CHAPTER ONE HUNDRED THIRTY THREE

THE ROLE OF SUSPENDED SEDIMENT IN SHORE-NORMAL BEACH PROFILE CHANGES

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ABSTRACT

Field measurements of suspended sediment-transport were made across a dissipative surf zone during a storm. A correlation between high suspended mass in the water column and periods of onshore flow caused a net onshore transport of suspended sediment even though the mean near-bottom flow was directed offshore. The observed onshore migration of a nearshore bar was predicted by gradients in the cross-shore suspended-sediment transport.

INTRODUCTION

The response of the nearshore profile to cross-shore sediment transport has been the focus of numerous theoretical and laboratory studies (e.g. Bowen, 1980; Watanabe et al., 1980). However, due to measuring difficulties, few field data have been obtained of cross-shore sediment transport and the accompanying beach profile changes. In this study, measurements of cross-shore suspended-sediment transport were made across the surf zone during a storm. Nearshore profiles were taken both before and after the transport measurements. We attempt to relate gradients in the cross-shore transport of suspended sediment to profile changes. We show that a bar migrated onshore due to net onshore suspended-sediment transport even though mean currents were directed offshore.

EXPERIMENT SETTING AND METHODS

An extensive field study investigating nearshore processes was conducted in the fall of 1982 at the U.S. Army Corps of Engineers Field Research Facility (FRF) in Duck, N.C. The FRF is located on a long straight beach of a barrier island (Fig. 1). Mason et al. (this volume) provide details on meteorology, deepwater waves and three-dimensional morphology at the FRF during the experiment. Surf-zone data were collected 500 m north of the FRF pier using the U.S. Geological Survey sea sled (Sallenger et al., 1983). The sled is moved both onshore and offshore using a double-drum winch and triangular line arrangement (Fig. 2). As the sled moved, the nearshore profile was measured with an infrared rangefinder on the beach and reflecting prisms mounted on top of the sled's 10 meter mast. The sled was also used to transport instruments to different positions in the surf zone. Instruments mounted on the sled included a pressure sensor, three bidirectional electromagnetic current meters

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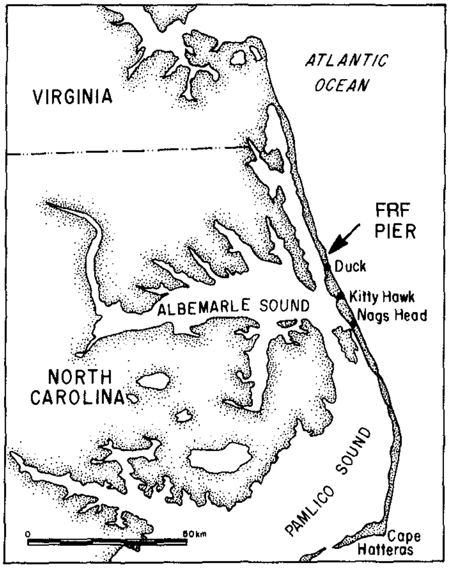

Fig. 1 Location map

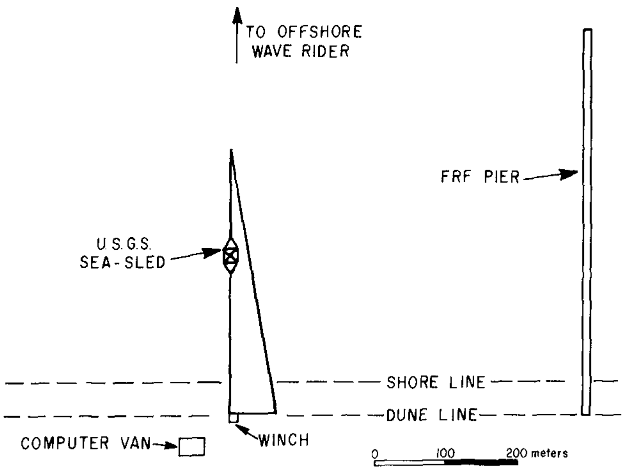

Fig. 2 Experiment set-up at the U.S. Army Corps of Engineers' Field Research Facility.

oriented to measure the cross-shore and longshore flow at 0.5, 1.0, and 1.75 meters above the bed, and a vertical array of five optical backscatter (OBS) sensors (Fig. 3). The OBS sensors measured suspended-sediment concentrations from 0.1 to 80 gm/kg at 0.10, 0.13, 0.19, 0.31, 0.61 m above the bed. The OBS array was mounted on an outrigger extending 0.85 m from the north side of the sled.

Data presented in this paper were collected as follows. First, the nearshore profile was measured. Second, 34.1 minute long records of sled instruments, sampled at 2 Hz, were obtained at seven stations distributed across the surf zone. Sled stations were occupied in a random sequence of offshore distances. Measurements were obtained around high tide to minimize sea level changes. To complete the data set, a second nearshore profile was taken six hours and thirty minutes after the first profile.

Fig. 3 Sled instrumentation. Shown are three current meters (CM), a pressure sensor (PS), and an array of optical backscatter (OBS) sensors (photo courtesey of Bruce Richmond).

The OBS sensors, which were used to measure suspended-sediment concentrations, were developed by John Downing and others at the University of Washington (Downing et al, 1981). The small sensor size (2.2 cm in diameter) allows for measurement of the vertical variation in suspended sediment. The OBS irradiates a 1.3 cm^3 conical volume and detects the intensity of backscattered light. Intensity of backscattered light is a function of sediment concentration and grain size. For a given concentration, smaller grains, with a larger ratio of surface area to volume, will backscatter more light than larger grains. Since backscatter intensity is a function of grain size, OBS sensors were calibrated in the laboratory with sand collected at the FRF 210 meters offshore from the baseline. The calibration sand had a mean diameter of 0.14 mm, typical for sand seaward of the bar at the FRF. Calibrations of the OBS sensors could be described by two linear segments with a break in slope around 2 ppt (Fig. 4). Since the grain size of bed material was coarser in the trough, this calibration would underestimate suspended-sediment concentrations in the trough if all of the bed material was suspended. For a description of the calibration technique see Downing et al, 1981.

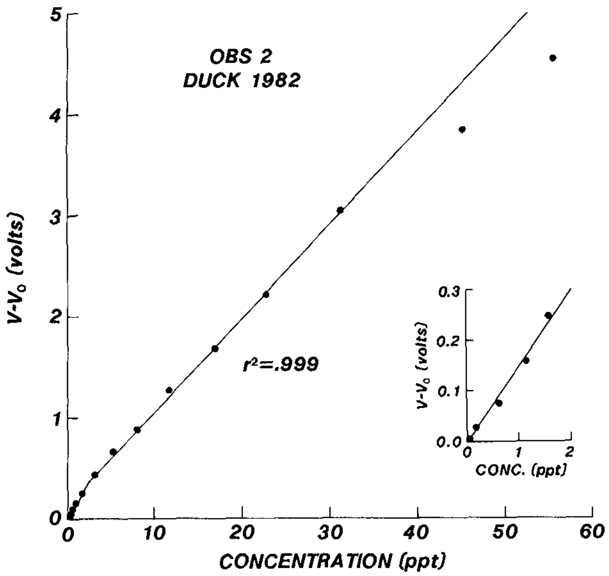

Fig. 4 Calibration curve for the optical backscatter sensor positioned 0.13 m above the bed. The calibration could be described by two least squares fits. The least squares fits only used concentrations below 30 ppt by weight because concentrations exceeded 30 ppt less than five percent of the time.

OBSERVATIONS

On October 13, 1982, during the final stages of an extratropical storm (northeastern), deepwater significant wave heights at Duck were 1.6 m and peak wave periods were 12 to 15 s (Mason et al, this volume). A surf-zone width (Xb) of 350 meters was calculated from a breaker height computed using measured deepwater wave characteristics (Komar and Gaughan, 1973), the nearshore profile, and measured ratios of surf-zone breaker height to depth. Visual observations were consistent with the calculated Xb. The surf zone was strongly dissipative, with three or four bores present at one time. We made measurements at X/Xb ranging from 0.1 to 0.65, where X was the cross-shore distance from the shoreline to the measurement location (Fig. 5E). These positions included three dynamically different regions; 1) the area seaward of the bar 2) the bar 3) the longshore trough. At measurement locations, mean water depths ranged from 2.1 to 4.3 m and RMS wave heights from 0.70 to 1.41 m (Figures 5C and 5D).

Measurements of horizontal water velocities were separated into mean and fluctuating vector components. The mean current speed at 0.50 m above the bed was highest in the longshore trough, 0.46 m/s, and decreased offshore except for sled station 6 where a strong longshore current increased the mean speed (Fig. 5A). Mean currents were directed offshore and to the north at all measurement stations. Standard deviations of current speeds, measures of the combined strengths of the oscillatory and turbulent fluctuations, are shown in figure 5B. The standard deviation calculation included infragravity oscillations.

Time-series measurements of suspended-sediment concentration showed that sand suspension occurred as intermittent events at all measurement positions. Figure 6 presents a 10 minute segment of a data record from sled station 6 (X/Xb = 0.5) showing water depth, cross-shore and longshore velocities at 0.5 m elevation and suspended-sediment concentrations at four elevations above the bed. This record is typical in that it shows long periods of low suspended-sediment concentrations interrupted by shorter periods of high concentration. A comparison of records from different stations shows that the high concentration suspension events occurred more frequently and were of shorter duration in deeper water. Since all of the measurement positions were well within the calculated plane-bed regime (Komar and Miller, 1975), suspension events were not due to vortices associated with small-scale bedforms.

Although suspension was intermittent, the time-averaged concentrations systematically varied with distance above the bed and cross-shore position (Fig. 7). Seaward of the bar crest, the mean concentration at 0.13 m above the bed decreased landward from 1.8 gm/kg at sled station 7 to 1.1 gm/kg at sled station 4. Just landward of the bar crest mean concentrations at 0.13 m increased greatly to concentrations equal to that measured at the most seaward station. Lowest concentrations occurred in the longshore trough. At all sled stations, concentrations decreased monotonically from 0.13 to 0.61 m above the bed and concentration gradients generally decreased in shallower water.

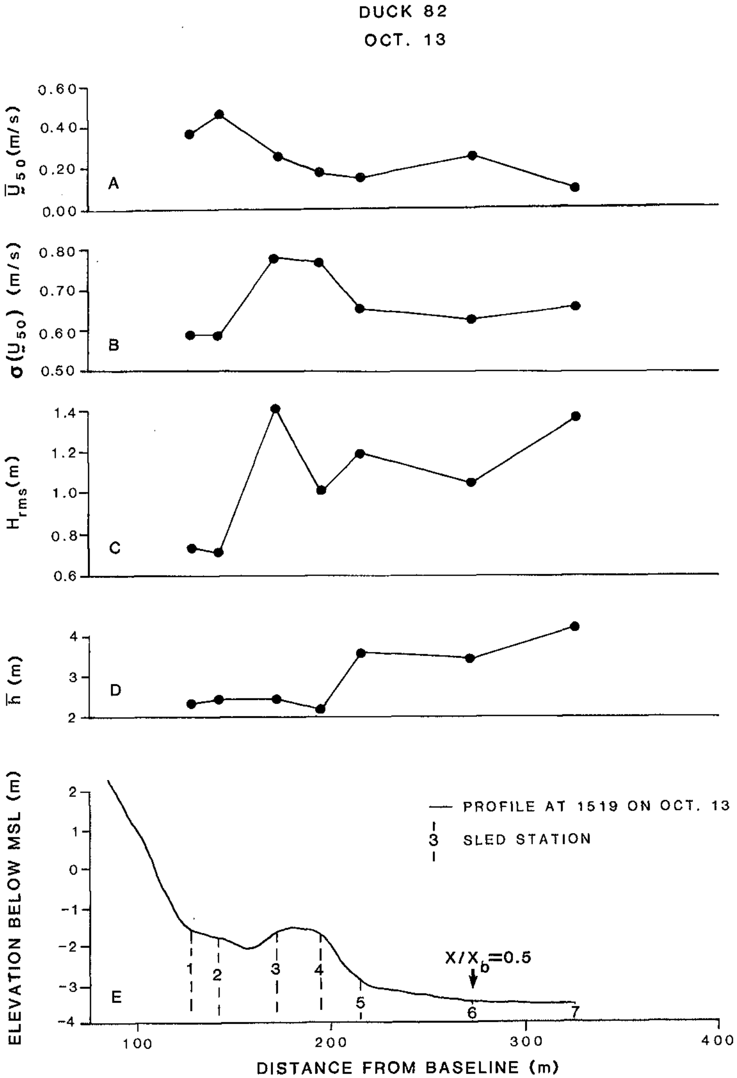

Fig. 5 Surf zone characteristics on Oct. 13th A) Cross-shore variation of the vector mean current speed B) Cross-shore variation of the standard deviation of the current speed C) RMS wave heights across the surf zone D) Water depths across the surf zone E) Shore-normal profile taken by the sled. The data collection sequence was sled station 7, 3, 1, 5, 2, 4.

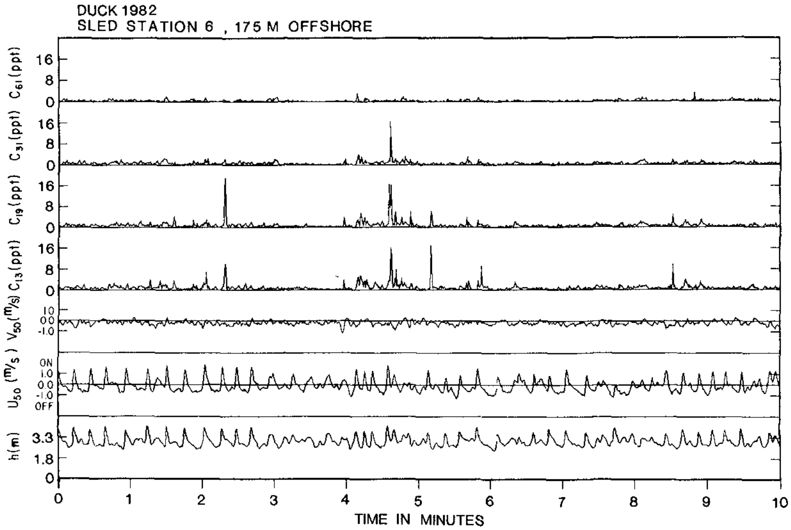

Fig. 6 Data time series from sled Station 6 (X/Xb = 0.5). From the bottom, the hydrostatic approximation to sea level (h), cross-shore velocity (u), longshore velocity (v), and suspended-sediment concentrations (gm/kg) at four levels above the seabed. Subscripts are elevations above the seabed in centimeters.

Mean concentrations at 0.10 m above the bed (not shown in figure 7) were within 0.1 ppt of the concentrations at 0.13 m. Concentrations were less at 0.10 m than at 0.13 m except at sled station 7. We were unable to find calibration errors for the OBS sensors that would explain the mean concentration decrease between 0.13 and 0.10 m. Still, we thought it unusual that the concentration would decrease towards the bed, so we did not use the 0.10 m readings when calculating suspended masses and fluxes.

The bar migrated onshore between 1519 hours and 2150 hours as its landward flank accreted and the seaward flank and longshore trough eroded (fig. 8D). Maximum vertical changes for the seaward flank, landward flank, and landward side of the longshore trough were -0.21, 0.18, and -0.31 meters, respectively. These profile changes are large compared to the measurement error of the sled system, which has been determined to be 0.045 m (Sallenger et al., 1983). To check the applicability of the 0.045 m figure, we estimated the total measurement error in the system on Oct. 13th. Bed elevations during occupation of a sled station were compared with bed elevations predicted by linearly interpolating the two measured profiles to the time of the occupation. The elevation differences were 0.01 to.0.05, with an average of 0.03 m, which is close to the 0.045 m standard deviation of change calculated by Sallenger et al, 1983.

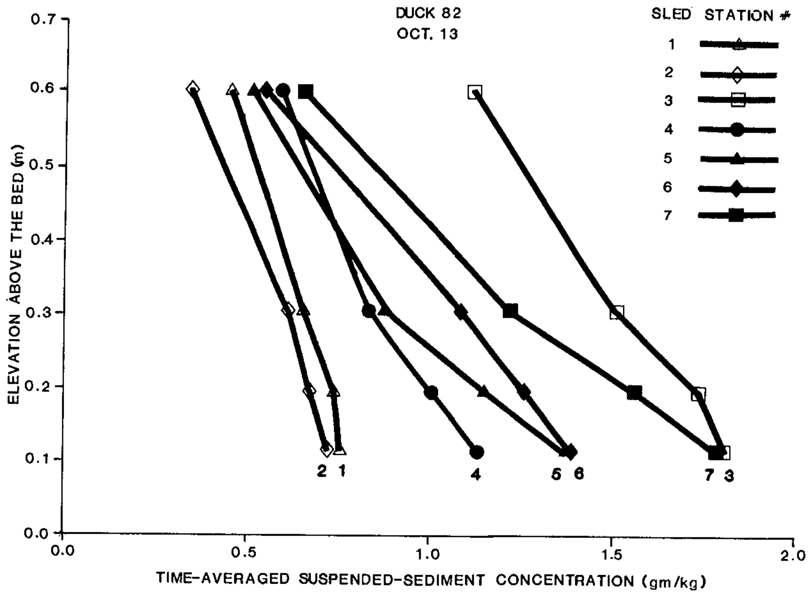

Fig. 7 Time-averaged suspended sediment concentration profiles. Each point represents the average of 4096 concentration measurements (34.1 minutes of data collected at 2 Hz). The data collection sequence was sled station 7, 3, 1, 5, 2, 4.

CALCULATIONS AND DISCUSSION

In order to calculate a suspended mass, concentrations were estimated in regions the sensors did not measure. Concentrations were linearly interpolated between sensors. Above the highest sensor, concentrations were estimated from a linear extrapolation from values at 0.31 m and 0.61 m. When the extrapolation produced a concentration greater than zero at the seasurface, the concentration at the seasurface was set equal to zero and concentrations linearly interpolated between the value at 0.61 m and the seasurface. Concentrations below the lowest sensor were also linearly extrapolated from the sensors at 0.13 and 0.19 m. With these estimations, concentrations were integrated over the total water column to obtain a suspended mass. In general, the suspended mass decreased moving onshore in the inner sixty-five percent of the surf zone with the notable exception of the sled station just landward of the bar crest where suspended mass was higher than at each of the other stations (Fig. 8A).

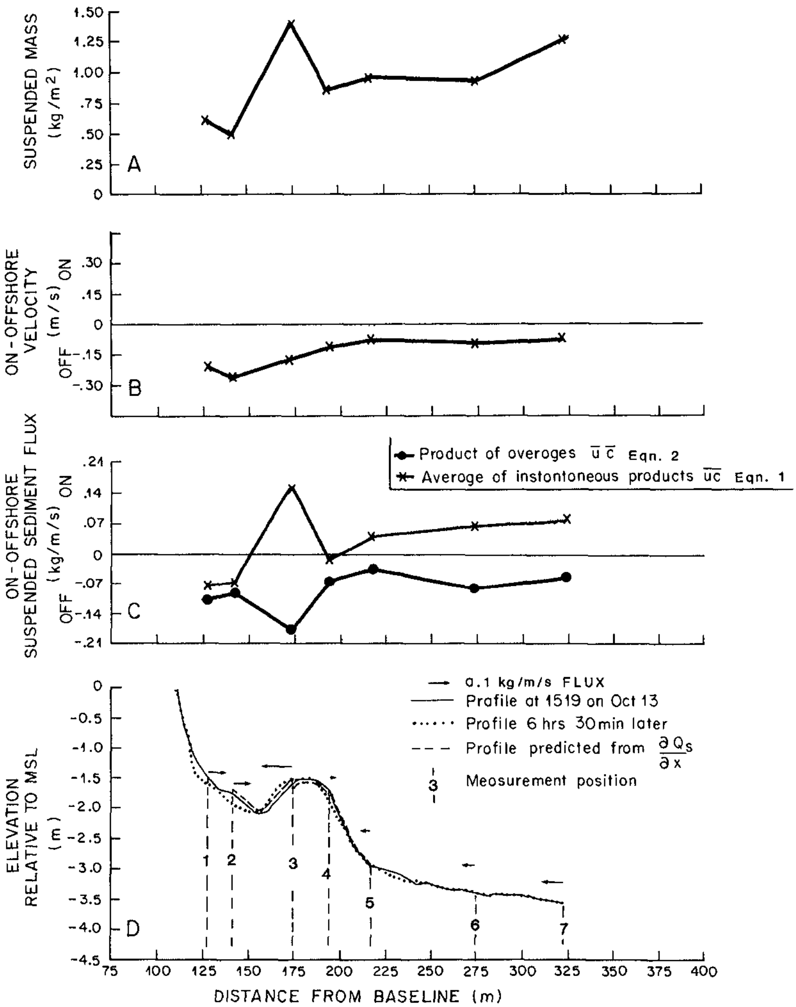

Fig. 8 A) Cross-shore variation in suspended mass B) Cross-shore variation of mean cross-shore velocities at 0.5 m above the seabed C) Comparison of suspended-sediment flux calculated from average and instantaneous quantities (D) Comparison of measured profiles with changes predicted by cross-shore gradients in suspended-sediment flux. The data collection sequence was sled station 7, 3, 1, 5, 2, 4.

Time-average cross-shore suspended-sediment fluxes were calculated for each measurement location in two manners. Fluxes, utilizing the high frequency measurements, were calculated using

$$\overline{cu} = \frac{1}{34.1} \int_{t=0}^{t=34.1\,min.} \int_{z=0}^{z=h} c(z,t)\, u(z,t)\, dz dt \qquad (1)$$

where c is suspended-sediment concentration, u is cross-shore velocity, z is elevation above the seabed, and h is the time-varying seasurface. Fluxes, given by the products of the time-average quantities, were also calculated using

$$\overline{c}\ \overline{u} = \int_{z=0}^{z=h} \left(\frac{1}{34.1} \int_{t=0}^{t=34.1\,min.} c(z,t)\, dt \right) * \left(\frac{1}{34.1} \int_{t=0}^{t=34.1\,min.} u(z,t)\, dt \right) dz \qquad (2)$$

Both calculations were performed using the vertical structure of velocity and concentration. Concentrations were extrapolated in the same manner as they were for suspended mass calculations. We assumed the oscillatory component of the cross-shore velocity was constant with elevation above the bed. This assumption overestimates velocity in the wave boundary layer, but, if the boundary layer was 0.05 m thick, the assumption would increase the flux by less than ten percent. The cross-shore mean current was linearly extrapolated to zero at the bed from the velocity at 0.50 m above the bed. The choice of a linear extrapolation was supported by the shapes of the velocity profiles.

Since near-bottom mean currents were offshore in the inner sixty-five percent of the surf zone, fluxes calculated using equation 2 were offshore at all measurement stations (Fig. 8C). However, fluxes calculated using equation 1 were onshore at four of the seven measurement stations (Fig. 8C).

The different results from the two methods of calculating the cross-shore flux occurred because a correlation existed between velocity fluctuations and concentration fluctuations. Rewriting the equations in terms of mean and fluctuating parts illustrates that eq. 1 includes the fluctuation correlations while eq. 2 does not. In the following analysis, an overbar denotes a time-averaged quantity and a prime denotes a fluctuating quantity.

The concentrations at an instant in time is composed of a mean concentration and a fluctuating concentration

$$c = \overline{c} + c' \qquad (3)$$

Likewise, the cross-shore velocity at an instant in time is

$$u = \overline{u} + u' \qquad (4)$$

Equation 1 multiplies the concentration and velocity before time averaging. Using the above notation, equation 1 can be written as

$$\overline{cu} = \overline{(\bar{c} + c')\ (\bar{u} + u')} \tag{5}$$

$$= \bar{c}\ \bar{u} + \cancelto{0}{\overline{\bar{c}u'}} + \cancelto{0}{\overline{c'\bar{u}}} + \overline{c'u'} \tag{6}$$

The second and third terms in Eq. 6 drop out because, by definition, the time average of the fluctuations is zero. This leaves

$$\overline{cu} = \bar{c}\ \bar{u} + \overline{c'u'} \tag{7}$$

In equation 2 the fluctuating quantities vanish before multiplying concentrations and velocities. Following the same procedure as above, equation 2 can be written as

$$\bar{c}\ \bar{u} = (\overline{\bar{c} + \cancelto{0}{c'}})(\overline{\bar{u} + \cancelto{0}{u'}}) \tag{8}$$

Subtracting equation 8 from equation 7 gives $\overline{c'u'}$, a measure of the correlation of concentration and velocity fluctuations. For lack of a better term, $\overline{c'u'}$ is referred to as a flux coupling. A low value for the flux coupling indicates a randomness of fluctuations relative to each other while a high value indicates a high degree of correlation.

The cross-shore flux coupling was positive (onshore) at every measurement position and increased with increasing water depth (Fig. 9). Again the position landward of the bar crest, sled station 3, was most active and had the highest flux coupling. The coupling of high suspended-sediment concentration with periods of onshore flow caused a net onshore transport of suspended sediment in the presence of a net offshore transport of near-bottom water.

Bed elevation changes were predicted from the cross-shore variation in the suspended-sediment transport calculated using equation 1. Convergences and divergences of the cross-shore transport contribute to accretion and erosion, respectively, of the nearshore profile. There was a convergence of cross-shore suspended-sediment transport on the bar's landward flank and a divergence on the bar's seaward flank (8D). The cross-shore suspended-sediment transport could account, qualitatively, for the migration of the bar landward in the presence of the mean offshore near-bottom currents. To see how much of the profile change could be attributed to the cross-shore suspended-sediment transport, average profile change between sled stations were calculated using a simplified form of the erosion equation.

$$\Delta\eta = \frac{1}{\phi}\frac{1}{\rho_s}\frac{\Delta Q_{sx}}{\Delta x}\Delta t \tag{9}$$

where η is the bed elevation in meters, ϕ is the porosity of the bed material equal to 0.40, ρ_s is the density of the sediment in kg m^{-3}, Q_{sx} is the mass flux of suspended sediment in kg m^{-1}s^{-1}, x is the cross-shore distance, and t is time in seconds. We assumed that

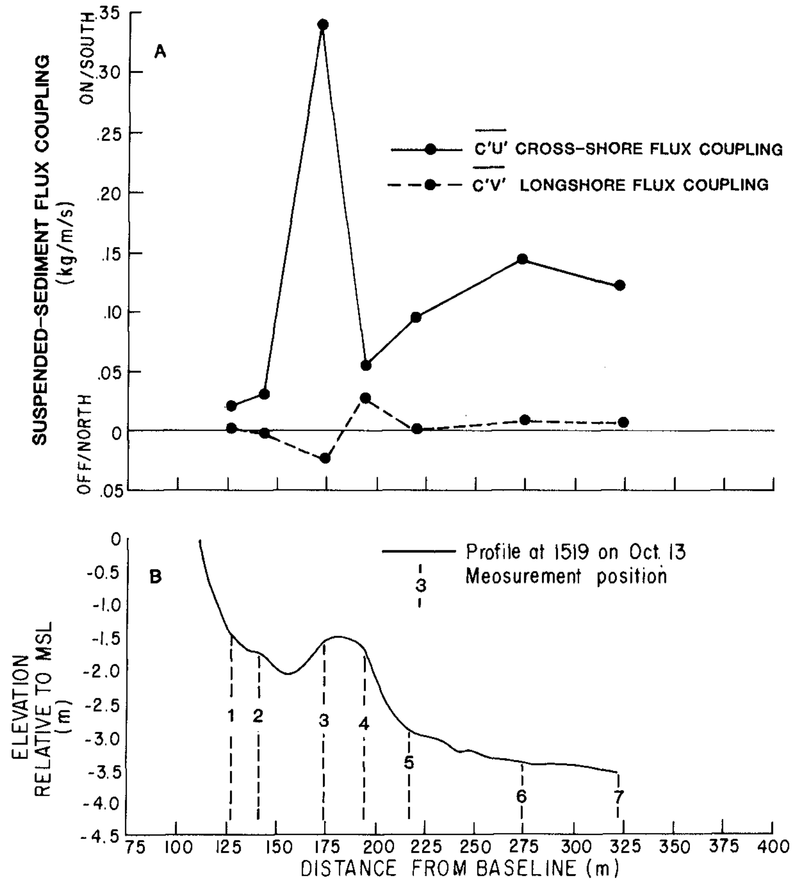

Fig. 9 Cross-shore variation of the longshore ($\overline{c'v'}$) and cross-shore ($\overline{c'u'}$) flux couplings. Flux couplings were calculated by subtracting Eq. 2 from Eq. 1. The data collection sequence was sled station 7, 3, 1, 5, 2, 4.

the 34.1 minute record of flux was representative for the six hour and thirty minute period between profiles. Profile changes calculated using equation 9 were compared to the observed profile changes. Figure 10 shows the relationship between predicted and measured average bed elevation changes between stations. Profile changes were calculated using both the total water column and only the lowermost 0.75 m to indicate the contribution of the flux extrapolations in the upper water column. Away from the bar, the observed erosion is not predicted. Possibly gradients in the longshore suspended-sediment transport or in the longshore and cross-shore bedload transport caused the observed erosion. Accretion was predicted on the landward flank of the bar and erosion on the seaward flank. The measured average profile changes exhibited the same pattern and were of similar magnitude.

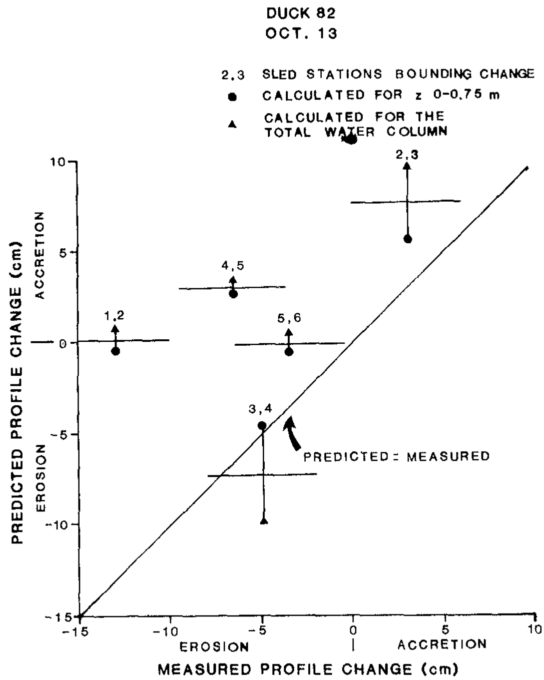

Fig. 10 Comparison of measured average bed elevation changes between sled stations with average changes predicted from convergences and divergences in the cross-shore suspended-

CONCLUSIONS

Measurements showed that a strong coupling existed between high suspended mass in the water column and periods of onshore flow such that a net onshore transport of sediment occurred even though the mean flow was in an offshore direction. In the vicinity of the bar crest, gradients in the cross-shore suspended sediment transport could account for changes in the nearshore profile. These results suggest suspended sediment is very important in surf zone processes.

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REFERENCES

Bowen, A. J. (1980): Simple models of nearshore sedimentation: beach profiles and longshore bars, in The coastline of Canada, S. B. McCann, Editor, Geological Survey of Canada, Paper 80-10, pp. 1-11.

Downing, J. P., Sternberg, R. W. and Lister, C. R. B. (1981): New instrumentation for the investigation of sediment suspension processes in the shallow marine environment, Mar. Geol., Vol. 42, pp. 19-34.

Komar, P. D. and Gaughan, M. K. (1973): Airy wave theory and breaker height prediction, Proc. 13th Coastal Eng. Conf., ASCE, pp. 405-418.

Komar, P. D. and Miller, M. C. (1975): The initiation of oscillatory ripple marks and the development of plane-bed at high shear stresses under waves, J.S.P., Vol. 45, pp. 697-703.

Mason, C., Sallenger, A. H., Holman, R. A., and Birkmeyer, W. A. (in press): A comprehensive experimentation storm-related coastal processes, Proc. 19th Coastal Eng. Conf., ASCE.

Sallenger, A. H., Howard, P. C., Fletcher, C. H., and Howd, P. A. (1983): A system for measuring bottom profile, waves and currents in the high-energy nearshore environment, Mar. Geol., Vol. 51, pp. 63-76.

Watanbe, A., Riho, Y., and Horikawa, K. (1981): Beach profiles and on-offshore sediment transport, Proc. Coastal Eng. Conf., ASCE, pp. 1106-1120.