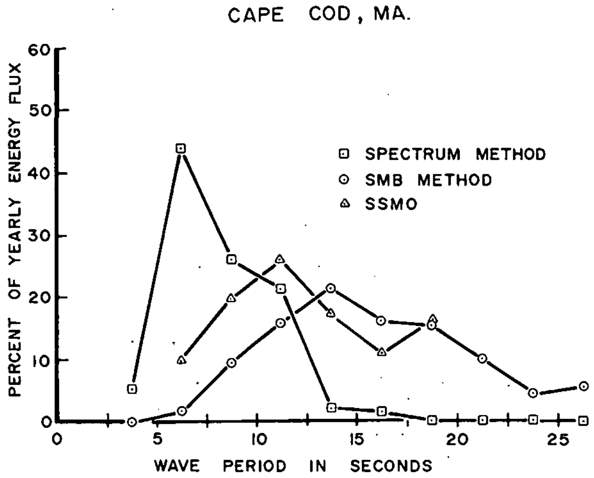
RESULTS

Four aspects of beaches and incident driving forces were examined in this study. For each location, a wave climate was formulated from existing data; these wave climates vary from quantitative at Torrey Pines (CA) to highly qualitative at Fairfield/Milford (CT) beaches. The magnitude of beach variability for each site was quantified. The degree of seasonality of beach variability was examined. Finally, as an example of the utility of the method, the effects of grain size on beach variability were quantified for the Cape Cod (MA) site.

WAVE CLIMATE

Documentation of the driving forces is an essential, but difficult, aspect of formulating models of beach variability, and in verifying or testing these models. In situ measurements of wave behaviour is the best way to document wave climate at this time, although numerical models of wave growth, propagation, and shoaling show much promise for the future. Even then, local measurements can provide information on the complete spectrum of the wave climate, whereas not all numerical models can handle spectral growth and decay. Alternative techniques for establishing a wave climate include hindcasting techniques (primarily using SMB techniques and the spectrum method), visual wave observations from shore, and ship observations (primarily the Summary of Synoptic Meteorological Observations--SSMO). All techniques have their limitations and biases which make it difficult to intercompare results from different beaches whose wave behaviour has been derived from different techniques.

As an example of the lack of agreement between these different techniques, a comparison was made for Cape Cod (MA) beaches using the SMB hindcast technique, the wave spectrum method, and compiling the SSMO data for the Boston region (Fig. 8). The results indicate that the three techniques yield wave climates which are about as different as reasonably can be expected for the open ocean. The spectrum method yields a modal period of about 5 seconds, the SSMO yields a modal period of about 11 seconds, while the SMB technique yields a peak of about 12.5 seconds. These results could certainly be improved by using more up-to-date hindcasting techniques, but the results indicate the disparity in wave climates obtained from different approaches. Consequently, the comparison of wave climates here can only be qualitative with no hope at this time for quantitative intercomparisons. For the following discussion, more detail on the wave climate can be found in the studies of each site referenced earlier.

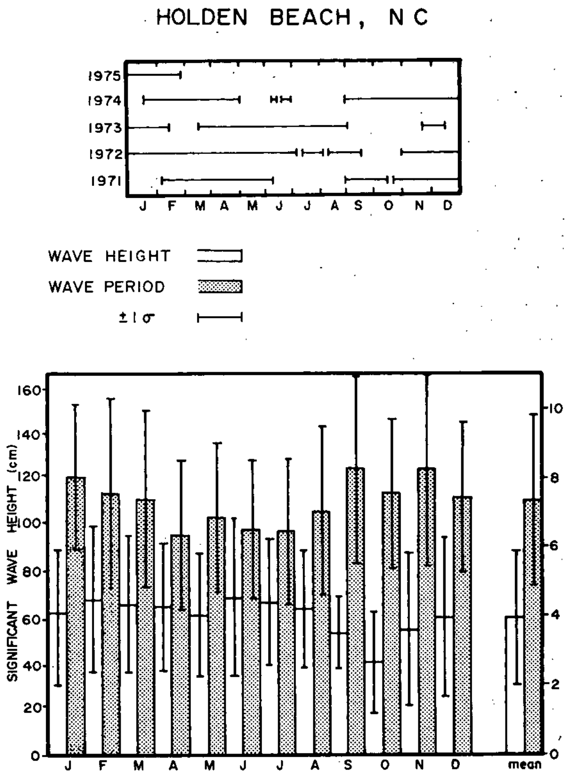


8) A graphic comparison of a nearshore wave climate as determined from three commonly used sources for wave data. The spectrum method and SMB method are both hindcasts, derived with the same basic meteorological data set. The SSMO (Summary of Synoptic Meteorological Observations) data are shipboard observations. The three wave climates differ markedly, covering the expected variability in wave climates along any open coast location. This type of uncertainty in nearshore wave climate emphasizes the need for either careful in situ measurements, or rigorously tested numerical wave hindcasting programs.

Torrey Pines, CA: This location has the best-documented wave climate due to work performed at the Scripps Institution of Oceanography. A linear, multi-sensor array of pressure gauges was deployed off the beach for a period of about five years (Pawka et al., 1976; Aubrey, 1979). Four-times daily measurements of directional wave characteristics have documented the wave climate to a high degree. This information was used in previous studies to relate beach changes to driving forces (e.g., Aubrey et al., 1980).

The wave measurements show the southern California region to be swell-dominated throughout the year. Locally-generated, higher frequency waves are more common in the winter than summer, as local storms pass through. The major difference between summer and winter conditions is in the wave energy, rather than in the period. This in turn affects the wave steepness, an indicator of beach erosion and accretion, according to some studies.

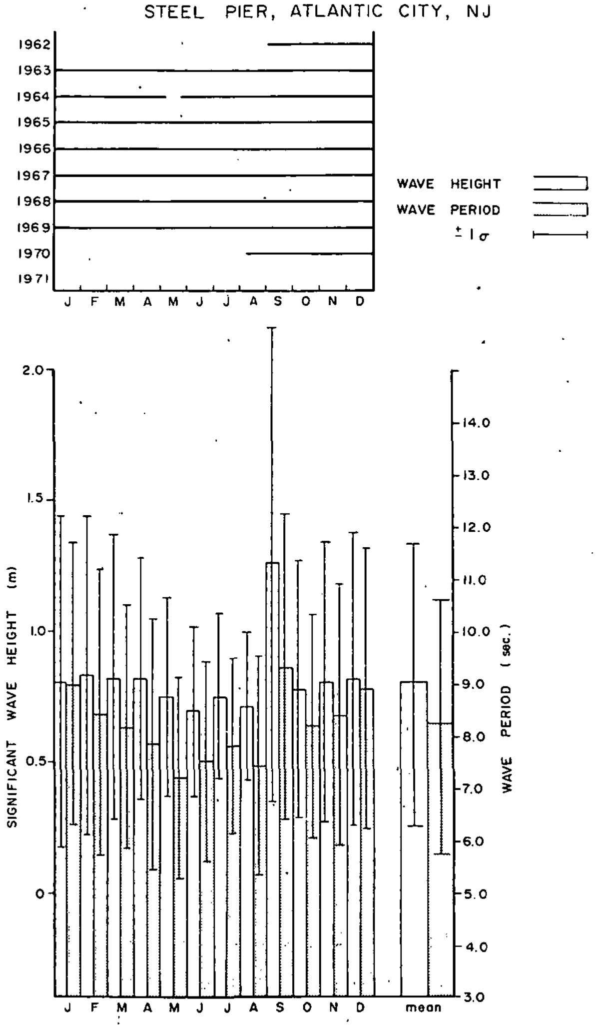
Holden Beach, NC: Wave climate from Holden Beach was established from direct measurements made along a fishing pier along Holden Beach (Thompson, 1977) and from Littoral Environmental Observations (LEO) consisting of visual observations (Miller, 1982). The continuous-wire staff measurements were made from February 1971 through February 1975 (with some periods of inactivity), with 1024 second measurements taken every 4 hours (Fig. 9). The data show a seasonality in wave period (averaged over monthly intervals), with a lower period generally from April through August. Wave height shows less of a seasonal periodicity. As mentioned earlier, the wave field nearshore at Holden Beach is significantly affected by Frying Pan Shoals to the east, so the nearshore wave climate is not directly reflecting the offshore wave climate. Mean yearly significant wave height is about 0.6 m, mean yearly period is about 7.5 seconds. LEO observations provide no additional information than the wave staff measurements, other than some indication of direction of wave approach.



9) Wave climate at Holden Beach, North Carolina, derived from CERC pressure sensor located off a pier along Holden Beach (see Fig. 5). Summary is given in terms of monthly averages of wave period and wave height. Source for data is Thompson (1977).

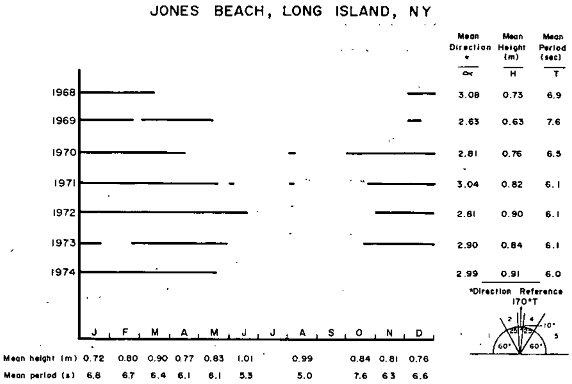
Long Beach Island, NJ: Wave information available for this study site include a nearby (35 km to the south) wave staff located on a pier in Atlantic City, SSMO data, and local visual beach observations from 1968-1974. For the forty-one month period from April 1964 through December 1967, mean significant wave height is 0.81 m, and mean wave period is 8.2 seconds (Fig. 10). Since the Steel Pier gauge at Atlantic City did not have directional capabilities, the only directional information available nearshore are the beach observations, which have coarse directional resolution.

Jones Beach, Long Island, NY: Wave information for Jones Beach is compiled from a variety of diverse sources. Hindcast data are presented in Panuzio (1968), as are results from occasional wave gauging from 1950-1954 off Fire Island Inlet. Results from the wave gauging yield an average height of 0.4 m for the period of measurement, which was neither continuous nor representative of the entire year. A surf observation programme from 1954-1957 yielded a probability distribution for breaking waves in the area (Short Beach Lifeboat Station), indicating waves generally less than 1.25 metres. A CERC wave gauge located at Steel Pier, Atlantic City, New Jersey, was discussed in the previous section; it is the closest CERC gaging location to Jones Beach. Results from that gage may not be representative, because it is located 160 km to the south of Jones Beach. Beach Erosion Programme surf observations were made along the beach from 1968 to 1974 along Jones Beach. Although poorly sampled through the year (July through September show almost no observations), they provide an indication of surf activity. The mean wave period was 6.5 seconds, and mean significant wave height was 0.8 m, with some variation in these numbers month-by-month (Fig. 11). Waves generally approach the beach from the southeast.



10) Wave climate at Atlantic City, New Jersey, derived from a CERC wave staff located off Steel Pier, in Atlantic City (south of Long Beach Island). Summary is given in terms of monthly averages of wave period and wave height. Source for data is Thompson (1977).

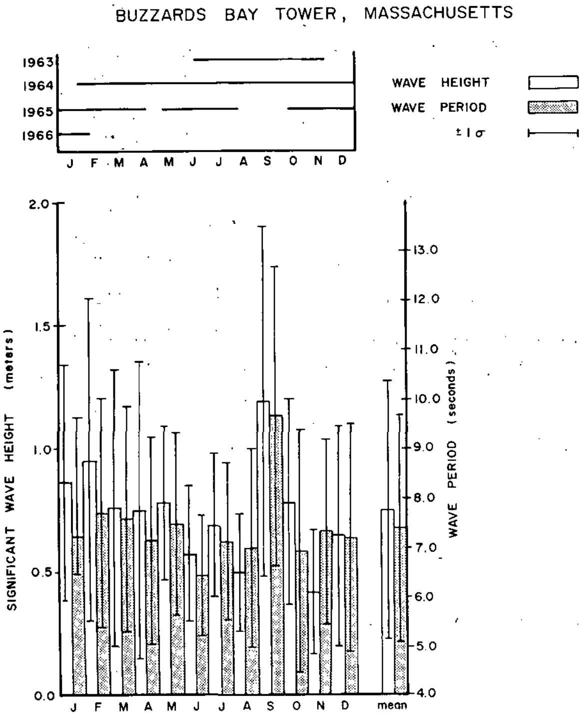
Fairfield/Milford Beaches, CT: There is no quantitative information about the wave field off Fairfield/Milford Beaches. Visual wave observations are not available, and there have been no long-term pressure sensor deployments within the western part of Long Island Sound. Waves incident on these beaches are all locally generated, with energetic periods limited to about six seconds or less. Because of a restricted fetch, wave height is similarly limited. This area, then, is dominated by locally generated high-frequency wind waves, which are significantly modified by offshore bathymetry and shoreline irregularities (such as Charles Island Bar).



11) Wave climate for Jones Beach, Long Island, New York. Source for data are Beach Erosion Program Visual Wave Observations from 1968-1974. Both yearly mean height and period are given, as well as monthly means. Coverage of the time period is shown in main graph, illustrating lack of observations during the summers.

Misquamicut Beach, RI: Wave information consists of visual observations taken as part of the BEP programme, pressure sensor measurements taken at nearby Charlestown Inlet by Raytheon Corporation, and CERC pressure gauge measurements made at Buzzards Bay Tower close to the study site. The Raytheon data, collected over a one-year period, were not available for detailed analysis; only a summary of results could be found. The summary indicates that over the period of study, wave height was less than 1.5 m 98% of the time (in 8 m water depth). Ninety-two per cent of the time significant wave height was less than one metre (Raytheon Corporation, 1975). Visual observations were taken from January 1968 through December 1975, with an average of 22 visual observations per month. Yearly mean breaker height was approximately 0.5 metres, with a mean period of 8.6 seconds. Mean wave direction was just east of south. CERC measurements were made from 23 January 1964 through 18 April 1975 by pressure gauge. Mean annual significant wave height (in 19.2 m water depth) was 0.75 m, with a mean period of about 7 seconds (Fig. 12).

Cape Cod, MA: Wave data for this section of shoreline consist of two hindcast techniques, SSMO visual wave observations, and in-situ gauging. The first three of these have already been discussed in a previous section (Fig. 8). LEO data, taken in the format described by Balsillie (1975), were taken near the northern and southern limits of the study area. These were not used to compile mean periods and heights. The gauging data consists of some pressure sensor data obtained off the south end of the study area by CERC, but the results are not generally available, and so were not used in this study. The final set of observations consist of directional wave estimates made by the author from 1980 to present, using a two-axis electromagnetic current sensor with a pressure gauge (Aubrey, 1980). Although the data from this study have not been compiled in a manner similar to other locations, mean wave periods range from about 8 to 14 seconds, with wave heights generally

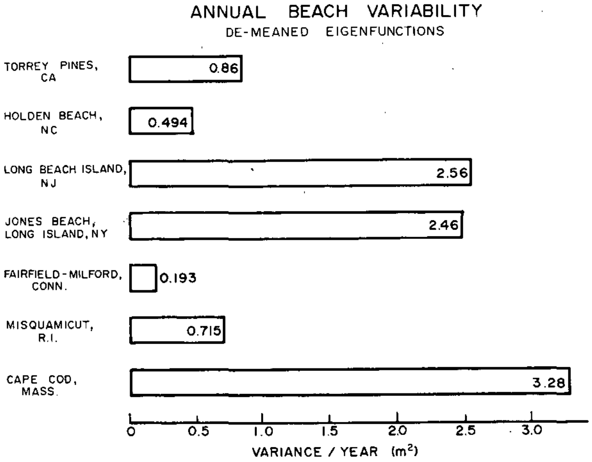


12) Wave climate at Buzzards Bay Tower, Massachusetts, derived from a CERC pressure sensor located in 63 m water depth in the middle of Buzzards Bay. Summary is given in terms of monthly averages of wave period and wave height. Source for data is Thompson (1977).

of the order of 1 m. The statistics for waves at this location are currently being generated. This study area has the most energetic wave climate of the seven sites examined.

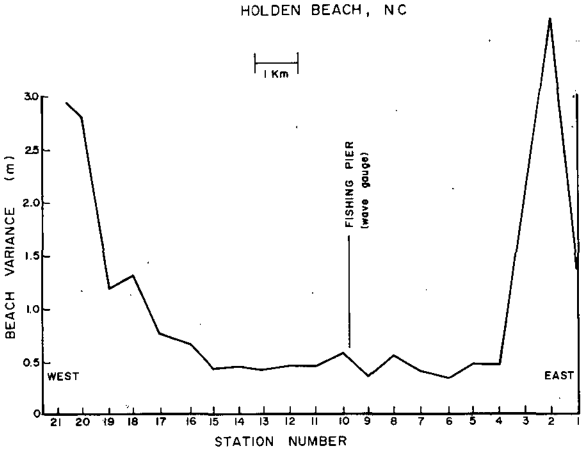
BEACH VARIABILITY

Using the profiles from each of the study areas, eigenfunctions were calculated after removing the mean profile from each profile (yielding de-meaned eigenfunctions). The sum of the eigenvalues for each profile line was determined, to represent the variability in the data. This value was then normalized to account for the active beach, and to obtain an annual beach variability. Results for each profile line at each of the seven sites were then averaged to obtain a mean variability for each site (Fig. 13). The three open ocean beaches showed the greatest variability (Cape Cod, MA, Long Beach Island, NJ, and Jones Beach, NY), with an average annual variability of 2.76 m^2. The two most closely located beaches, Long Beach Island and Jones Beach, which are separated by only 100 km, have variances of 2.56 and 2.46 m^2, respectively, within 4% of each other, as one might expect, given similar grain sizes and similar wave climates. Torrey Pines (CA) and Misquamicut Beach (RI) have lower variances by a factor of four, and represent partially sheltered coastal reaches. Smallest variance is at Fairfield/Milford Beaches, which are completely sheltered from open ocean wave conditions, and exposed only to locally generated seas.



13) Beach variability at each of the seven study sites, where the variability is normalized as in equation 5.

Analysis of beach variance can provide insight into beach processes on a more local scale as well. Two examples are given here. Holden Beach (NC) is a continuous barrier island, bounded to the west by Shallotte Inlet, and to the east by Lockwoods Folly Inlet. Along this beach are distributed 21 profile lines, with line one to the east, and line 21 to the west. Beach variability shows a strong longshore trend (Fig. 14), with the greatest variance along profile lines 1-3 and 18-21, which are all within 2.5 km of the two bounding inlets. This greater beach variability is not related to grain size, or to longshore wave variability (according to wave refraction analysis discussed in Miller, 1982), except that scattering behaviour associated with the ebb tide deltas of the inlets. The variability is probably due to inlet processes, including ebb delta influence on wave refraction, sand bypassing across inlets (a periodic event for some types of bypassing), dredging and dredge spoil disposal. Beach variability along the remainder of the barrier island is fairly constant, reflecting roughly uniform distribution of driving forces alongshore.

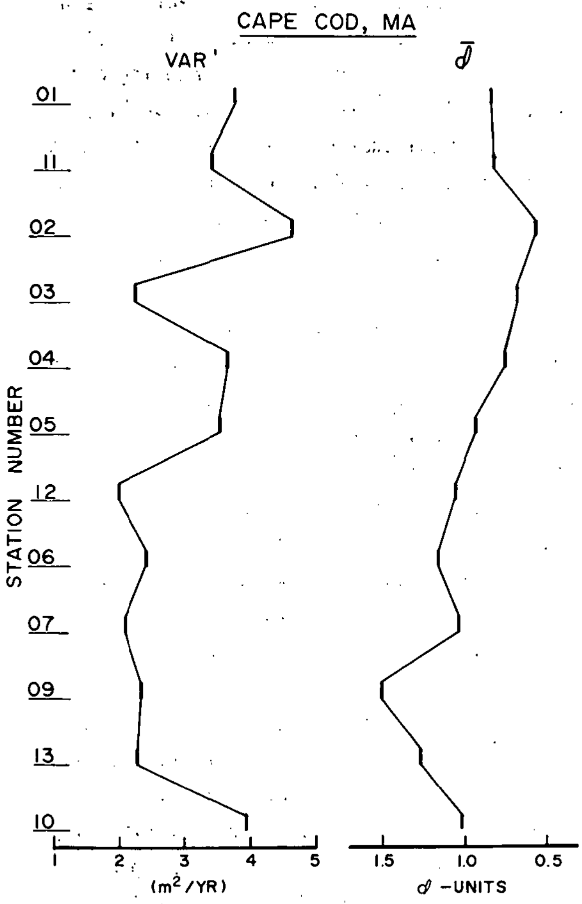


14) Beach variability as defined by equation 5, along the barrier island of Holden Beach. Variability is much higher near the active inlets of both ends of the barrier, reflecting inlet processes (including sand bypassing, dredging/ spoil disposal, and wave/current interactions).

The second example is from Cape Cod (MA), which has an alongshore gradient in median grain size, decreasing in size from north to south (Fig. 15). Beach variability also has a north-south gradient, with greater variance in the north than in the south, mirroring the grain size trend. Wave refractionperformed along Cape Cod show no systematic longshore variation in energy or energy flux (Isaji et al., 1976), suggesting that a variable driving force is not responsible for this trend in beach variability. Tidal range shows a very slight longshore gradient, but incomplete data does not allow us to rigorously assess its control over beach variability. The influence of grain size on beach variability has been suggested before; this example shows the importance of including this parameter in modelling studies.

SEASONAL BEACH VARIABILITY

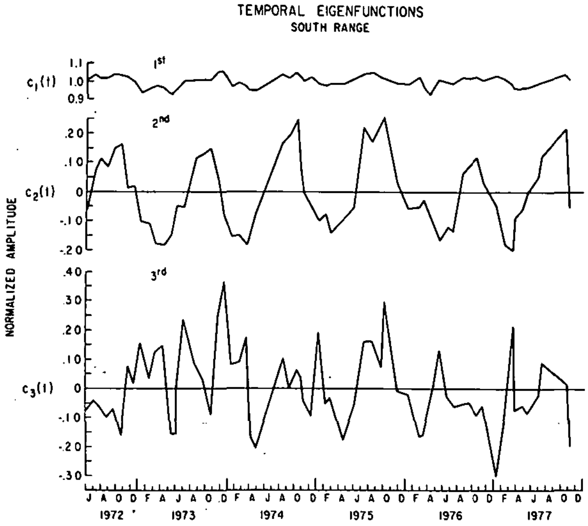
A certain portion of the annual beach variability can be attributed to a seasonal cycle in beach change. This seasonality has long been recognized for U.S. west coast beaches (e.g., Shepard, 1950), but has been a matter of debate along the U.S. east coast, although investigators have shown some seasonality to exist (e.g., Everts and Czerniak, 1977; Goldsmith, Farrell, and Goldsmith, 1974; Dewall, 1977 and 1979; and Everts et al., 1980). Eigenfunctions will show seasonal trends if they are energetic enough, so eigenanalysis has also used to document seasonality of beach response (Aubrey, 1979). Computer simulations of the



15) Beach variability along Cape Cod beaches as a function of grain size. Independent studies show the wave climate is consistent along this length of beach, so grain size appears to be a dominant factor in explaining the increasing beach variability to the north.

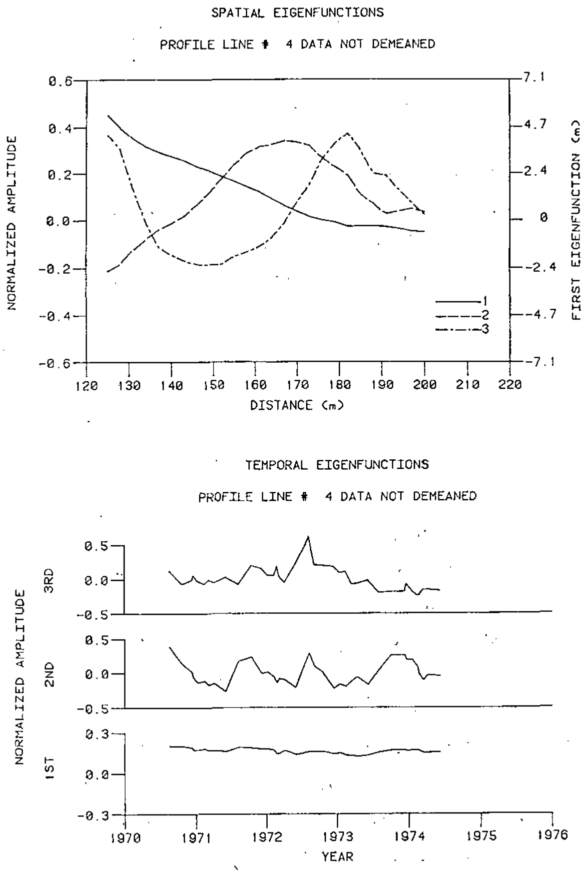
sensitivity of eigenanalysis to noise level is described briefly in Aubrey (1978).

Strong seasonal signals are found in temporal eigenfunctions from Torrey Pines (CA) and Cape Cod (MA) (Figs. 16 and 17). Seasonality was found over some profile lines along the remainder of the beaches, with the exception of Fairfield/Milford beaches where there is an almost total absence of seasonal signature. Weak seasonality can be due to a number of factors, some of which are related to the physical regime, some of which are due to inadequate sampling. Structures, such as groins and jetties, can affect the response of a beach to seasonality in wave climate. This is likely a contributing factor in the Long Beach Island (NJ) case. Offshore bathymetry may also limit seasonal response; this is a contributing factor to Holden Beach, where Frying Pan Shoals severely modifies the incident wave climate. Seasonality is also absent where the wave climate is not seasonal or only weakly so; this is the case in restricted fetch regions such as Fairfield/Milford Beaches.



16) Temporal beach eigenfunctions for Torrey Pines Beach, California. Second beach eigenfunction shows distinct seasonal trend, and accounts for nearly 80% of the variability in the data set.

Poor sampling can also affect the seasonal beach signature. The six U.S. east coast beaches have a peculiar characteristic of poor sampling in the summer months, particularly July. This type of undersampling in the summer can lead to poor definition of seasonal cycles.



17) Seasonal beach changes along Cape Cod, Massachusetts, beaches. The second temporal eigenfunction displays the seasonal response to a seasonal wave climate. It accounts for approximately 75% of beach variability.

DISCUSSION

The results point out a close relationship between the rigorously defined beach variability and the poorly defined wave climate. Exposed open ocean beaches have the highest beach variability and the most energetic wave climate. Cape Cod has both the high incident wave energy and highest beach variability. Long Beach Island and Jones Beach have the next most energetic wave climate and beach variability, with their beach variabilities within 4% of each other. This similarity in beach response is encouraging, since the two sites are exposed to nearly the same wave climate. Torrey Pines Beach is the next most exposed location, with the next highest wave climate, followed closely by Misquamicut Beach. These two have similar beach variabilities, but are a factor of four less than the variability at the more open coast beaches. Holden Beach is sheltered in large part by Frying Pan Shoals to the east, so its wave climate is much less than that along the open ocean beaches close by. Its variability is consequently much lower than that at more energetic beaches. The most sheltered of all beaches, with the lowest wave energy, is the Fairfield/Milford area, exposed only to locally generated wind waves. Its beach variability is an order of magnitude lower than that at open coast beaches, and a factor of four lower than the partly sheltered Torrey Pines and Misquamicut Beach areas.

The relationship between beach variability and energy has been shown before by Aubrey et al. (1980) for a single beach. It has also been discussed elsewhere for specific beaches, but not quantitatively compared at different sites. The unfortunate fact remains that the wave climate at most coastal sites is so poorly known that even an empirical relationship between wave climate (suitably represented by wave eigenfunctions, for instance) and beach change cannot be made at this time. The wave hindcast models now in existence may give us better data sets in the near future so we can improve on the qualitative statements made in this paper (specifically the WES model should be available in the time span of a year or so, providing us with data coincident with the profiling efforts).

Seasonal beach changes, which respond to seasonal patterns in the driving forces, have been documented before in many places. This study shows most beaches have a seasonal signature unless prevented by one of several factors. The fetch and/or exposure of a beach site may be such that the seasonality in weather patterns may not be reflected in the wave climate. Examples are Fairfield/Milford Beaches where the restricted fetch limits the size of waves and hence the seasonal differences in wave characteristics. An example of exposure limiting wave seasonality is Holden Beach (NC), where Frying Pan Shoals limits the size of waves reaching the barrier island. Large waves will break one or more times on the shoal, limiting the energy reaching the shore during large northeast storms which inflict much of the beach erosion on the more exposed shoreline bounding the study site to the north.

Eigenfunction analysis has graphically shown two beach relationships which might not otherwise be apparent during routine analysis of profile data. At Holden Beach (NC), beach variability is greater near the inlets bounding the barrier island, than near the middle of the island. Magnitude of beach variability near the centre of island probably represents the part of the beach variability driven by the incident wave field, while the outer parts of the barrier are more affected by inlet behaviour. Examples of inlet influence include modification of the nearshore wave field because of wave refraction around the ebb tide delta (due both to bottom topography and wave-current interactions--steepening and breaking), longshore sand bypassing episodes along the ebb tide delta imparting large signatures to beach change, and dredging/spoil disposal near the inlet channels. This type of longshore dependence of beach variance may be reflected in the biological communities inhabiting these different areas, although these effects may be difficult to see in light of expected differences in response to different physical and chemical conditions due to inlet proximity.

Another observation clarified by eigenanalysis is the coincidence of beach variability on grain size, the example here being Cape Cod beaches. Grain size decrease from north to south is mirrored by decreasing beach variability from north to south, despite no apparent longshore gradients in energy flux incident on the beach. Grain size responds to source proximity and longshore sorting of material; this difference in grain size is reflected in markedly different beach slopes alongshore. The reason for the higher beach variability in coarser grained beaches is not apparent at this time. Possibilities include the influence of greater pore space in coarser material, increasing permeability, and transmitting greater fluid pressure to each grain of sand. This would allow the sand to respond much more quickly to wave activity than a less permeable sand. This effect has not been quantified.

CONCLUSIONS

Eigenanalysis has quantified relationships between beach change and driving forces along seven beaches with markedly different wave climates, spanning a variety of grain sizes degree of and structural shoreline modification. Neglecting long-term beach trends, open coast beaches have the greatest variability on an annual basis, while partially sheltered coasts are lower in variability by about a factor of four. Beaches nearly completely sheltered from open ocean wave conditions (restricted to short, local fetches) have the least variability, down by an order of magnitude from open ocean beaches. A gradation from open coast to completely sheltered beaches exist, only a sample of which were analyzed in this study. Sheltering can result from offshore islands (Torrey Pines, CA), convoluted shorelines (Misquamicut Beach, RI), or unusual bathymetry (Holden Beach, NC) such as shoals. Although the relationship between wave exposure and beach change is qualitative, improvement in predictive capability can be expected once improved wave hindcasting procedures provide us with realistic nearshore wave climates for the periods coincident with the beach studies. Although the profile data examined in this study was of variable quality (in terms of both spatial and temporal uniformity), the major inadequacy of the data set was in the knowledge of wave climate, which varied from well-known (Torrey Pines, CA) to poorly known (Fairfield/Milford Beaches, CT).

Beach variability found in this study is not easily expressed in terms of a single morphological model (such as Short and Wright, 1983), because this study addresses only total variability, not cross-shore spatial structure. These profile shape factors are discussed in a paper presently in preparation.

Patterns of beach variability along a single beach provide insight into some relationships which need to be explained in more dynamical terms. Along a barrier island bounded by two tidal inlets (Holden Beach, NC), annual beach variability was greater within 2.5 km of the inlets than in the middle of the barrier. This pattern reflects the influence of the inlet on beach processes, particularly through modification of the incident wave field, sand bypassing episodes, and dredging/spoil disposal operations. Beach variability along the middle of the barrier island was nearly constant, suggesting that this segment was undisturbed by inlet behaviour.

Along a beach with a sharp longshore gradient in mean grain size (Cape Cod, MA), the magnitude of beach variability increased with increasing grain size, even though the wave climate showed no correlative pattern. This data set suggests the possibility of testing more dynamical models of beach change as a function of grain size.

Eigenanalysis has proved to be a useful tool in synthesizing beach profile data from a number of different locations, exposed to different forcing conditions, and sampled with highly variable uniformity. The technique allows some quantitative comparison between beach behaviour at different locations, which has not been commonly done in the past. Whether or not this particular analysis is adopted as a routine procedure for examining beach profile data, scientists and engineers must consider how best to intercompare results from one beach with results from another beach, rather than concentrate on a single data set. Insight into dynamics of beach change, and guidance to much needed modelling of the process, will occur only when we can synthesize existing data, and analyze future data in a manner consistent with the need for intercomparison.

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