The previously discussed characteristics of rhythmicity at the study site suggest that a still more realistic hypothetical set of circumstances would include longshore migration, or phase shifting, of the sinusoidal contours. Three cases will be explored using random phase variations within 90, 180, and 360 degree (1/4, 1/2, and full wavelength, respectively) envelopes. One-hundred synthetic contour lines were generated in each case. No on/offshore migration of the beach is included in the analyses discussed here; inclusion of this signal does not alter the basic results.

The mean contour and the first and second eigenvectors calculated by the EOF analyses for the 90 degree, 180 degree, and 360 degree phase variation cases are shown in Figures 3a, b, and c, respectively. Any apparent distortion of the mean contour from a perfect sinusoid occurs because the wavelength is not an even multiple of the spacing between variables (beach profiles). It can be noted that the amplitude of the mean decreases with increasing phase shift envelope. Eigenvectors 1 and 2 are sinusoidal and exactly 90 degrees out of phase in all instances. They are also out of phase with the mean by approximately 25 and 205 degrees. This phase offset from the mean accounts for the longshore phase shifting in the data. As phase variation in the data increase, the second vector becomes increasingly important. The 90, 180, and 360 degree phase envelope examples, respectively, have eigenvector 2 to eigenvector 1 ratios, of percents of variance accounted for, of approximately 0.07, 0.14, and 0.06. With longshore migration of a rhythmic shoreline, factor scores still indicate 'how much' of a vector must be added to the mean to regain the original data. However, they now include the longshore location of rhythmic features relative to the mean. When analyzing real data, the meaning of the vector weights must be evaluated subjectively, based on the shapes of the mean and dominant eigenvectors, and the phase relations between them.

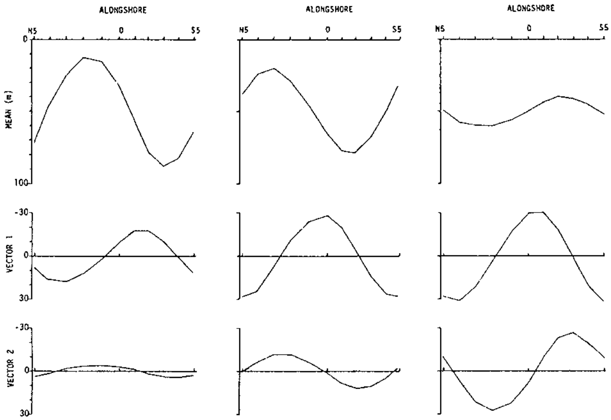

Figure 3. Mean contours and first and second eigenvectors for data depicting a longshore rhythmic pattern with amplitude variations, and a) 90° envelope phase shifting; b) 180° envelope phase shifting, c) 360° envelope phase shifting.

Finally, the influence of noise in the data was investigated. For the case of a matrix consisting solely of random noise, the mean contour is a straight line. EOF analysis produces the same number of eigenvectors as there are variables, all accounting for approximately equal amounts of variance. The vectors themselves are irregular when plotted. In an effort to determine how much noise could be present in a matrix based on a longshore rhythmic beach system and still yield interpretable results, many analyses were run on matrices similar to those just discussed, but including amplitude variations, on/offshore variations in beach position, and varying amounts of noise. It was determined that noise can hinder interpretations of the mean and eigenvectors when it is of the same order of magnitude, or larger than the amplitude of the rhythmic signal. In general, this condition can be identified by the need for more than two or three eigenvectors to account for more than 90% of the variance.

EOF Analysis of the Field Data

For analysis of the Siletz Spit topographic data, EOF analysis was run for seven different elevation contours spaced 0.5 m apart. Plots of the means and eigenvectors are shown in Figure 4. All mean contours appear rhythmic with approximately the same lengthscale of 800-850 m. For higher elevation contours, those nearest the dunes, the first eigenvectors show lower amplitude rhythmicity and account for less of the total variance in their matrices than do the first eigenvectors for contors further offshore.

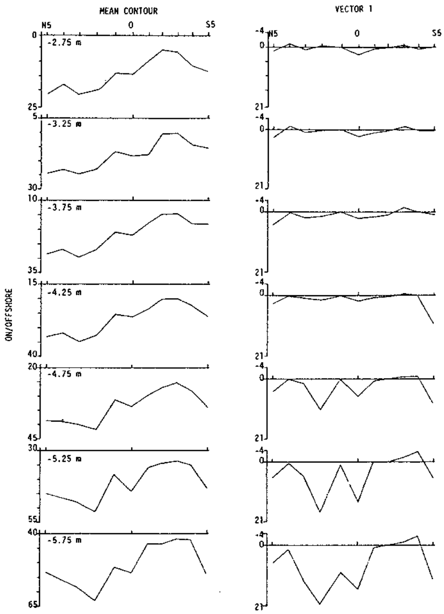

Figure 4. The mean contours and first eigenvectors for each of the seven Siletz Spit contour data sets.

The results of EOF analysis of the seaward-most data are shown more fully in Figure 5. The alongshore patterns are more irregular than those of the synthetic analyses, as would be expected in a natural system, but they definitely reflect some characteristics of the shoreline rhythmicity. The mean contour is obviously rhythmic with a longshore wavelength of 800-850 m and an amplitude of approximately 20 m. Two eigenvectors account for 83% of the variance in the data suggesting that although there is some noise in the system, it is probably much less than the amplitude of the rhythmicity signal. The shapes of the first two vectors are reassuringly similar to those determined in analyses of the hypothetical rhythmic shoreline with amplitude variations and phase shifting of the pattern. Eigenvector 1 departs from the expected phase relation with the mean for this model in the southern part of the area. The nature of the departure suggests that phase shifting at this site was possibly accompanied by small changes in the wavelength of the rhythmicity. Eigenvector 2 also departs from the expected phase relation with the mean, but it is 90 degrees out of phase with vector 1 for most of its length and this is consistent with the model. The amplitudes of the mean, first eigenvector and second eigenvector are 20 m, 25 m, and 15 m, respectively. This is very reminiscent of the synthetic data set with 180 degree phase shifting. The percentages explained by the first two vectors from the Siletz data are also similar to this hypothetical case. The ratio of percent explained by eigenvector 2 to that explained by eigenvector 1 de-emphasizes the noise in the natural system. The ratio for the hypothetical example with a 180 degree phase envelope is 0.15, and for the Siletz field site is 0.17.

Examination of eigenvector 1 shows it to have a mean of 6.4 m, implying an associated on/offshore movement of the contour. Sites labelled S1, S2, S3, and S4 have values near zero, while sites to the north have larger values indicating a greater on/offshore fluctuation in position. Figure 6 shows plots of the sum of the mean contour and

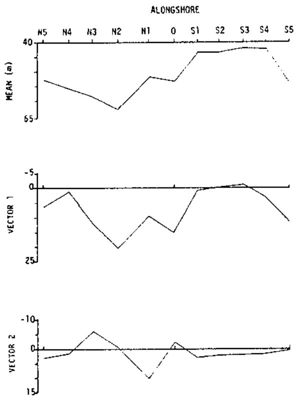

Figure 5. The mean contour and the first and second eigenvectors for the seawardmost contour of the Siletz Spit data set.

the most positively and most negatively weighted first eigenvectors in the data set. From these it is concluded that a change from large positive to large negative for vector weights would describe erosion in the north, a broadening of the embayment in the south, and migration of the cusp to the north with a concurrent decrease in amplitude. Though examination of vector 1 alone suggests that it might describe variation in the wavelength of the rhythmicity, it does not appear to do so within this data set. Eigenvector 2 has a mean near zero and shows most variation in the northern half of the study area. Figure 7 shows plots of the most positively and most negatively weighted second vector in the data set added to the mean contour. A transition from large positive to large negative second eigenvector weights represents a straightening of the beach to the south, a large increase in topographic complexity to the north, and a concurrent decrease in amplitude and northward migration of the southernmost embayment. Vector by vector reconstructions of the data, such as this, can prove extremely enlightening in understanding both the significance of the vectors and the dynamics of the beach system.

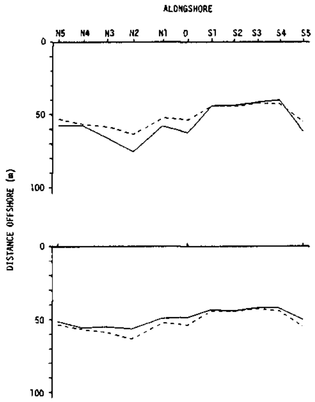

Figure 6. The sum of the mean contour and the most positively weighted (top) and most negatively weighted (bottom) first eigenvectors (solid lines). For reference, the mean contour is shown as a dotted line.

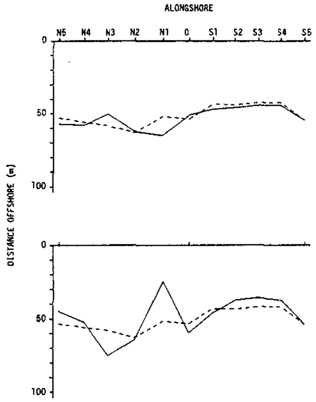

Figure 7. The sum of the mean contour and the most positively weighted (top) and most negatively weighted (bottom) second eigenvectors (solid lines). For reference, the mean contour is shown as a dotted line.

This analysis confirms the visual and survey observations that there are three primary components in the beach variability data. These are general accretion or erosion of the shoreline, amplitude of a dominant 800-850 m wavelength rhythmic pattern, and longshore location or phase of the rhythmic pattern through approximately 180 degrees (or 400 m). EOF analysis is useful in verifying the importance of these components, as demonstrated here and in the analyses of the synthetic data. Furthermore, it is capable of separating accretion/erosion and rhythmicity amplitude variations in a simple two-component system where these morphologies are independent.

Unfortunately, in an interdependent multiple component system, or a phase varying sinusoidal system (both of which apply to the Siletz data), the resulting eigenvectors fail to provide a simple separation of the three topographic parameters.

Quantification of the Components of Beach Morphology

To study the relationships between topography and wave and tide conditions, it is desirable to separate the three morphologic components and express each by a meaningful numerical parameter. On/offshore position, and amplitude of rhythmicity, can be described by the mean and standard deviation of the distance offshore to a contour at a given time (Fig. 8). For a truly sinusoidal pattern, the standard deviation of a contour produces a low estimate of rhythmic amplitude. In light of the variations found in natural systems, however, it seems to be a satisfactory descriptor. One possibility for quantification of longshore position of the signal would be longshore location of extrema. The signal produced by the real data is sufficiently noisy to preclude this approach. Recall that for any rhythmic shoreline exhibiting less than about 200 degrees of longshore phase shifting, EOF analysis produces a single eigenvctor which describes much of the topographic variation. Vector weights for each excursion are meaningful numerical descriptors of the overall topography. In this instance, if the on/offshore movements of the shoreline and amplitude variation signals can be removed from the data, then the first eigenvector calculated by EOF analysis should describe only the phase shifting, or longshore migration of the rhythmic pattern.

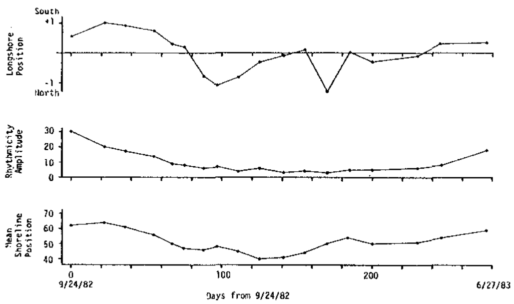

Figure 8. On/offshore position of the shoreline and amplitude of rhythmicity can be described by the mean and standard deviation of the distance offshore to a contour at a given time. The weightings of the first eigenvector of the normalized data matrix can be used as quantitative descriptors of longshore position of the rhythmic pattern.

To this end, the seaward-most contour data was normalized to the same mean and standard deviation. This normalization results in varying amounts of noise for different excursions, increasing the noise in low amplitude (mid-winter) data sets relative to higher amplitude data sets. Figure 9 shows plots of the mean contour, first, second, and third eigenvetors from EOF analysis of the normalized data. Because of the increased noise, 5 vectors are necessary to account for 90% of the variance. For the non-normalized data, the same amount of variance is explained by only 3 vectors. Longshore migration of the rhythmic pattern is described mostly by eigenvector 1. Eigenvectors 2 and 3, primarily 'fine-tune' the shape of the topographic features by narrowing cusps and broadening embayments. Comparison of the first vector weights of the normalized data (Fig. 8) to topographic maps of the beach for each excursion (Garrow, 1985), confirms that these weights can be used as quantitative descriptors of longshore position of the rhythmic pattern. Large negative weightings describe a number of the winter beaches when the embayment was located in the north central part of the site.

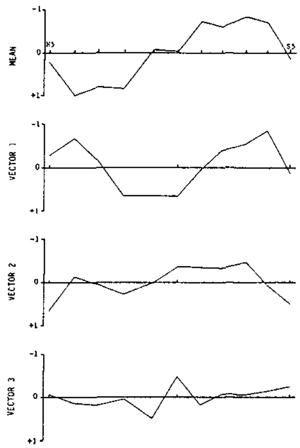

Figure 9. The mean contour and the first, second, and third eigenvectors from EOF analysis of the normalized -5.75 m contour matrix.

Careful analysis of the topographic data reveals three primary components of topographic change on Siletz Spit and suggests three independent and quantitative parameters to describe them. On/offshore position of the shoreline is best described by the mean distance offshore to a predetermined contour for each excursion. The amplitude of rhythmic topography is most simply and accurately described by the standard deviation of a contour about its mean offshore distance. The longshore position of rhythmic features is best expressed by the weights of the first eigenvector as calculated by EOF analysis of the contour data set in which each sample is normalized to the same mean and standard deviation.

Waves, Weather, and Topography

Relationships between parameters which represent important characteristics of shoreline morphology and the wave, tide, or weather conditions permit us to: 1) improve our understanding of which variables are important in producing rhythmic topography, 2) make estimates of the response times for the beach morphology components, and 3) learn something about the way in which rhythmic topography forms. Regression analysis between the available topographic and environmental variables confirms some well established trends, but also provides new insights and surprises. The values used to represent wave and weather conditions in this investigation are the means for the time periods between surveys.

Though the linear correlation between mean significant wave height and the position of the mean shoreline is not high (-0.720), the expected relationship exists (Fig. 10). As significant wave height increases, the mean shoreline position moves onshore (decreases) as a result of beach erosion. It is suggested that the correlation is as low as it is due to the rather slow response time of the mean shoreline to changes in incident wave conditions. Although the bi-weekly sampling precludes comments on very rapid responses, the mean shoreline position changed, at most, five meters between surveys.

Of interest, the amplitude of the rhythmicity also shows a negative correlation (-0.614) with mean significant wave height (Fig. 11). This is opposite to the relationship observed previously during major episodes of erosion on Silitz Spit. At those times, erosion resulted from embayments impinging on the foredune during storms with incident wave heights exceeding six or seven meters (Rea, 1975; Komar and Rea, 1976; McKinney, 1977; Komar, 1983).

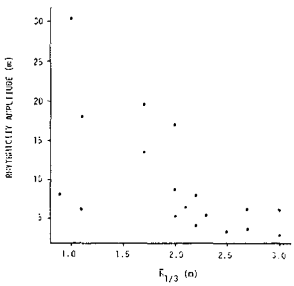

Figure 10. Mean Significant wave height versus mean shoreline position showing a negative correlation between these variables.

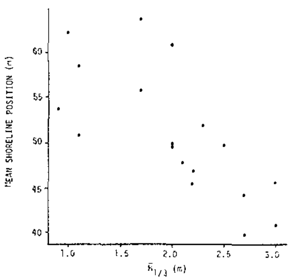

Figure 11. Mean significant wave height versus rhythmicity amplitude. The negative correlation between these variables differs from a positive correlation observed during major erosional episodes of the 1970's.

The winter of 1982/83 was characterized by anomalous weather and tide conditions due to El Niño. Consideration of three well documented periods of significant dune erosion on Siletz during the 1970's (McKinney, 1977), reveals a fundamental difference in conditions between those periods and the 1982/83 winter. First, incident wave conditions do not differ appreciably between the 'erosive' winters and the winter of 1982/83. Incident wave periods during the three major erosive storms varied from 9 to 17 sec. and significant breaking wave heights ranged from 6 to 7 m. However, barometric pressures in the winter of 1982/83 were anomalously low. Monthly mean barometric pressures for January through April were the lowest since sometime before 1971 (Huyer et al., 1983). This difference reflects that storm centers were closer to the Oregon coast in 1982/83, being located off the central California coast, than during the periods of major erosion when they were located in the North Pacific, just south of the Aleution Islands in the Gulf of Alaska (McKinney, 1977). It is speculated, then, that incident wave characteristics related to the proximity of a storm center may be important in determining the amplitude of rhythmic topography on Siletz Spit.

Of interest, the amplitude of the rhythmicity in the 1982/83 winter showed larger responses to incident wave conditions than did the mean shoreline position. Up to 10 m of change occurred during any two-week period. The relationship between mean shoreline position and rhythmicity amplitude can reveal whether the rhythmic topography is erosional or depositional in origin. The correlation between these two morphology components is +0.841, indicating that the amplitude increased as the shoreline prograded (Fig. 12). However, spectral analyses of the high water lines on air photo mosaics obtained in previous years (Garrow, 1985) suggest a possible negative correlation between these same two variables. The photographs showing significant spectral peaks were taken during August, September, October, February, and April of the several years of photo availability. The high spectral energy found on the fall and mid-winter

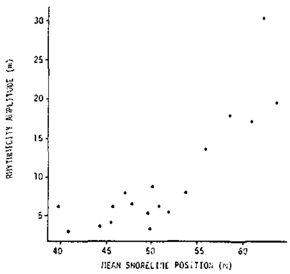

Figure 12. Mean shoreline position versus rhythmicity amplitude. The positive correlation indicates rhythmic topography was of a depositional origin during the time of this study.

photographs indicate that the rhythmic topograpy may also form, as well as show rapid growth under erosional conditions. It is probable, however, that the development of rhythmicity to very large amplitudes is most likely to occur under erosional conditions. This seems likely, given the more rapid response of rhythmicity amplitude than of mean shorline position to changes in significant wave height.

Conclusions

Emperical orthogonal eigenfunction analysis of a matrix containing offshore distances to an elevation contour provides a means for determining the important morphologies variables in an area. These may not correspond to single morphologies deemed important by the researcher if these morphology components do not behave completely independently over the period represented by the measurements. They will also not correspond if longshore migration of a sinusoidal pattern occurs during the time of study. Reconstruction or partial reconstruction of the original data by summing weighted eigenvectors or 'new variables' with the mean can provide insights into the significance of the vectors and the dynamics of the beach system.

Three important morphologic components were identified on Siletz Spit: overall accretion or erosion of the shoreline, amplitude of an 800-850 m wavelength rhythmic topography, and longshore position or phase of the rhythmic features. EOF analysis was useful in verifying the importance of these components but was not able to provide a simple separation of them.

It was determined that the mean shoreline position and rhythmicity amplitude can be quantified, respectively, by the mean distance offshore to a specified contour and the standard deviation of the contour about that distance. Longshore position or phase of the rhythmic pattern can be described by the weights of the first eigenvector, calculated by EOF analysis, of a contour data matrix in which each contour is normalized to the same mean and standard deviation. This should also apply for other, similar systems showing less than about 200 degrees of longshore migration.

This quantification permitted evaluation of the effects of various wave and weather conditions on the shoreline morphology. As expected, the mean shoreline position moved onshore as wave height increased. The amplitude of the rhythmicity was inversely correlated with wave height, though there is some question as to whether this is true for all winters on Siletz Spit. During the winter of 1982/83, rhythmic topography formed and increased in amplitude under deposítonal conditions. Again, there is some question as to whether this is always the case at this site. Mean shoreline position was shown to change, at most, 5 m during a two-week period, whereas, rhythmicity amplitude changed by as much as 10 m. This difference in rates of change should make formation and development of rhythmic topography possible under erosional conditions, as well as under the depositional conditions observed during this study.

Acknowledgments

The author wishes to thank R.A. Holman and P.D. Komar for their advice throughout the study and for their critical and rapid review of the manuscript. This work is a result of research sponsored by the NOAA Office of Sea Grant, Department of Commerce, under Grant No. NA81AA-D-00086 (Project No. R/CP-17). The U.S. Government is authorized to produce and distribute reprints for governmental purposes, notwithstanding any copyright notation that may appear hereon.

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