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SEDIMENT DYNAMICS AND PROFILE INTERACTIONS: DUCK94

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ABSTRACT

Beach profiles and sediment samples were collected on a daily basis along three cross-shore transect lines during the DUCK94 nearshore experiment lasting for 18 days in October 1994. Conditions ranged from near calm during the first week of the experiment to full storm conditions during the second and third weeks, with a two day initiation of beach recovery at the end of the experiment. The profiles responded with similar elevation change, with little morphologic variability during the calm period. During the storm, the bar migrated seaward 70 to 100 m, but the foreshore exhibited little change. The bar began to migrate shoreward at initiation of recovery. Sediment grain-size distributions vary in the cross-shore direction, with medium size grains on the upper foreshore, coarse gravel deposits on the lower foreshore and progressively finer sands in the offshore direction. After the storm, the foreshore and bar/trough samples were coarser with little change in the nearshore sediment distributions.

INTRODUCTION

To quantify sediment distribution response to forcing functions on the foreshore, bar/trough and nearshore along a three-dimensional beach area, a sediment sampling and analysis experiment was conducted as part of the DUCK94 nearshore field experiment (see Birkemeier et al., 1997 for overview of DUCK94 experiment). This experiment was designed to examine the three-dimensional natural sediment distribution and its relationship to profile change at the U.S. Army Engineer, Waterways Experiment Station, Field Research Facility (FRF) at Duck, N.C. (Figure 1). Sediment distribution changes were measured over the short-term (18-day period) during October, 1994. To increase our understanding of sediment distribution, the experiment focused on our knowledge of the short-term 3-D sediment variations of the entire active profile to document relationships between beach morphology and sediment dynamics from the high water line, seaward to closure depth.

Sediment grain-size distributions for different beach environments change as the beach erodes and accretes in response to changes in wave and tidal forcing. A previous long-term study at the FRF along one profile line characterized a cross-shore variability pattern in

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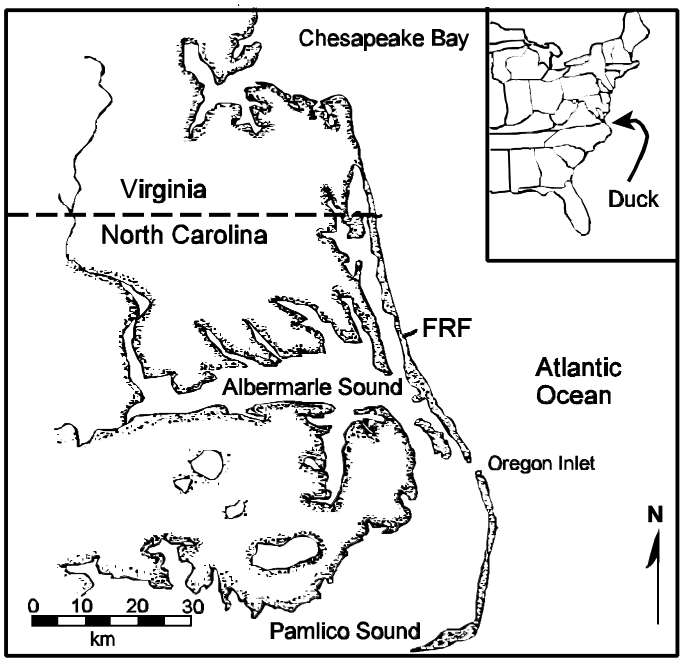

Figure 1. Location map.

grain-size distributions (Stauble, 1992). During the SUPERDUCK (1986) experiment, a short-term storm erosion and recovery study showed a high degree of three-dimensional grain-size variability but was limited to the foreshore and hinted at nearshore control of the foreshore sedimentation (Stauble et al., 1993). A lack of knowledge exists in relating three-dimensional sediment movement on the entire active beach profile during both fair weather and storm periods to the processes that cause the movement. These processes include a) the swash processes on the foreshore, b) wave breaking, longshore currents, and/or cell circulation (rip currents) in the bar and trough area, and c) wave, tidal and wind driven circulation on the nearshore slope out to closure depth and beyond. The variation in grain sizes in each of these environments is indicative of the different active processes.

EXPERIMENT DESIGN

The experiment design included collection of profile data and sediment samples along three lines, approximately 100 m apart, extending from the dune base to the 6-m depth contour (Figure 2). Surface sediment samples were collected at the dune base, mid-berm, berm crest (area around high water), mid-tide, swash (area around low water), trough, bar crest, and the 3-m, 4-m, 5-m, and 6-m depth contours. Shallow surface sediment samples were collected daily with a hand scoop from the foreshore to wading depth and with a grab sampler on subaqueous portion of each profile using the Coastal Research Amphibious Buggy (CRAB), during the beach profile survey. Samples were collected around the time of low tide on the foreshore. The sampling schedule included daily profile and sediment collection of the foreshore and alternate days for the nearshore area sediment collection for a duration of 18 days in October, 1994. The data sampling time period covered physical conditions ranging from near calm to storm conditions.

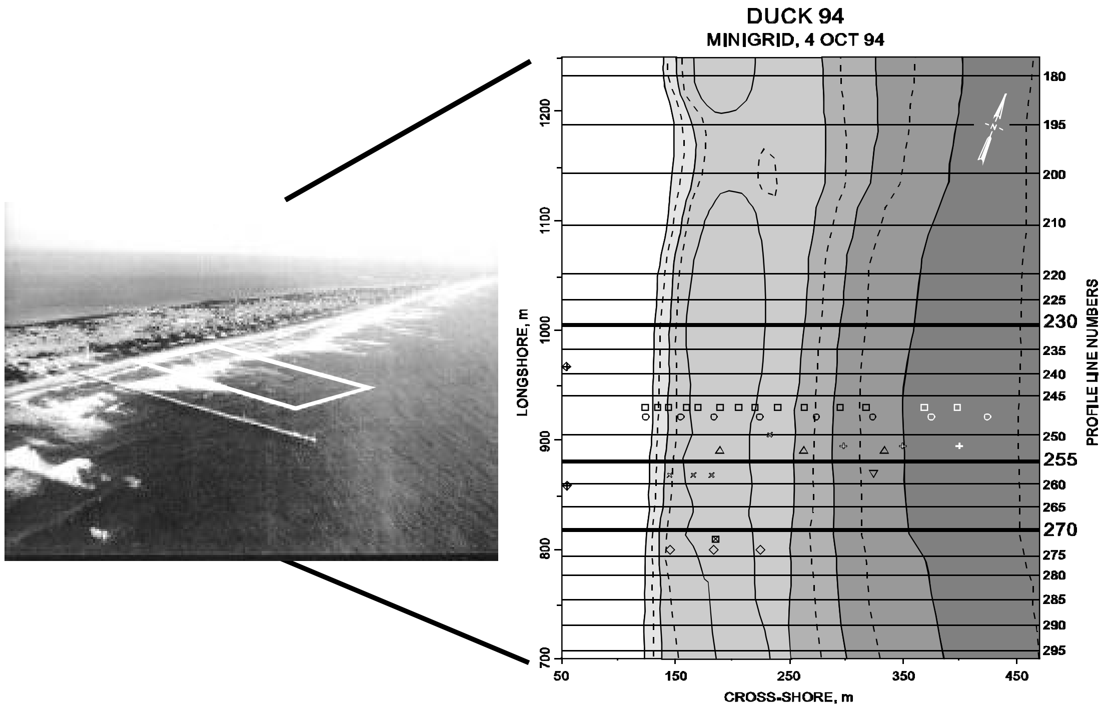

Figure 2. Location of profile transects samples (Lines 230, 255, and 270).

DATA ANALYSIS

Physical data: During the experiment several arrays of wave gauges and current meters were deployed within the study area. An offshore wave gauge array was located in 8 m of water, just offshore of the data collection area. Figure 3 shows the mean wave height (H_{mo}) and peak period (T_p) recorded from 2 to 22 October 1994. Profile and sediment data used in this paper were collected from 4 to 21 October. The experiment began just after a period of high wave activity, as the waves diminished to an average H_{mo} of around 0.5 m and a T_p between 3 and 7 sec. This relatively calm period lasted until 9 October. Currents recorded in the trough area landward of the bar between transects 245 and 250 (Figure 2), indicated that the longshore velocity was near zero and the cross-shore velocity ranged from 0 to 0.2 m/s in the offshore direction during this time period (data courtesy of S. Elgar). At the onset of the storm (10-13 October), H_{mo} rapidly increased to around 2 m and T_p increased from a low of 3 sec to around 7 sec. The longshore currents reached their maximum velocity (around 1.3 m/s) to the south, with a steadily increasing offshore component. The wave gauge recorded its maximum H_{mo} of around 4 m on 15 October as T_p increased to around 11 sec. The longshore currents reversed during this time reaching a peak velocity (1 m/s) to the north as the storm progressed up the coast and wave approach angles switched from a northeasterly direction to a more easterly to southeasterly direction. The offshore velocity component in the trough continued to increase to a maximum of around 0.64 m/s on 19 October. The wave height decreased to around 1.5 to 1.0 m as the experiment ended, but the wave period remained around 14 sec.

Profile Data: Beach profile data were collected from a shore-parallel baseline landward of the dune out to a depth of 6 m, some 700 m seaward of the baseline. All profiles are referenced to the 1929 National Geodetic Vertical Datum (NGVD). Profile data were

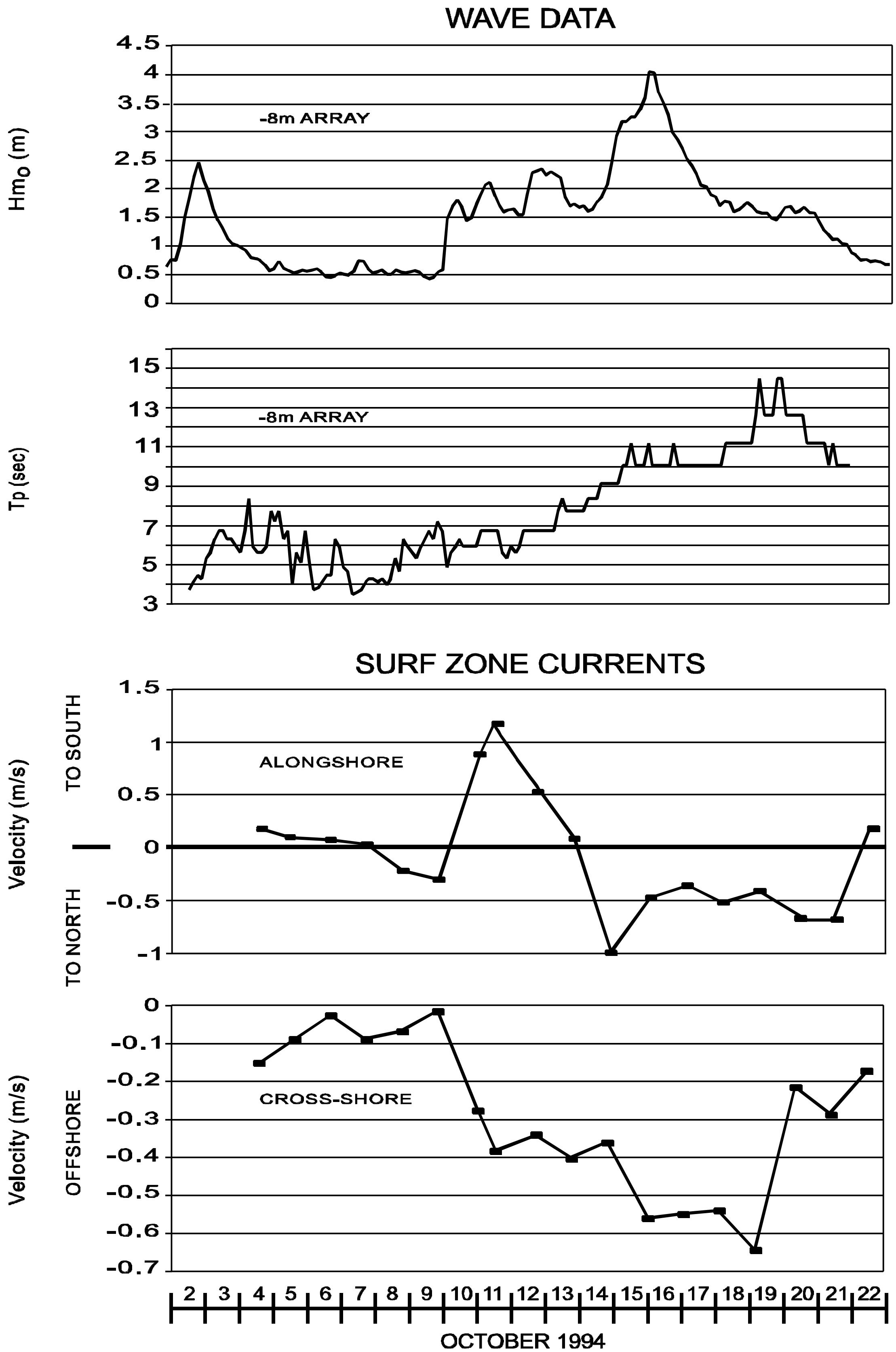

Figure 3. Plot of nearshore wave parameters and surf zone currents in trough.

analyzed and plotted using the Interactive Survey Reduction Program (ISRP) as described by Birkemeier (1984). Plots of the pre-storm beach profile (5 October) at all three transects showed that the bar crest was about 250 m from the baseline (Figure 4). With the increase in wave height beginning on 10 October, the bar migrated seaward. By 15 October the bar had moved to around 280 m seaward of the baseline. Just one day later, at the height of storm wave activity, the bar had moved to between 310 and 350 m offshore. With steadily decreasing wave heights and long period swell (as the storm moved out of the area), the bar migrated back onshore at profile lines 255 and 270. Profile line 230 was the location of a rip current and the bar remained in its seaward position through 21 October The foreshore did not change significantly in elevation over the study. During the low wave period at the beginning of the experiment the foreshore was planar, but beach cusps developed on 20 and 21 October as the waves subsided.

Sediment Data: A total of 256 sediment samples were collected and sieved using a sonic sifter at quarter-phi (¼ ϕ) intervals, ranging from -3 ϕ (8.0 mm) to 4.25 ϕ (0.53 mm), and weight percentages for each interval were computed. Statistical data were calculated using the method of moments (described in Friedman and Sanders, 1978). High variability was found in the cross-shore grain-size distributions, with the foreshore exhibiting the highest variability. This area between the berm crest and low tide swash contained a bi-modal gravel component along with sand size fractions. A localized source of coarse relict sediment has been identified in the area of the FRF by previous investigators (Calliari, 1994). The highest variability in profile elevation and sediment distribution occurred in the lower foreshore and trough/bar area, however the gravel component was restricted to the beach foreshore. The grain-size distribution was much more well-sorted and more uniform in mean size in the nearshore, both temporally and spatially. Figure 5a shows an example of the cross-shore sediment distribution on profile line 270 collected just at the beginning of the storm, representative of the sediment distributions deposited during the period of low wave activity. In contrast, at the end of the high wave period on 20 October, the bar had migrated offshore and the trough had widened. The grain-size distributions (Figure 5b) show a coarser and more poorly-sorted sample from the foreshore to the 3-m depth. Little change in nearshore sand distributions were found between low and storm wave conditions, while an increase in coarse material was measured on the foreshore. The finer-sized sediments were removed from the foreshore, trough and bar crest area, leaving behind a coarse lag deposit.

ANALYSIS AND DISCUSSION

Alongshore and cross-shore sediment distribution variability was related to beach morphology changes as a function of wave and current fluctuation. During the October 1994 experiment, the alongshore beach shape was uniform for the low wave period (first six days) and a "linear" beach was the prevalent form. The cross-shore profile elevation change and sediment grain-size distribution exhibited more variability, with a zone of medium size sands on the upper foreshore and coarse material in the lower foreshore. The size distribution became progressively finer in the offshore direction, through the nearshore trough, over a single bar feature, and the sloping nearshore region.

On 10 October, an extratropical storm system developed over the northern Gulf of Mexico and migrated northeastward into the Atlantic Ocean off of Cape Hatteras on 15 October. During this "northeaster", longshore currents increased to the south and offshore

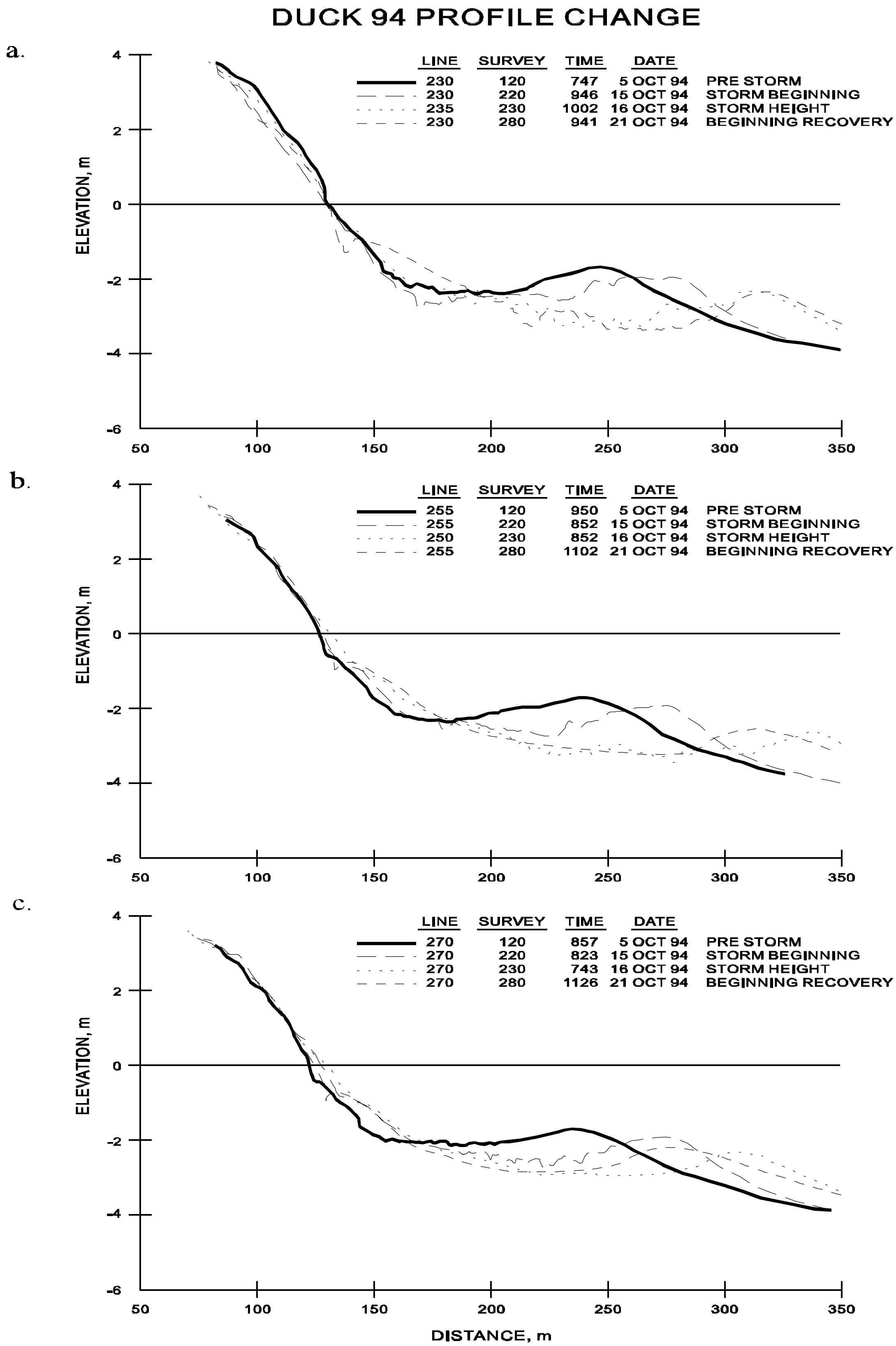

Figure 4. Plot of selected profiles showing bar migration due to storm.
a) line 230, b) line 255, and c) line 270

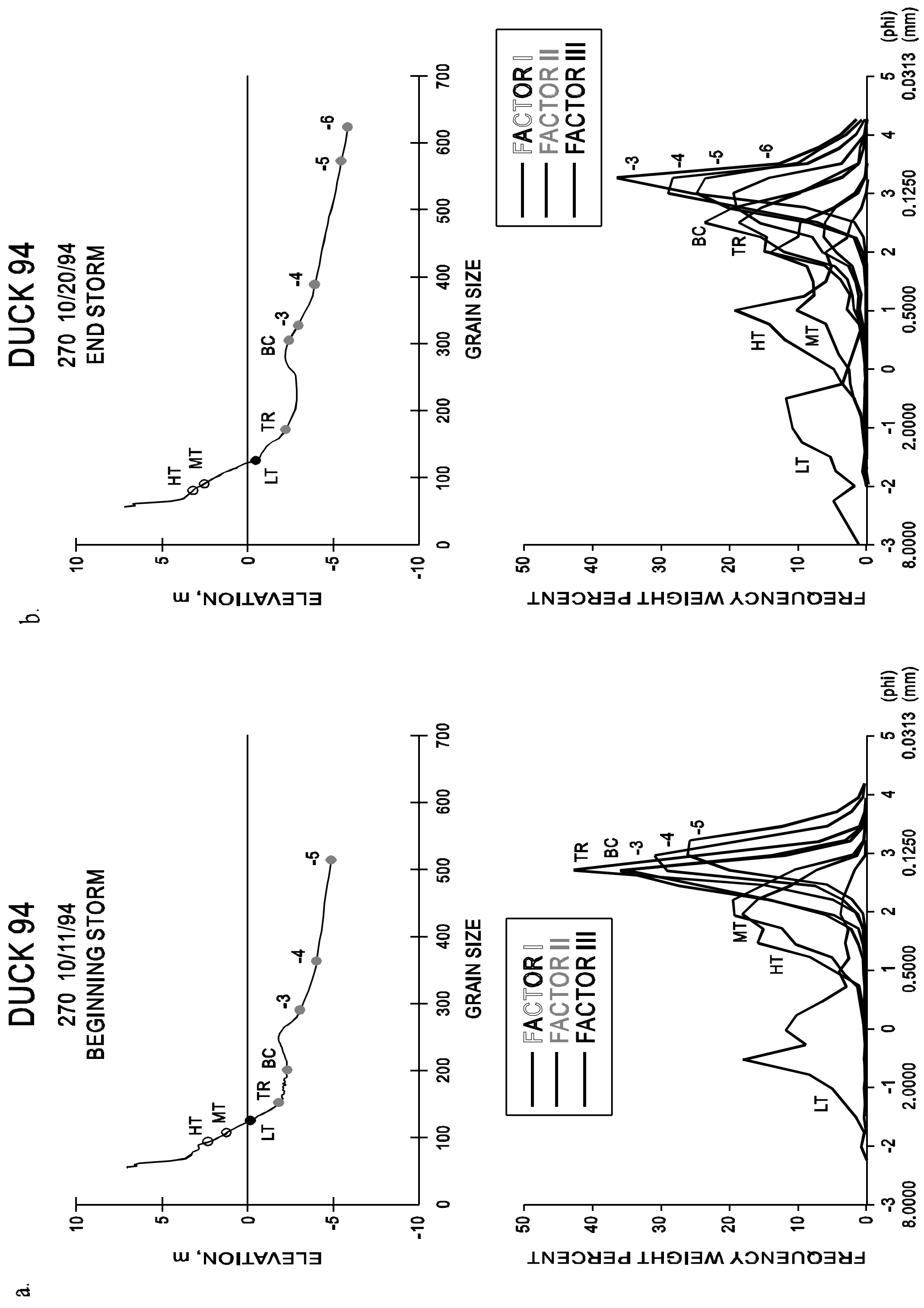

Figure 5. sediment sample locations and grain-size distributions on line 270
a) pre-storm and b) post-storm

HT = High tide, MT= Mid tide, LT = low tide, TR= trough, BC = bar crest,
-3 = 3 meter depth sample, etc...

flow increased in the trough area. During this phase of the experiment, the bar feature migrated in the offshore direction, while the foreshore maintained a uniform planar shape along the study area. Wave heights continued to grow and reached a maximum of 4 m at the 8-m depth wave gauge on 15 October.

High pressure developed over the eastern United States on 16 October and continued through the end of the experiment. During this phase of the experiment, the longshore drift switched from a southward to northward direction. In the surf zone, offshore currents reached their peak on 19 October. The profile responded with continued seaward migration of the bar feature and widening of the trough. Wave heights decreased on the last two days of the experiment, as long period swell conditions prevailed. Beach cusps formed and a rip current was present at the northern end of the study area. The beach began to take on more three-dimensional profile features with the bar migrating onshore in the southern region as offshore currents rapidly decreased in velocity.

In order to improve our understanding of both spatial and temporal variability in grain-size distribution during high energy events and compare them with calm periods, foreshore samples were collected and analyzed along all three lines, on a daily basis throughout the experiment. Nearshore sediment data collection was planned on a two-day cycle, but large waves precluded collection in the nearshore during the height of the storm event. However, nearshore samples were taken immediately before and after the storm.

Standard statistical techniques were used to analyze the sediment distribution of each beach and nearshore environment. Mean and standard deviation values were calculated for each sample. In general the coarser samples tended to have poorer sorting. The widest range in mean and sorting values was found in the low tide sediments, where the samples contained coarse shell and gravel components, as well as medium to fine quartz sand material. The upper foreshore (high and mid tide) samples had a coarse to medium-sized sand that was better sorted than the low tide (less of a coarse shell and gravel component). The nearshore (trough to the 6-m depth) had a relatively narrow range of mean grain sizes in the fine sand range, with little shell and no gravel size components.

Analysis of a suite of sediment samples using just the mean and standard deviation values is somewhat limiting. The use of Q-mode factor analysis (Klovan, 1966) provides a method to determine the relationship between grain-size distribution and variability in the 3-D sedimentation of the beach and nearshore. Q-mode factor analysis, as applied to sediment investigation, involves the determination of interrelationship between sediment samples. With this method, a group of sediment samples can be arranged into a meaningful order so that the relationship between each sediment distribution is deduced (Davis 1973). One of the main advantages of Q-mode factor analysis is that the entire grain-size distribution is considered in the analysis, yielding a detailed relationship especially when ¼ ϕ sample intervals are used. Using an analytical method to determine statistical relationships is more objective because it does not require arbitrary statistical descriptors or a-priori knowledge of the environment and location of samples (Klovan, 1966). A large number of samples can be objectively analyzed without having to manually compare each pair of curves. This reduces the "human interpretation" in relating large numbers of grain size distributions.

Q-mode factor analysis relies on how similarity between samples is defined (Reyment et al., 1993). In this application, the technique of Imbrie and Purdy (1962) for defining similarity was used. They defined an index of proportionality, or cosine theta function, to determine the degree of similarity in weight percent in each size class between each pair of samples. The cosine theta matrix shows all the information on the relationship between the sample vectors, but it is difficult to interpret (Klovan, 1966). Factor analysis provides a means of analyzing the cosine theta matrix to determine the minimum number of mutually orthogonal "factor axes" needed to account for most of the information in the cosine theta matrix. The first axis accounts for the majority of the information in the cosine theta matrix, the second axis accounts for most of the remaining information in the matrix, and so forth. Thus, the problem is to determine the number of eigenvalues needed to account for most (95-99%) of the information in the cosine theta matrix. Eigenvalues and eigenvectors were determined for the sediment sample data set. Factor loadings, a measure of each sample's weighting or correlation to each factor, can then be determined from the eigenvectors and eigenvalues. This provides the coordinates of the samples in a space of reduced dimensionality (Syvitski, 1991). Lastly, a varimax method of factor rotation is used to rotate the factor axes to maximize the variance of the factor loadings on each factor axes, while retaining their orthogonality.

The sample's weight percent in each phi-class interval is used to represent the sample distribution and can be used to "place" the sample relative to other samples in the Q-mode analysis. For example, if a sample is sieved into twenty-seven phi intervals, the sample can be defined as a vector in 27-dimensional space whose position is uniquely determined by the amount of sediment in each of the 27 classes (Klovan, 1966). With this technique, similarities and differences between samples can be determined and comparisons from day to day can also be made. Factor analysis relates the sediment distribution curves of similar shape, and dominant grain-size distribution peaks. Three factors accounted for 88.7% of the variance in the sample distributions. Factor I accounted for 57.8% of the variance and represented the medium sands between 1 and 2 ϕ (0.5 and 0.25 mm). Factor II accounted for 18.3% of the variance and represented fine sands with a peak frequency of occurrence between 2 and 3 ϕ (0.25 and 0.125 mm), and Factor III accounted for 12.6% of the variance and represented coarser sands, with a peak between -1 and 0 ϕ (2.0 and 1.0 mm). Figure 6 is a triangular diagram, which illustrates the distribution of the sediment samples within the three factors from the Q-mode analysis. Samples that are at the corners of the triangle represent the "end-members" of each factor group and depict a particular sediment distribution (Klovan 1966). The other samples within the triangle can be considered as a mixture of these three sediment distributions. The sediments from the high and mid tide area were strong in Factor I and embody medium grain-size distributions. The samples collected from the nearshore (trough to -6 m) covered a range from strong Factor II through near Factor I and comprise fine to medium grain-size distributions. The low tide samples were strongest in Factor II and include predominantly coarse sands.

To better understand the temporal changes over the duration of the 18 day experiment, factor analysis was run on each individual group (i.e. all high tide or all 3-m depth samples) within the cross-shore distribution of sediment data set to investigate the differences in grain-size distributions at each profile position over time. The factors will change depending on which sediment distributions are more dominant within each data set. Each cross-shore sediment data set was compared to differentiate the change over the low to high wave activity period. Little change was found in the nearshore sediment groups, with each data set grouping around Factor I (representing the fines) over the study period. A somewhat

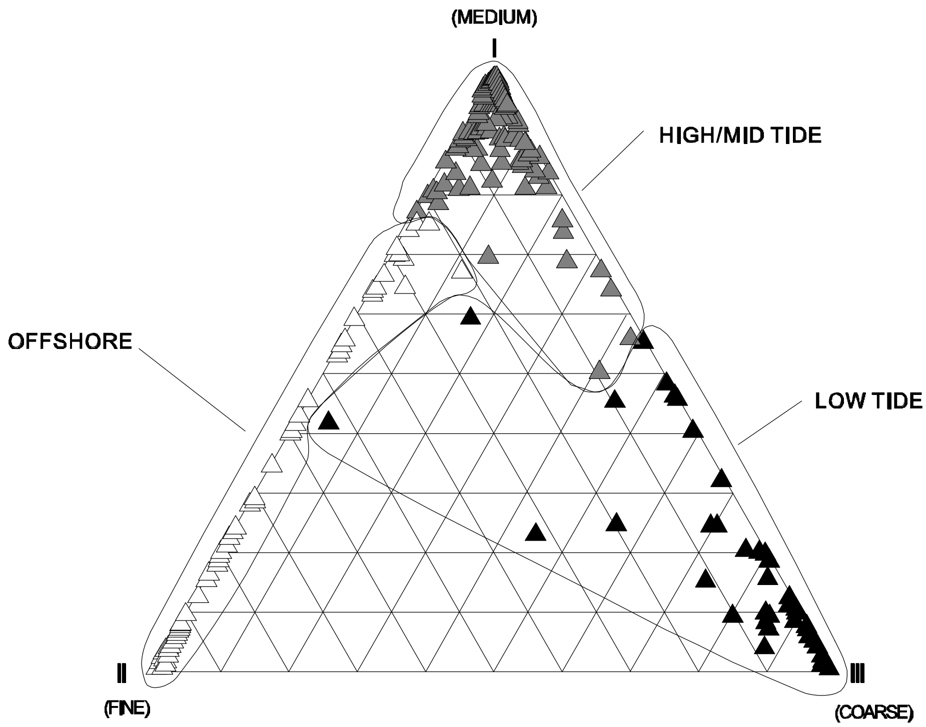

Figure 6. Triangular plot of Q-mode factor analysis of all samples.

more complex grouping was found for the individual foreshore samples over the 18 day study, with the high and mid tide samples grouping more commonly between Factor I (finer) and Factor III (medium), and the low tide samples around Factor II (coarser).

To remove some of the high spatial variability in the foreshore samples, a mathematical composite was made of the high, mid and low tide samples to allow a more clear picture of the temporal change due to storm activity. The 54 composite samples mathematically derived from each of the three profiles per day were analyzed and the grain size variability of the composites was described by three factors representing 94.2% of the variance. Figure 7a shows the triangular plot of the sample distributions within the three factors and representative frequency plots of "end member" samples. Factor I accounted for 79.2% of the variance and represented the finer distributions with peaks around 2 ϕ (0.25 mm). Factor II accounted for 12% of the variance and represented coarser grain-size distributions with peaks around -1 ϕ (2.0 mm). There was no strong Factor III end member, which accounted for only 3.1% of the variance. Samples that plotted in this area of the diagram had peaks in the medium size range between 1 and 2 ϕ (0.5 and 0.25 mm).

To give physical significance of the results of this analysis requires inferring what the end member samples indicate and how the samples group together around these end members. Foreshore composite samples collected from the period of low wave activity (4-10 October) all have a strong grouping toward Factor I. This grain-size distribution is represented by the composite of 9 October on profile line 230 (Figure 7b). All three profile lines exhibited similar composite grain-size distributions. During the period of higher waves (11-19 October) the composites plotted in two groups, one between Factor I and Factor III representing a shift to more medium grain sizes and the second strongly associated with Factor II, the coarse grains. A bi-modal sample from profile line 230 collected on 19 October is representative of this group. Except for the line 230 composite of 20 October

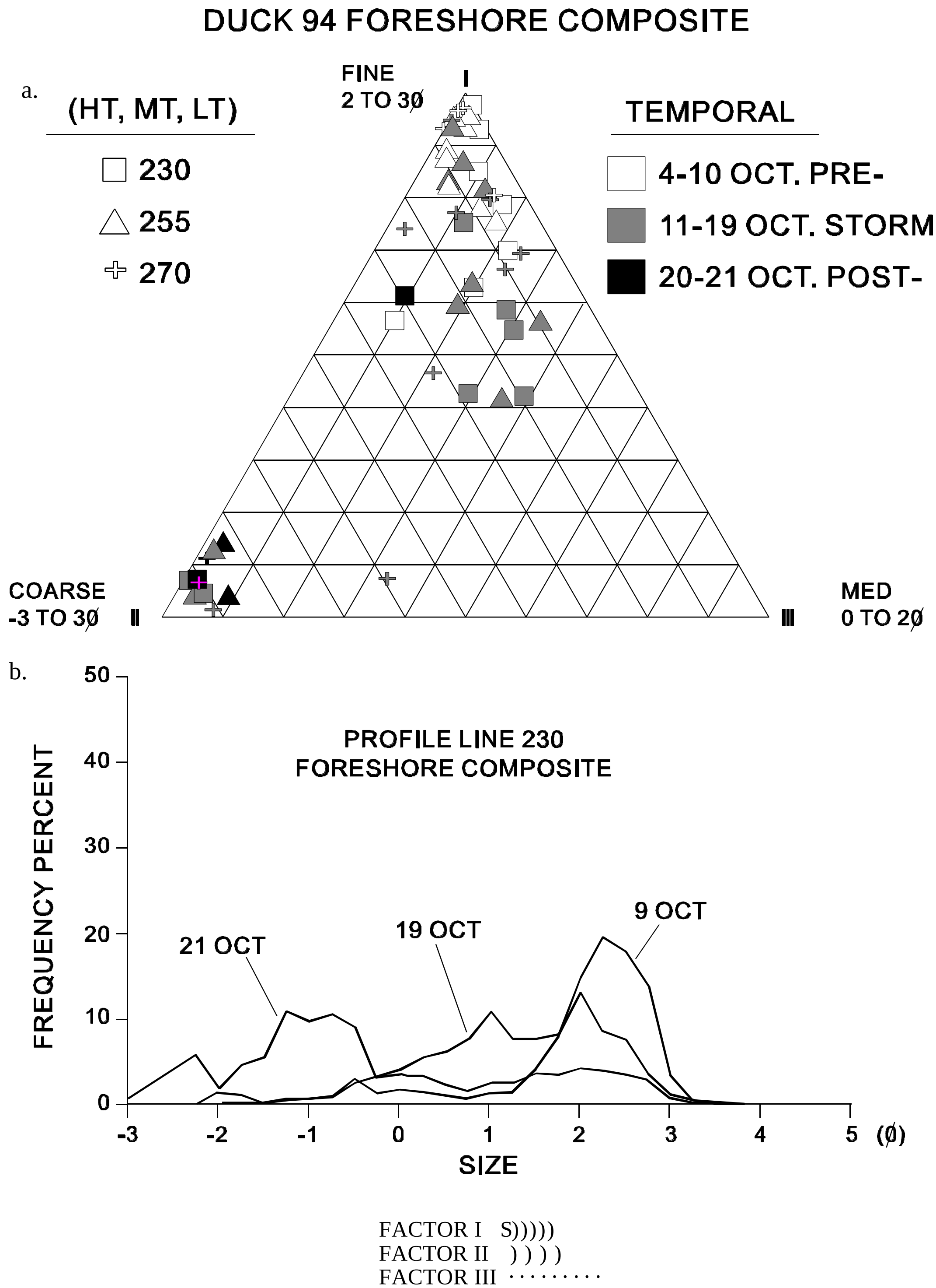

Figure 7. a) Foreshore composite factor analysis and b) examples of grain-size distributions representing Factor I, II and III groups.

all post-high wave samples (20-21 October) plotted strongly as coarse Factor II distributions. The 21 October line 230 sample distribution is an example of this coarse distribution resulting after the storm.

A picture emerges that foreshore and nearshore sediment dynamics are controlled by the wave and current input. During the time of low wave and current activity at the beginning of the experiment, little change was measured on the profile of the foreshore or bar/trough positions and little change in sediment distributions occurred. During the time of high wave and current activity at the latter part of the experiment, the foreshore remained basically unchanged, but the bar migrated seaward and the trough expanded in width. The sediment on the foreshore became coarser and more poorly sorted, particularly in the lower foreshore. Samples from the trough, bar and the 3-m depth also became coarser. Figure 8 illustrates the general trend of the pre- to post-storm sediment distribution change using the mid tide and 3-m depth samples from profile line 270 as an example. A coarse component is present in the grain-size distribution after the storm, possibly a lag deposit of underlying coarse layers exposed as the surficial finer material was removed. Further seaward at the 4-m, 5-m and 6-m depth samples, there was a minimal change in distributions as a result of the storm.

Correlation of sediment data in the trough, bar crest, 3-m, 4-m, and 5-m depth positions, with near real-time physical data such as significant wave height and mean cross-shore and mean longshore currents were possible with an array of sensors positioned 45 m to the north of the center line of sediment sampling. This array of 9 stations extended from the trough seaward over the bar to approximately the 5-m depth contour. The change in longshore current from flow to the south to flow to the north maintained the trough area while strong offshore currents were associated with seaward movement of the bar and the

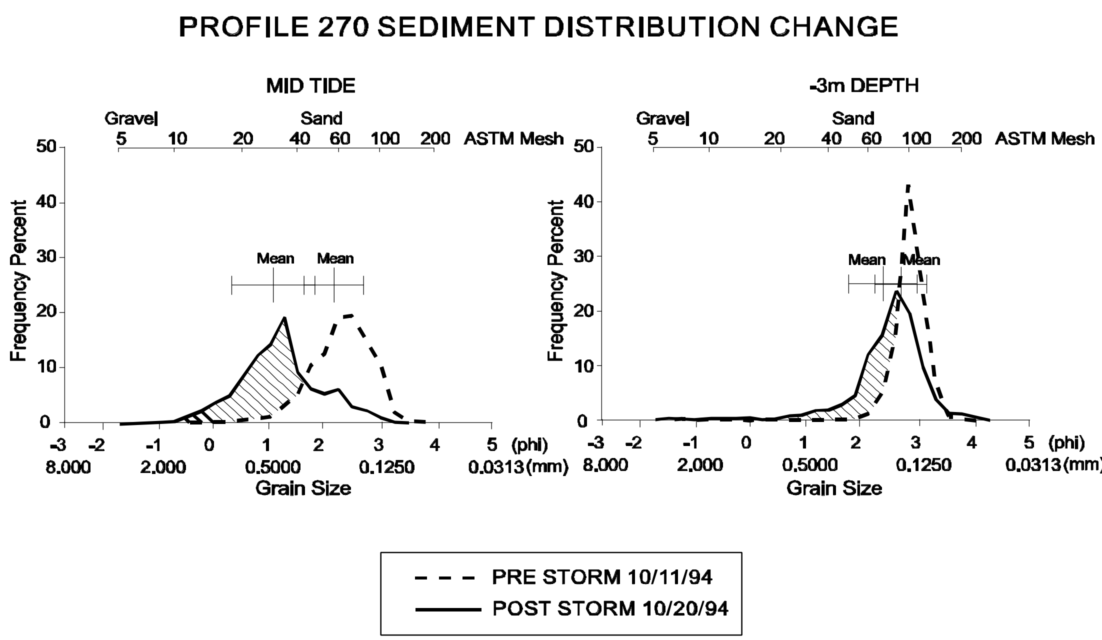

Figure 8. Post-storm coarsening of sediment at mid tide and -3m depth at profile line 270.

development of a rip current. On the last two days of the experiment the strong currents dissipated and the bar moved landward. The 3-D component of beach morphology was observed with the formation of beach cusps and the rip current at the northern end of the study area. Sediments became much coarser on the foreshore, and a coarser component was present even in the trough, bar and at the 3-m depth position.

CONCLUSION

The dynamics and evolution of sedimentation patterns on beaches and their link to hydrodynamics are poorly understood and present problems in effectively managing erosion control and storm damage reduction. Present research, using sediment statistical data analysis, is proving beneficial to characterize beach sediment distributions and their spatial and temporal deposition patterns. This study afforded a unique opportunity to couple the beach profile evolution, sediment deposition patterns and their resulting grain size distributions with the physical processes active at that coast.

This research examines the interaction of sediment along a three-dimensional active profile during both erosional and accretional events. Previous sediment studies at the FRF were a long term (17.8 month) study limited to one profile (corresponding to Line 230 in this study) (Stauble, 1992) and a 3-D study of a small 50 m wide area of the foreshore during SANDYDUCK (Stauble et. al, 1993). The DUCK 94 profile response covering one storm event was typical of long-term profile response where the most active part of the profile (bar/trough area) alternately moved seaward during storms and landward during fair weather conditions. From the 3-D perspective, the erosion during high wave and strong offshore surf zone currents moves the bar seaward uniformly with a linear foreshore planform. The recovery phase was more three-dimensional. The bar remaining in a fixed seaward position in the presence of a rip current (north end of the study at Line 230), while the bar migrated landward as the wave and surf zone current energy decreased outside of the rip area (southern area of the study at Lines 255 and 270). The foreshore was also very three-dimensional with the formation of beach cusps during this recovery period.

A better understanding of the dynamic processes of sediment deposition and interaction with profile elevation change on a natural beach was documented. The zonation of sediment characteristics over the entire active beach profile provides a picture of cross-shore grain-size data variability, with highest variability on the foreshore. The low tide samples were the most coarse and poorly sorted, with decreasing grain size and better sorting in the offshore direction. Q-mode factor analysis indicated that the foreshore was finer during the calm period at the beginning of the experiment and became coarser during the storm and recovery period. A coarse lag component contributed to the coarsening of the foreshore. The present study provided more detail to similar findings of Stauble (1992) and Stauble et al. (1993). The nearshore became slightly coarser over the bar and out to the 4-m depth. The seaward most sample distributions (5-m, 6-m depth) remained unchanged throughout the study.

Future research needs should focus on the zonation of coarse material and the interaction of the vertical distribution of layered beds on the foreshore/trough area. Conservation of grain-sizes within the three-dimensional beach (cross-shore and alongshore) is still not well understood. A better understanding of sediment processes can provide input into beach profile numerical models. These studies will ultimately help to understand the fate of beach fill material placed anywhere on the beach profile.

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REFERENCES

Birkemeier, W.A., 1984. A User's Guide to ISRP: The Interactive Survey Reduction Program. Instructional Report CERC-84-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS., 114 p.

Birkemeier, W.A., Long, C.E., and Hathaway, K.K., 1997. DELILAH, DUCK94, SandyDuck: Three Nearshore Field Experiments. *Proceedings 25th International Conference on Coastal Engineering*, Orlando, FL, ASCE, New York, N.Y., (this issue).

Calliari, L.J., 1994. Cross-shore and Longshore Sediment Size Distribution on Southern Currituck Spit, North Carolina: Implications for Beach Differentiation. *Journal of Coastal Research*, Vol. 10 (2), pp. 360-373.

Davis, J.C., 1973. Statistics and Data Analysis in Geology. John Wiley and Sons, New York, N.Y., 550 p.

Friedman, G.M. and Sanders, J.E., 1978. Principals of Sedimentology. John Wiley and Sons, New York, N.Y., 792 p.

Imbrie, J., and Purdy, E.G., 1962. Classification of Modern Bahamian Carbonate Sediments. *In*, Ham, W.E. (ed.), Classification of Carbonate Rocks, a Symposium, American Association of Petroleum Geologists Memoir 1, pp. 253-272.

Klovan, J.E., 1966. The Use of Factor Analysis in Determining Depositional Environments from Grain-Size Distributions. *Journal of Sedimentary Petrology*, Vol. 36 (1), pp. 115-125.

Reyment, R.A., Joreskog, K.G., and Marcus, L.F., 1993. Applied Factor Analysis in the Natural Sciences, 2nd Ed. Cambridge University Press, Cambridge, England, 371 p.

Stauble, D.K., 1992. Long Term Profile and Sediment Morphodynamics: Field Research Facility Case History. Technical Report CERC-92-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS., 252 p.

Stauble, D.K., Holem, G.W., Byrnes, M.R., Anders, F.J., and Meisburger, E., 1993. SUPERDUCK Beach Sediment Sample Experiment: Beach Profile Change and Foreshore Sediment Dynamics. Technical Report CERC-93-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS., 41 p.

Syvitski, J.P.M., 1991. Factor Analysis of Size Frequency Distributions: Significance of Factor Solutions Based on Simulation Experiments. *In*, Syvitski, J.P.M. (ed.), Principals, Methods, and Application of Particle Size Analysis, Cambridge University Press, Cambridge, England, pp. 249-263.