CHAPTER 205

THE CONTRIBUTION OF SUSPENSION EVENTS TO SEDIMENT TRANSPORT IN THE SURF ZONE

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ABSTRACT

Suspension of sand in the surf zone is intermittent. Especially striking in a time series of concentration are periods of intense suspension, suspension events, when the concentration is an order of magnitude greater than the mean. We used field data collected in the inner half of the surf zone during a large storm (greater than 1.5 m wave heights and 13 second periods) to define and describe suspension events and determine the contribution of events to the sediment transport.

Large suspension events were found throughout the inner half of the surf zone, occurred about once every 1 to 2 minutes, and each had a duration of about 5 seconds. These events tended to occur during onshore flow under the wave crest, resulting in an onshore contribution to the suspended-sediment transport. Even though large events occurred less than 10 percent of the total time, at some locations onshore transport associated with suspension events was greater than the offshore directed transport during non-event periods, causing the net suspended sediment transport to be onshore. Events and longshore velocity were not correlated. However, events did increase the longshore suspended-sediment transport by approximately the amount they increase the mean concentration, ranging from 15 to 55 percent depending on the definition used for events. Because of the lack of correlation, the longshore suspended-sediment transport can be adequately modeled as the vertical integration of the product of the time-averaged longshore velocity and the time-averaged concentration.

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INTRODUCTION

Ever since the first surf-zone deployment over 25 years ago of a fast-response instrument that monitored the amount of sediment in suspension (Brenninkmeyer, 1976a,b), researchers have observed short periods of intense suspension when sediment reaches high (order 1 m) into the water column. These intense suspensions were separated by longer quiescent periods when sediment concentrations were an order of magnitude less and suspension was confined to near the bed (order 10 cm). Brenninkmeyer, 1976a, called these intense periods "sand fountains". We will refer to them as "suspension events" following the terminology of Downing (1983).

Models for sediment suspension currently are not able to predict the occurrence of suspension events in the surf zone. In this paper, field data are used to objectively define event periods from a suspended-sediment concentration time series collected in the surf zone during a large storm. The average properties of suspension events are described and the contribution of events to the longshore and cross-shore suspended sediment transport are determined. We show that large suspension events tend to occur during onshore flow under wave crests and result in an onshore transport that can dominate the net suspended transport.

EXPERIMENT SETTING AND METHODS

A large cooperative field experiment investigating the morphologic response of the nearshore to storms was conducted at the Army Corps of Engineers Field Research Facility (FRF) at Duck, North Carolina in the Fall of 1982 (see Mason and others, 1984, for a description of the experiment). The FRF is located on a long straight beach with bi-modal sand on the foreshore (1.0 mm and 0.3 mm modes), sand and pebbles in the longshore trough, and fine sand (~0.15 mm) offshore.

As part of this experiment the US Geological Survey deployed an underwater sea sled (Sallenger and others, 1983) equipped with instruments to measure waves, currents, sediment suspension, and profile change. Waves were measured using a pressure sensor and horizontal currents were measured at 3 elevations (0.5, 1.0, and 1.75 m above the bed) using 1" Marsh-McBirney electromagnetic current meters Suspended-sediment concentration was measured at 5 elevations (0.10, 0.13, 0.19, 0.31, and 0.61 m above the bed) using optical backscatter sensors (OBS, Downing, 1981). The nearshore profile was measured using an infrared range-finder sighting on prisms mounted on a 10 m mast as the sled was pulled offshore and onshore by a winch and lines and a system of blocks.

Sled measurements were carried out for a two-week period during which one large extra-tropical cyclone (northeaster) and a smaller storm generated large waves and strong currents at the field site. The standard daily measurement regime was a starting profile extending several hundred meters offshore, processes measurements at up to 8 locations across the surf zone, and an ending profile to determine changes during the processes measurements. The entire procedure took about 6 hours and bracketed the time of high tide to minimize sea-level changes through the measurement period. At each of the measurement locations, 34.1 minutes of data were collected at 2 Hz for each sensor.

The largest profile response occurred during the northeaster of October 10-15. A linear bar formed on October 10th (Sallenger and others, 1985, Mason and others, 1984) and evolved into a crescentic bar by October 15th. The position of the bar crest on the sled transect moved offshore during the 10th, 11th, and 12th at rates as great as 2.2 m/hr and then migrated onshore on October 13th. The data presented in this paper were collected on October 13th.

The waves and currents were influenced by the barred profile of October 13th (Fig. 1). Because of the length of line pulling the sled, it was limited to operating in the inner six-tenths of the surf zone. Measurements were made at 7 locations between 17 and 224 m offshore, in water depths ranging from 2.3 to 4.3 m. The wave period ranged between 13 and 15 seconds. The standard deviation of the horizontal velocity was maximum at the bar crest, lowest in the trough, and fairly uniform at the measurement locations seaward of the bar. The magnitudes of the 34.1-minute-averaged speed and cross-shore velocity at 0.5 m above the bed increased toward the beach and had maximums at the measurement location nearest the deepest part of the longshore trough. The cross-shore mean currents at 0.5 m above the bed were directed offshore at all measurement locations (Fig. 1).

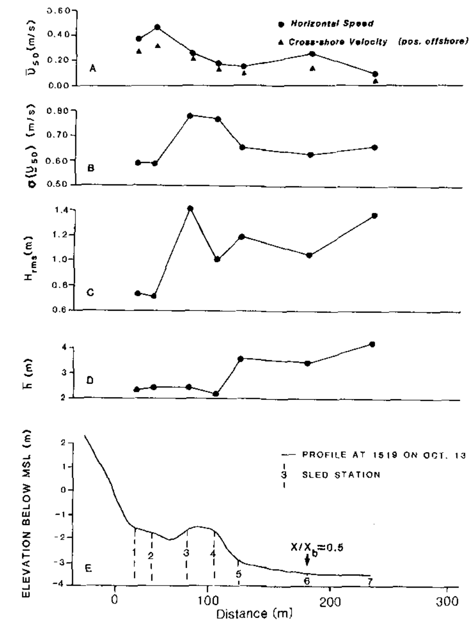

Figure 1- Conditions in the inner half of the surf zone at the Army Corps of Engineers Field Research Facility at Duck, NC during October 13, 1982. Shown from bottom to top are: 1) nearshore profile and measurement locations, 2) depths, 3) RMS wave heights, 4) standard deviation of the horizontal velocity at 50 cm above the bed, 5) mean horizontal speed and cross-shore velocity.

DEFINITION OF SUSPENSION EVENTS

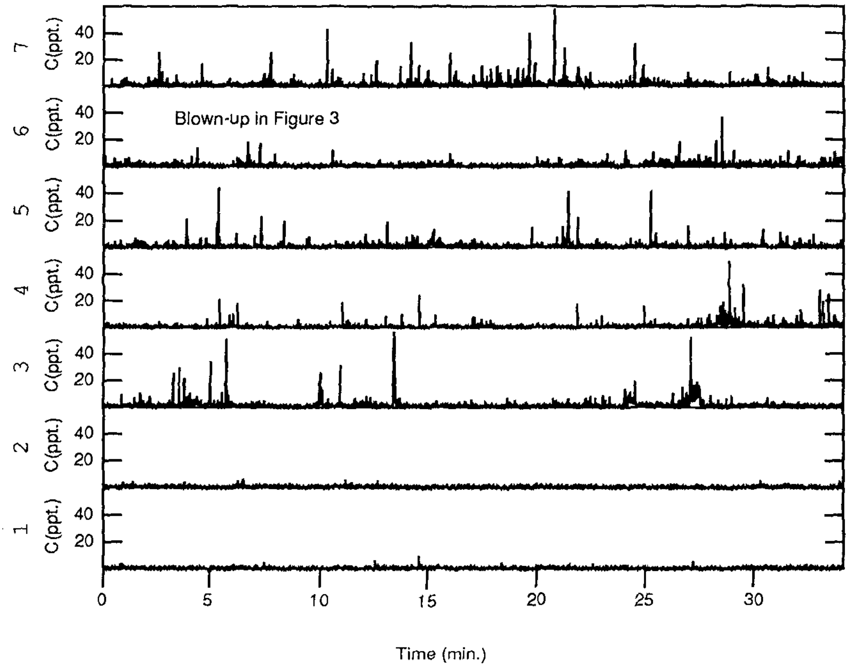

Figure 2- Time series of suspended sediment concentration at 13 cm above the bed for 7 measurement locations.

Suspension of sediment was intermittent at all measurement locations and at all OBS sensor elevations on October 13th. At 13 cm above the bed, concentrations were highest at the bar crest and at the offshore measurement location (Fig. 2, Figure 7 in Jaffe and others, 1984) and lowest in the longshore trough. At the 3 higher sensors (19, 31, and 61 cm) suspension was also intermittent with the intensity of suspension and the rate of occurrence of intense suspension decreasing higher in the water column (for example, see Fig. 3). For the 10-minute period shown in Figure 3 the intense suspension occurred during the passage of wave groups (intense suspension associated with wave groups was also observed by Hanes and Huntley, 1986). Suspension events were not associated with wave groups for other locations in the surf zone. Intense suspension was observed at other measurement locations following a strong offshore flow (also observed by Downing, 1983 at a beach in Washington). Since all of the measurement position were well within the the calculated plane-bed regime (Komar and Miller, 1975, Grant and Madsen, 1982), suspension events were not due to vortices associated with small-scale bedforms. Osborne (this volume) has recently found that larger, irregular bedforms sometimes form under the conditions observed at some of the measurement locations, so we can not rule out flow disturbances from this class of bedform creating suspension events. It is beyond the scope of this paper to

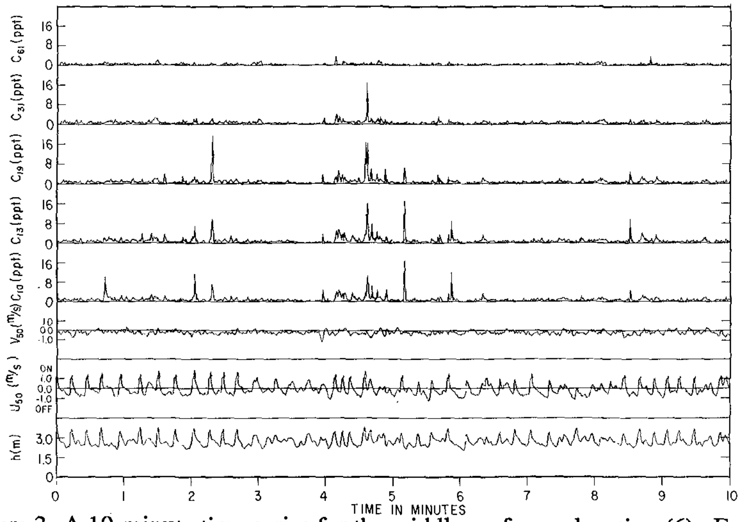

Figure 3- A 10-minute time series for the middle-surf-zone location (6). From the bottom, the hydrostatic approximation to sea level (h), cross-shore (U) and longshore (V) water velocities at 50 cm above the bed, and sediment concentrations (ppt) at 13, 19, 31, and 61 cm above the bed. The time period corresponds to 2 through 12 minutes shown in Figure 2.

determine the processes responsible for producing suspension events. This paper will, however, quantify the characteristics of these periods of intense suspension and their contribution to transport in the surf zone.

Before quantitatively describing the character and transport contribution of the intense suspension periods, an objective criteria must be developed to distinguish these periods from less energetic periods of suspension. One simple definition would be to call periods when the concentration exceeds a threshold value a suspension event. The choice of threshold level will dictate how many events occur and their characteristics. For example, if 20 ppt was chosen as the event threshold there would be no events in the longshore trough (locations 1 and 2) and some periods where suspension was episodic and intense at other measurement locations would not be considered events (a good example is location 6). To make the choice less arbitrary, event thresholds used in this paper were based on the statistical properties of the concentration distribution. Using the statistics for each location makes the definition of an event scale with the overall intensity of suspension at that location. The distribution of concentrations measured in the surf zone were skewed, with many low values and fewer high values (Fig. 4). Several event thresholds based on the mean and standard deviation of the concentration distribution were tried in order to define events. Two event thresholds are used in this paper to define events. A event was defined to occur when the concentration was greater than the mean plus one standard deviation (Fig. 5). Large events occur when the concentration exceeds the mean plus three standard deviations. In order to include the beginning and end of the event, an event start/end threshold was chosen. In this

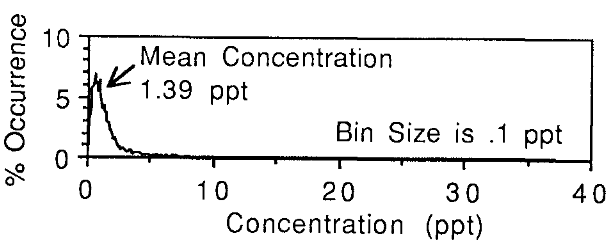

Figure 4- Frequency distribution of sediment concentrations at 13 cm above the bed for the middle-surf-zone location (6).

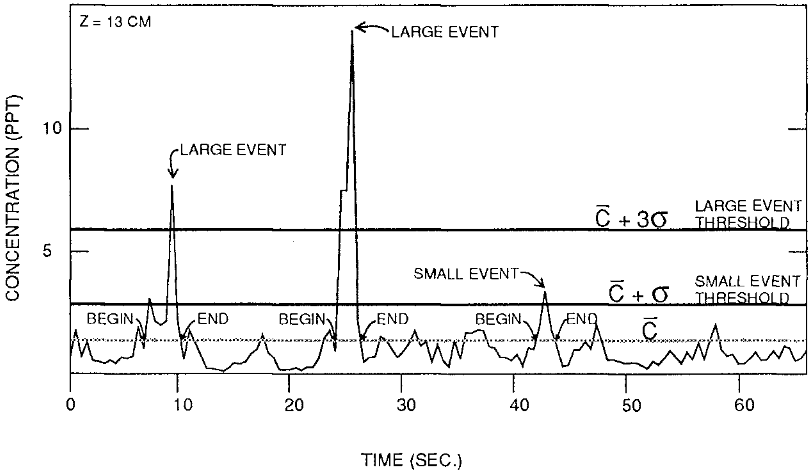

Figure 5- Suspended-sediment time series showing definition of suspension events

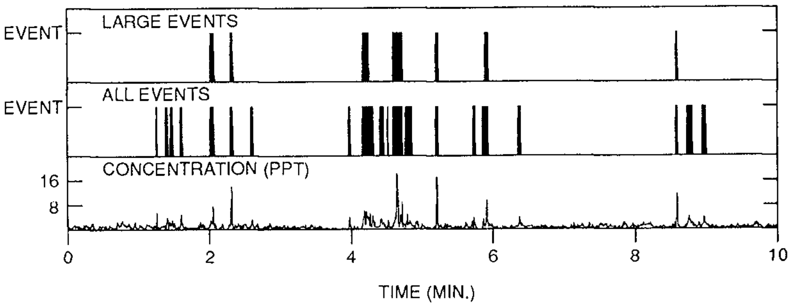

Figure 6- Application of suspension event definitions to the 10-minute series in Figure 3. From bottom to top are: 1) the concentration time series, 2) all events shaded, 3) large events shaded.

paper, the event start/end threshold used was the mean concentration.

Using the above definitions, time series of suspended-sediment concentrations at 13 cm above the bed were transformed to event time series to allow an automated analysis of suspension events (Fig. 6). Characteristics of events, including duration, rate of occurrence, and percent of the total time and concentration, are discussed in the next section.

PROPERTIES OF SUSPENSION EVENTS IN THE SURF ZONE

Time series of large suspension events are shown for the 7 measurement locations in Figure 7. The measurements were not synoptic, so no information about phasing between events at different cross-shore locations can be extracted from the figure. The number of large events in the 34.1 minute records varies from a low of 15 near the bar crest (location 3) to a high of 37 at the mid-surf-zone location (6). Events tend to occur in packets and there are long intervals of several minutes or more between events at all measurement locations.

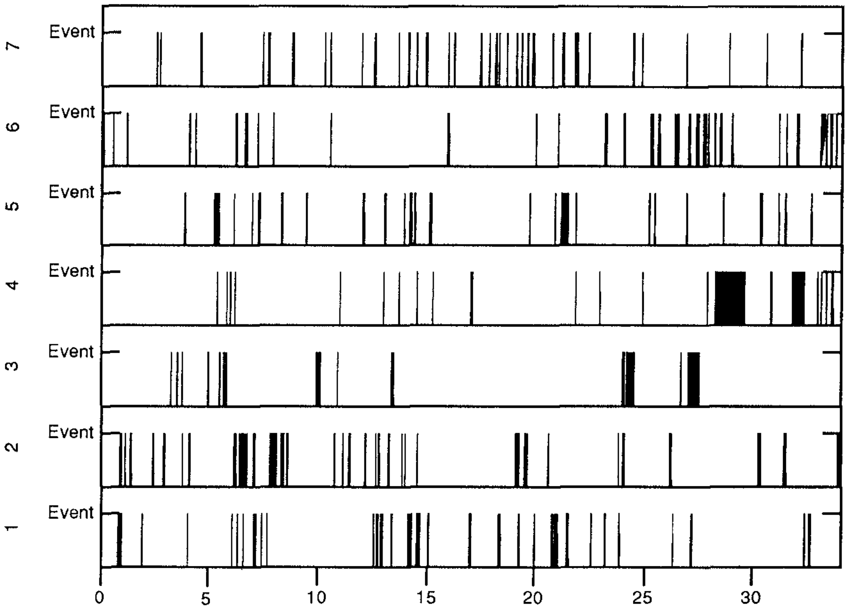

Figure 7- Large event time series for the 7 measurement locations.

The mean behavior of both events and large events are shown in Figure 8. On the average, large events occur about every minute away from the bar crest and every two minutes at the bar crest (Fig. 8a). Events defined with a lower threshold occur more frequently, but the cross-shore structure is similar to the structure for larger events. In the longshore trough these events occur about 5 times a minute (once every 12 seconds) which is less than the wave period, 13 seconds.

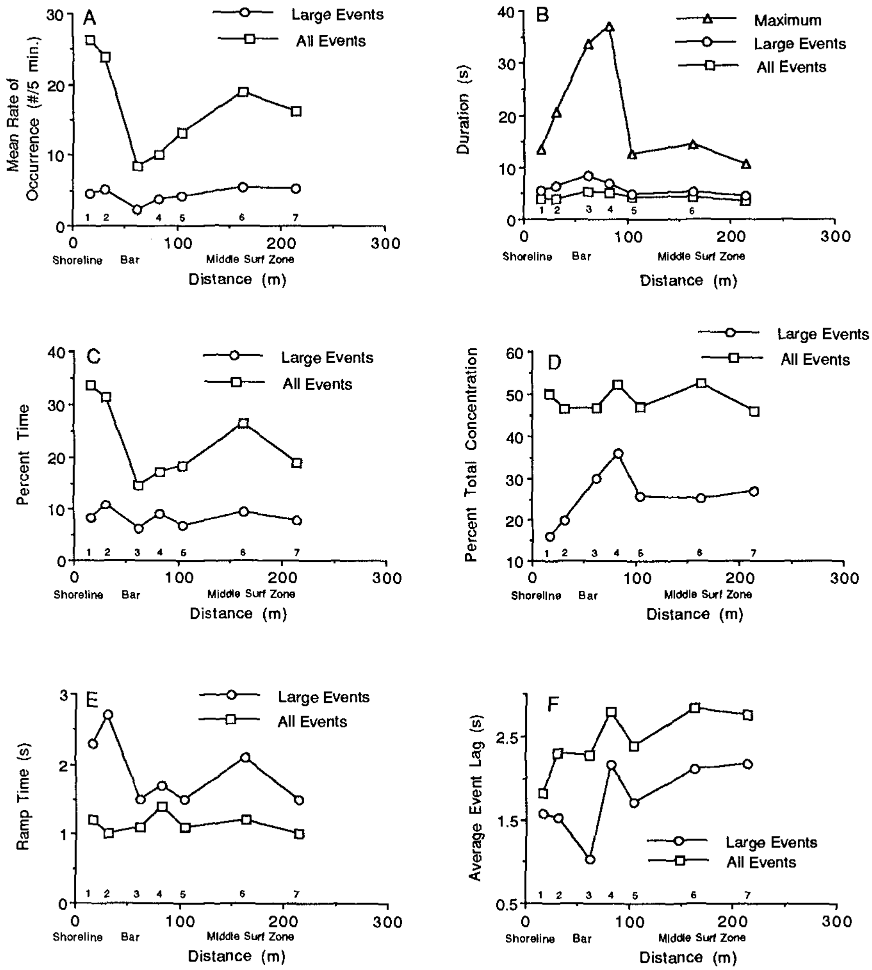

Figure 8- Average event properties for large and all events showing; a) mean rate of occurrence, b) duration, c) percent of the time events occur, d) percent of the total concentration, e) ramp time, and f) average lag of the event relative to the velocity zero up-crossing.

Both large and small events last an average of about 5 seconds, with larger events lasting longer (Fig. 8b). The maximum event duration, about 35 seconds, was near the bar crest where conditions were most energetic. At other locations in the surf zone the longest events lasted 15 or 20 seconds. The quickest events were only 1 or 2 seconds long. Typically, there was a wide distribution of event durations at each measurement location.

Because events occur infrequently and do not last long the percent of time that events occupy is relatively low, about 10 percent for large events and 15 to 35 percent for all events (Fig. 8c). However, the contribution of events to the total concentration is large, about 15 to 35 percent for large events and 45 to 55 percent for all events (Fig. 8d).

Events are typically asymmetric with a rapid increase in concentration and a more gradual decrease. The ramp time, the time from the start of the event until the maximum concentration, averages between 1.5 and 2.7 s for for large events and between 1.0 and 1.4 s for all events (Fig. 8e). The ramp time for large events is minimum near the bar crest, one of the most energetic measurement locations. The shortest ramp time combined with the longest average duration makes events near the bar crest the most asymmetrical. Events are the most symmetrical in the trough of the bar.

Events tend to start several seconds after the flow reversal from offshore flow under the wave trough to onshore flow under the crest. On the average, large events start from 1.0 to 2.2 seconds after the velocity zero up crossing (Fig. 8f). The minimum lag time is at measurement location 3, the landward side of the bar crest. Lags are longest at the seaward side of the bar crest (location 4) and the middle-surf-zone locations (6 and 7). When all events are included the average lag time increases, ranging from 1.8 to 2.8 seconds. The distribution of lag times is not symmetrical about the average for large events. For instance, at the middle-surf-zone location (6) the largest number of events was near 0 lag time from the velocity zero up crossing, but the average was several seconds after the crossing because of a few events with long lag times.

CONTRIBUTION OF SUSPENSION EVENTS TO TRANSPORT

Because suspension events occur infrequently and last for a short time one might think their contribution to the total suspended sediment transport is not very large. On the other hand, because suspension events increase the overall mean concentration by a significant amount, it could be postulated that events are significant to the total transport. To determine the event contribution to transport we made four calculations; 1) transport during large events, 2) transport during all events, 3) transport during non-event periods, and 4) total transport (2 + 3). These transport calculations were for one elevation and used the concentration measured 13 cm above the bed and horizontal velocity measured at 50 cm above the bed. The results, presented below, show that event contributions to longshore and cross-shore transport were very different.

Longshore Transport

Events increase the longshore suspended sediment transport by approximately the amount they increase the mean concentration. For large events, the contribution ranged between 15 and 35 percent at all measurement locations on October 13th. For all events, the contribution was about 50 percent.

There is no preference for events to occur when the longshore velocity is either higher or lower than the mean. The contribution of events to longshore transport, $\overline{VC}_{event}$, is approximately equal to the product of the mean longshore velocity, $\bar{V}$, the mean concentration during events, $\bar{C}_{event}$, and the percentage of time events occurred, p_{event}. During non-event periods, the concentrations are also not correlated to the longshore velocity so the non-event transport, $\overline{VC}_{non\text{-}event} p_{non\text{-}event}$ is approximately $\bar{V}\,\bar{C}_{non\text{-}event}\, p_{non\text{-}event}$. The total longshore suspended transport can be adequately calculated by $\bar{V}\,(\bar{C}_{event}\, p_{event} + \bar{C}_{non\text{-}event}\, p_{non\text{-}event})$, or $\bar{V}\,\bar{C}_{total}$. The time variation of the concentration is not needed to accurately predict the longshore suspended sediment transport. However, the vertical structure of the mean velocity and concentration must still be known because suspended-sediment concentration is high near the bed where longshore velocity is low and low higher up in the water column where velocities are higher.

Cross-shore Transport

Suspension events make a significant contribution to the cross-shore suspended-sediment transport. Figure 9 shows the contributions of large events and non-event periods to the total cross-shore transport. The average transport during large events is onshore for all measurement locations seaward of the longshore trough. Transport during non-event periods, moving in the same direction as the near-bottom current, is offshore for all measurement locations. The total suspended-sediment transport is approximately, but not exactly, equal to the sum of large event and non-event periods because transport during small events is slightly offshore. The total transport is offshore for the longshore trough (measurement locations 1 and 2), landward side of the bar crest (3), and middle-surf-zone (6) locations, near zero seaward of the bar at location 5, and onshore on the seaward side of the bar crest (4) and the farthest seaward location (7).

The timing of suspension relative to the wave-induced oscillatory flow results in an average onshore transport during large events. For example, two events at the beginning of the time series in Figure 10 qualitatively show that the most intense suspension occurs during or just after the onshore flow under the wave crest. The average large event starts about 1 to 1.5 seconds after the velocity zero up-crossing (Fig. 8f) when the flow is onshore. Because the maximum

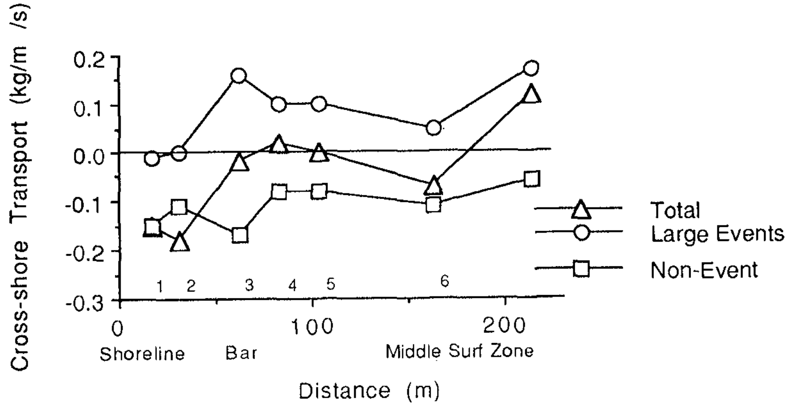

Figure 9- Cross-shore transport 13 cm above the bed for large events, non-event periods, and total. Small event transport is not shown but is small and offshore directed.

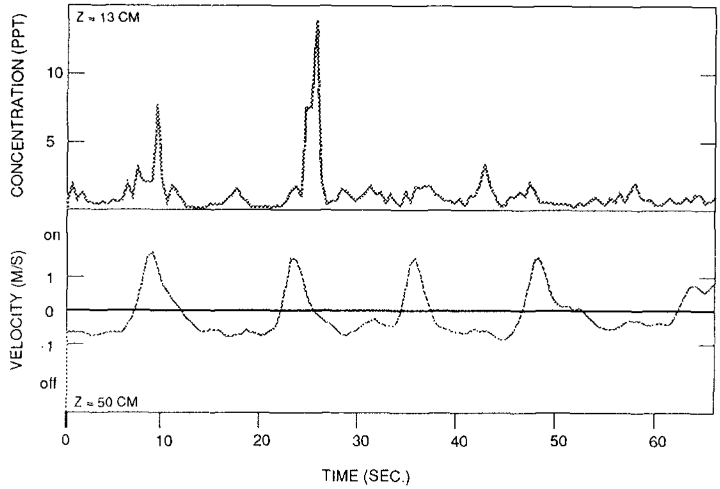

Figure 10- Time series of velocity and concentration showing the tendency for events to occur during onshore flow

concentration is reached quickly, about 1.5 to 2.5 seconds later (Fig. 8e), it too usually occurs during onshore flow.

Ensemble averages for the cross-shore velocity and concentration for three different measurement locations are shown in Figure 11. These averages included all large suspension events and were constructed using the velocity zero up-crossing time for reference for both the velocity and concentration time series. The phase of events in the longshore trough varied widely resulting in an average large-event concentration with no distinct peak. This lack of phasing between the concentration and velocity resulted in a near zero net transport during large events for longshore trough measurement locations (Fig. 9). Large events at the bar crest and the middle surf zone tended to occur shortly after the velocity zero up-crossing resulting in a peak in the concentration (Fig. 11) and a net onshore transport contribution (Fig. 9).

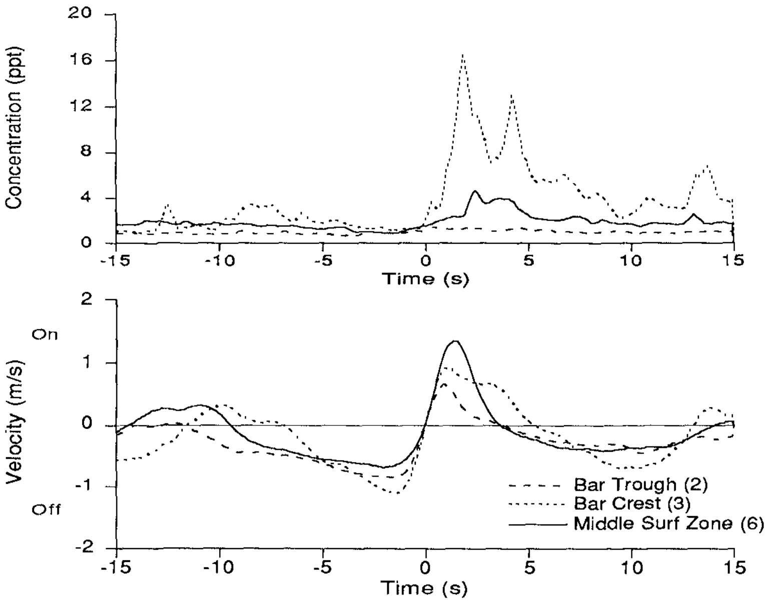

Figure 11- Ensemble averaged velocity and concentration for all events at measurement locations in the bar trough, bar crest, and middle surf zone. The time series are averages of velocities and concentrations for large suspension events with the velocity zero-upcrossing as the common time reference. .

DISCUSSION

We have found that much of the net cross-shore suspended sediment transport at 13 cm above the bed was contributed by large suspension events. To accurately model the cross-shore transport the event magnitude and phase with velocity must be well predicted. Without modeling the large events, the predicted transport will be more strongly influenced by the mean current velocity (offshore) which would result in a predicted transport in a different direction than the actual transport at some measurement locations.

The results show that events are not as significant to predicting longshore suspended transport because events are not strongly correlated with the longshore velocity. However, inability to model events would result in an underprediction of the magnitude of the longshore transport up to about 50 percent, but unlike the cross-shore transport the direction would be accurately modeled.

Event transport is one part of the "fluctuating flux" addressed in Jaffe and others, 1984. The results in this paper support the conclusion that the time dependency of the flux (transport) is important to the net cross-shore flux, but not to the longshore flux (Jaffe and others Figures 8 and 9). Not addressed in this paper, but still an important property of the cross-shore transport is the tendency for low concentrations (less than the mean) to be correlated with offshore flow.

An improvement to this study would be to asses the vertical variation of events and their contribution to transport. Although we do not expect the conclusions to be significantly altered, the changes in concentration/velocity phasing in the vertical would be helpful information for modeling events.

The definitions for suspension events could possibly be improved. Because the concentration distribution was used to generate the statistics (mean and standard deviation) for the event definitions, it could be argued that instead of defining suspension events we are just looking at a tail of the distribution, which will always exist, so events will always exist. Although it is true there will always be concentration values in the tail, the timing of these high concentration values is not related to the distribution. For example, all the points in the tail could occur in one section of the time series and create one event or they could occur as single points equally spaced in time or a large number of other possibilities. Our definition does a good job of choosing the points that are visually striking when examining a time series of suspension.

CONCLUSIONS

1) Suspension events, periods of intense suspension, can be defined on the basis of the concentration distribution. Two types of events were defined in this paper: 1) event periods when the concentration exceeded the mean plus one standard deviation, and 2) large events periods when the concentration exceeded the mean plus three standard deviations.

2) Large events were found throughout the inner half of the surf zone, occurred about once every 1 to 2 minutes, and lasted about 5 seconds.

3) Large events tended to occur during onshore flow under the wave crest, resulting in an onshore contribution to the suspended-sediment transport. Even though large events occurred less than 10 percent of the total time, at some locations their onshore transport was greater than the offshore transport during non-event periods . As a consequence, net suspended sediment transport was onshore.

4) Events were not correlated with the longshore flow and increased the longshore suspended sediment transport by approximately the amount they

increased the mean concentration, ranging from 15 to 55 percent depending on the definition used for events. Because concentration and longshore velocity were not strongly correlated, the longshore suspended sediment transport can be adequately predicted as the vertical integration of the product of the time-averaged longshore velocity and the time-averaged concentration.

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