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Technical Report

Funding was provided by the Office of Naval Research
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Department of Biology

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1 Introduction

Predicting locations where particles will first contact a flat surface is possible in steady, unidirectional, boundary-layer flows by using momentum flux as an analog to particle flux (e.g., Schlichting, 1979). Predicting particle behavior in flows over complex surfaces is more difficult (Paola, 1983; Middleton and Southard, 1984). Particle contact with a surface in flow is determined by particle characteristics, such as size, density and sinking velocity, and flow characteristics such as free-stream flow velocity, turbulence, shear stress and flow separations in the boundary layer. Hydrodynamic processes that determine particle contact with a surface also may influence initial settlement of benthic invertebrate larvae in controlled laboratory flows (Hannan, 1984; Butman, 1986, 1987; Mullineaux and Butman, 1991) and in the field (Duggins et al., 1990; Keen, 1987; Mullineaux and Butman, 1990; Mullineaux and Garland, in prep). It is often difficult, however, to determine which flow characteristic is responsible for the resulting settlement pattern. Furthermore, the post-contact exploratory behavior of larvae can also cause deviations from settlement patterns expected from hydrodynamic considerations alone.

The utility of using the flat plate approach in controlled laboratory flows is that different configurations of the leading edge of flat settlement plates allow alteration of boundary-layer flows without changing the character of the surface. Leading edges can be constructed to generate a variety of boundary-layer flows differing in boundary-layer thickness, turbulence, plate-ward advection, and shear stress. Although these characteristics co-vary downstream from the leading edge in a classical boundary layer over a thin flat plate, they do not always co-vary in flows over more complex surface geometries. In some of these cases, each flow characteristic can be isolated, and its effects studied independently. Because movements of relatively small particles are strongly influenced by flow (e.g., Nowell, 1983), sites and rates of initial contact onto plates should be predictable from boundary-layer flow characteristics. Contact of particles with plates in these flows is, in turn, a useful analog for initial contact of passive larvae onto similar surfaces.

The objective of the present study was to quantify: (1) the location, relative to the leading edge, where small, low-density particles first contact a flat surface in a developing boundary layer (based on varying downstream turbulence, shear stress and vertical advection); and (2) the relationship between contact rate of particles on flat surfaces and particle flux parallel to the surface in a uniform, fully-developed, boundary layer. These contact rates and patterns were then used to model initial contact of passive larvae and propagules onto flat plates. Relatively small (< 100 μm), low-density larvae are the focus of this study for two reasons: (1) they are more likely to be passive in boundary-layer flows than large larvae because their swimming speeds tend to scale with their size; and (2) small larvae, hydrodynamically similar to the particles used in this study, are prominent in the deep sea (Mullineaux, 1992) where these models will be tested. This study was designed to help define the role of flow in larval contact and settlement onto natural surfaces in deep-sea habitats and for evaluating collection characteristics of larval settlement plates. If, for example, larval contact rates can be predicted from larval concentration in controlled laboratory flume flows, then settlement rates onto plates can be used to estimate quantitative larval abundances in the field, assuming that larvae initially contact plates like passive particles (Mullineaux and Butman, 1991).

2 Methods

2.1 Plate Design and Flow Measurements

In order to correlate particle contact onto surfaces with specific flow characteristics, flat plates were constructed with three types of leading edge configurations: "faired", "bluff", and "split" (Fig. 1). Each leading edge configuration generated unique boundary-layer flows that could be used to determine flow characteristics that may be responsible for influencing particle contact with plates. All three plates were 10 cm wide by 26 cm long and were constructed from polycarbonate plastic sheets.

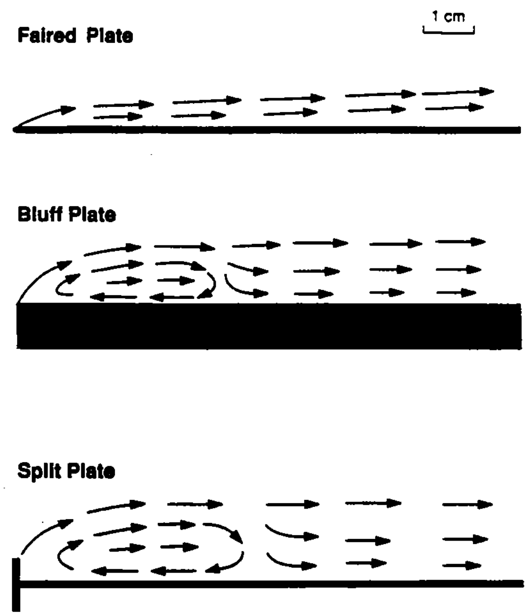

Figure 1. Plate design and qualitative velocity vectors drawn from LDV measurements of vertical and horizontal velocities at a along-stream flow speed of 10 cm s^{-1} (measured at 10 cm above flume bottom). Flume flow is from left to right in diagram.

The three plate types were configured to develop the boundary layer flows described in Mullineaux and Butman (1991). The "faired" plate was 0.15 cm thick along its entire length, with the leading edge tapered to create a fairing for the oncoming flow. A classical boundary layer, described by "flat plate" theory (e.g., Schlichting, 1979) was expected to develop along this plate. The "bluff" plate was 1.0 cm thick along its length. Over this plate, the flow was expected to separate at the bluff surface of the leading edge and reattach downstream at a location determined by the along-stream velocity and leading edge thickness (Ruderich and Fernholz, 1986). The "split" plate was 0.15 cm thick along its length but had a "splitter bar", consisting of a 1.0 cm high polycarbonate strip attached normal to the flow, at the leading edge. Flume studies (Mullineaux and Butman, 1991) showed that the flow separation created by this configuration was qualitatively similar to that of the bluff plate, but differed in size and turbulent intensity. In addition, the splitter bar caused the mean horizontal velocity and shear stress immediately downstream of the leading edge to be substantially reduced relative to similar locations on the bluff and faired plates.

Flow over the three plate types was measured using a two-axis, forward-scatter laser Doppler velocimeter (Agrawal and Belting, 1988). The plates were set up individually for LDV measurements in an open-channel flow (see Butman and Chapman [1989] for a description of the flume and Mullineaux and Butman [1991] for a detailed description of profiling above a flat plate using the LDV). The flume was 17 m long and 60 cm wide, with an experimental "test section" located 12 m downstream from the flow straighteners. The flume was filled with freshwater to a height of 12 cm and the flow was adjusted to one of the two flow speeds (5 or 10 cm s^{-1} at 10 cm above the flume bottom).

Single plates were placed in the flume at the center of the test section, with the plate edges 25 cm from the flume side-walls. The plates were elevated 5 cm above the flume bottom on thin plastic legs in order to raise them above the region of highest shear within 2-3 cm of the bottom. Plates were oriented horizontally with their long dimension parallel to the flow. Vertical velocity profiles were measured with the LDV at successive locations downstream from the leading edge. The two axes allowed for simultaneous measurements of instantaneous along-stream (u) and vertical, or plate-ward (w) velocities. Velocity means ($\overline{u}$, $\overline{w}$), standard deviations [rms(u'), rms(w')], and variances (u'^2, w'^2) were calculated from measurements taken for 4 minutes at each position. Turbulence [rms(w')] and mean vertical advection (w) were calculated by integrating over the boundary layer from measurements taken at eight heights between 0.1 and 2.0 cm above the plate, as in Mullineaux and Butman (1991). Shear stress was calculated from the turbulent kinetic energy (u'^2) at a height of 0.1 cm above the plate. The downstream locations and spacing of profiles varied slightly among plate types and flow speeds, and depended on the presence and location of flow separation and reattachment points. No velocity profiles were measured over plates at 2 cm s^{-1} flows because of limitations of the flume pump at slow speeds. Instead, dye was released at the leading edges of the plates at an along-stream flow speed ranging from 2 to 13 cm s^{-1}, in order to visualize flow separations and the boundary-layer thickness. These studies were useful for determining critical flow speeds for development and destabilization of flow separations over each plate.

2.2 Particle Contact Experiments

Particle contact experiments were performed using the same experimental plates but in a different flume (Fig. 2). A racetrack-style flume (the Paddle-Wheel Flume described in detail in Butman and Grassle, submitted) was chosen for the particle contact studies because of its smaller volume (approximately 1800 liters as opposed to approximately 100,000 liters in the 17-Meter Flume). The number of particles required to seed the flow in the Paddle-Wheel Flume was almost 20 times less than the number needed to achieve similar concentrations in the 17-Meter Flume.

The Paddle-Wheel Flume was 8.5 m long and 50 cm wide. Eight paddles attached to flexible linkages revolved on a large paddle wheel and drove the flow at a constant velocity. The designated "test section" where flow disturbances from the channel bend had dissipated, was located 4.2 m downstream from the first bend following the paddles, and 1.5 m (three channel widths) upstream from the downstream bend. Flow speeds were adjusted by a

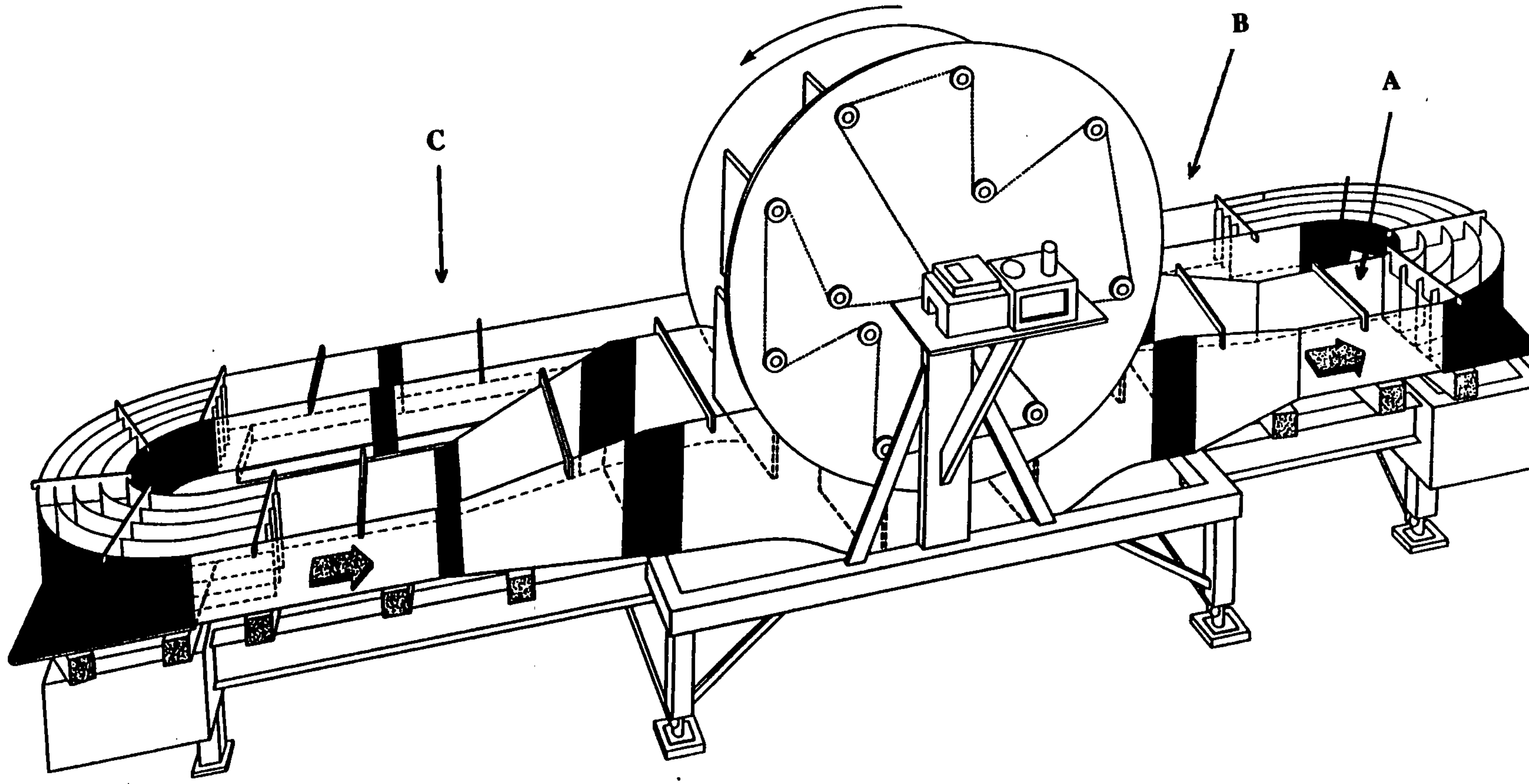

Figure 2. Schematic drawing, approximately to scale, of the Paddle Wheel flume used for the particle contact studies. Locations A, B, and C are regions where pump samples were taken to determine particle distribution in the flume. The "test section" where experimental plates were placed is located at C. Arrows represent direction of flow in the flume. Flow separators are located at both ends of the flume to reduce cross-stream flows generated while water flow around bends (Figure from Butman and Grassle, submitted).

rheostat that controlled the paddle wheel motor and were verified with a Marsh McBurney electromagnetic current meter. The flume was filled to a height of 14 cm with 10 μm filtered seawater at ambient room temperature and was allowed to warm up and deaerate overnight. This procedure was necessary because inflowing seawater at ambient winter-time temperatures was supersaturated with gasses. Deaerating the water overnight prevented bubbles that interfered with particle retention on the plates from forming during the experimental runs.

Due to the water depth in the flume (14 cm), cross-stream flow at the bottom and along the surface was expected (Butman and Grassle, submitted), but because the plates were near the center of the water column (5 cm above bottom), this cross-stream flow was not expected to quantitatively affect the outcome of this study. Furthermore, cross-stream flows should have dissipated at the test section.

Spores from the club moss *Lycopodium* sp. (Duke Scientific Company, product #215, Palo Alto, CA) were selected for use as particles in this study because of their low gravitational fall velocities and their low cost. *Lycopodium* releases pale yellow spores that, when hydrated, are 40-70 μm in diameter. The spore density in freshwater was 1.03 g cm^{-3} (Duke Scientific, pers. comm.). The fall velocities of these spores were expected to be in the range of passively sinking, deep-sea larvae and propagules, most of which are approximately 64-250 μm in diameter (Mullineaux, unpub. data), and have predicted settling velocities of < 0.1 cm s^{-1} .

A stock mixture of particles and seawater was made by mixing 0.25 - 0.50 g of dried spores with approximately 20 ml of 0.2 μm filtered seawater. The mixture was shaken vigorously until most of the spores were suspended. A few drops of Betadine surgical scrub were added to relieve surface tension. The spores were then allowed to hydrate for one hour at room temperature. A small aliquot was drawn from the stock mixture, loaded into a hemacytometer, and the average number of spores per milliliter determined from the mean of six subsamples.

The flume was seeded with a known concentration of the spore-containing stock mixture. The stock mixture volume was adjusted to yield a final concentration of 75 spores per milliliter in the flume, and then was diluted to 4 liters and mixed vigorously before introduction into the flume. Spores were distributed homogeneously throughout the flume water volume by pouring the stock mixture along a full circuit of flume, in the direction opposite to the flow at 10 cm s^{-1} to minimize deposition on the flume bottom. The spores were allowed to circulate two times around the flume before the rheostat was readjusted to attain the desired flow speed.

During the experimental runs, particle concentrations in the flume were measured at plate height (5 cm above the bottom). Particles were collected with a peristaltic pump sampler similar to that described by Hannan (1984). Small water samples, of known volume (150 - 250 ml), were drawn from the flume through a thin glass tube (6 mm in diameter), bent so that the intake faced directly into the flow. The tube, which was the only part of the apparatus disturbing the flow, was positioned vertically with a vernier caliper. Spores in the pump samples were retained on a 1.2 μm Millipore filter, and counted with a dissecting microscope. Prior to and immediately following the experimental runs, particle concentrations were measured at three heights above the bottom in three locations around the flume (locations A, B, and C in Fig. 2) to determine whether particles were well-distributed, both vertically and horizontally, throughout the flume during the course of an experimental run. No consistent trends in particle concentration, such as an increase in particles near the bottom due to settling, or near the inner, lower corners of the flume due to cross-stream flows (as described by Butman and Grassle, submitted), were observed.

The three plate treatments (faired, bluff, and split) were coated with a thin layer of Dow Corning 340 Heat Transfer Compound (DC 340), a white, viscous, silicon-based adhesive that retained particles in locations where they first contacted the plates. DC 340 was chosen over a variety of other coatings on the basis of five criteria. When applied to the plates in a thin coat, it: (1) contrasted in color with the particles; (2) formed an even, flat surface; (3) was insoluble in seawater and retained its adhesive properties over time; (4) was nontoxic for use in the flume, where live animals were frequently used, and (5) did not deform under high along-stream flows or shear stresses. Erosion experiments demonstrated that once a particle contacted a coated surface, the particle could not be dislodged even at shear stresses much higher than those occurring during experimental runs (unpub. data).

The three experimental plates, coated on their upper surfaces with adhesive, were chilled to a temperature that matched the seawater in the flume (8.5 - 12.5^{o}C). Flume water depth averaged about 14 cm, but ranged from 13.0 to 14.5 cm; thus, the width-to-depth ratio (3.85 - 3.45 respectively) was suboptimal for one-dimensional, open-channel flow (Nowell and Jumars, 1987). Potential effects of wall boundary layers were addressed experimentally with flow visualizations and particle contact analyses. Plates were added to the flume after flow speed had been established for each experiment. Three plates were placed in the test section horizontally (side-by side, in a random order) and elevated 5 cm above the bottom on thin legs. Dye studies were conducted to determine the horizonal spacing needed to dissipate the vortices generated at the corners of the plate leading edges before they interfered with the flow over adjacent plates. The dissipation distance, of approximately 3 cm, resulted in 7 cm clearance from each flume wall. Dye studies showed that this arrangement minimized side-wall flow effects, while keeping the leading-edge flow disturbances from influencing adjacent plates.

During an individual run, three separate experiments were conducted, one at each of three flow speeds (2, 5, and 10 cm s^{-1}). In order to conserve spores, the flume was not emptied and reseeded between the three flow speed treatments; instead, between treatments, flow speed was increased to the maximum setting (approximately 20 cm s^{-1}), and a squeegee was used to resuspend particles that had settled out of suspension. Flow speed was then decreased and allowed to equilibrate to the new setting before the next set of plates was introduced. An estimate of spore concentrations during each replicate run was made by pumping water 5 cm above the bottom (plate height) at a location 4 m upstream of the test section (location B in Fig. 2). Nine pump samples were collected during each replicate run (three samples in each flow speed treatment) to determine whether particle concentration in the flume changed significantly between subsequent flow treatments, and between replicate runs.

Particles were allowed to accumulate on the plates for 30 minutes. A fresh set of three plates was introduced at the start of each flow speed treatment. The positions of the three plate types, relative to the inner and outer walls of the flume were randomized for each flow speed treatment. In addition, the temporal order of flow treatments was randomized for the replicate runs. Flow speeds were measured at 10 cm above the bottom and verified before each flow speed treatment with a Marsh McBurney current meter. Boundary shear velocities of the flume flow were chosen to cover a range of naturally occurring deep-sea (slow) flows.

After a 30-min replicate run, plates were removed from the flume. Particle accumulation patterns within 3 cm of the leading edge of each plate were quantified by counting spores under a dissecting microscope in successive 0.5 cm bands downstream from the leading edge. Only the central 6 cm in a band were counted to avoid regions near the edge that could have been affected by secondary flows (e.g., roll vortices in Ruderich and Fernholz, 1986). Between 4.5 and 20.5 cm from the leading edge of the plates, spores were counted in 1.0 cm bands, centered at 2.5 cm intervals from the leading edge. The bands were narrower near the leading edge because strong downstream gradients in flow characteristics were expected in that region, whereas flow gradients were expected to be more gradual further downstream. Each 0.5 or 1.0 cm band was further subdivided into six 1.0 cm cells across the plate to quantify cross-stream particle distributions. Particle abundances on the plates from each flow treatment, $P_{p(i)}$, were adjusted to normalized values $P'_{p(i)}$ by multiplying them by the ratio of the mean particle concentration in the flume from all replicate runs $[\overline{P_w}]$ to the flume particle concentration during the time interval of the replicate run $[P_{w(i)}]$.

$$P'_{p(i)} = P_{p(i)} \cdot [\overline{P_w}] \,/\, [P_{w(i)}]$$

This normalization permitted comparison of particle abundances on plates between flow speeds and between replicate runs.

2.3 Statistical Analyses

Comparisons between particle abundances and flow characteristics were conducted with Kendall's τ correlation coefficient (Siegel, 1956). For each plate type in the two faster flow treatments (5 and 10 cm s^{-1}), mean particle abundances in the eight bands between 0 - 8 cm were calculated using the three replicate runs. These mean abundances were ranked for comparison with ranked values of the three flow characteristics, (vertical [plate-ward] advection, turbulence and shear stress), from comparable locations on the plates. In cases where flow measurements had not been made at the same location as particle counts, values were interpolated from the closest measurements. Similar comparisons between particle contact and flow characteristics at 2 cm s^{-1} flow speeds were not performed because detailed flow characteristics had not been measured at this flow speed.

Additional analyses were conducted for the sole purpose of investigating possible flow biases in the experiments. Cross-stream variations in particle abundance were analyzed with a one-way ANOVA (Systat, version 2.1) on each of the 27 plates (three plates in each of three flow speed treatments in three replicate runs). The analyses were done separately for the leading edge region (0-8 cm) and the mid-plate region (10-20 cm) of each plate, to isolate effects in the developing boundary layer from those in the relatively uniform boundary layer downstream. Cross-stream variations in particle contact in the leading-edge region were of interest to evaluate the potential influences of secondary flows (e.g., roll vortices) produced at the leading edges of the plates. Cross-stream variations in the mid-plate region were expected to be less influenced by leading-edge disturbances, but were examined to determine if cross-stream flows in the flume channel influenced particle contact.

Downstream variations in particle abundance (i.e., at the leading edge versus the mid-plate regions of the 27 plates analyzed for cross-stream effects) were also analyzed separately for each plate type, using an one-way ANOVA. Replicate plates were not used as replicates in the analysis because they had been placed in a different position in the flume (i.e., inner, middle, outer) during each replicate run. Downstream particle abundances were expected to co-vary with flow gradients in the leading edge region of plates, but particle abundances were not expected to vary in the mid-plate region, where there was only moderate downstream variation in boundary-layer flow characteristics. The one-way ANOVAs tested this prediction so that particle abundances in the mid-plate region could be pooled for further analyses. Since the reliability of all above analyses depended on the assumption that particle abundances in contiguous bands on a plate were independent, the results were interpreted cautiously.

3 Results

3.1 Flow Over Experimental Plates

Boundary-layer flows measured by the LDV over the three plate types at 5 and 10 cm s^{-1} flow speeds (Fig. 3) corresponded to those predicted by classical boundary-layer theory and measured in open-channel flows (Kiya and Sasaki, 1983; Ruderich and Fernholz, 1986). On the faired plate, no flow separation was detected. At both 5 and 10 cm s^{-1} flow speeds, a classical boundary layer developed, with boundary thickness increasing with distance downstream from the leading edge. Vertical advection (away from the plate) decreased downstream from the leading edge as the boundary layer grew, but did not drop below zero (i.e., where vertical advection would be toward the plate). Turbulence and shear stress tended to be elevated slightly at the leading edge where the boundary layer was thin and a slight bow wave may have existed. The exception was shear stress at the leading edge in the 5 cm s^{-1} flow, which was lower than over the rest of the plate. This anomalous result may have been due to the measurement being taken slightly above the boundary layer, rather than within it (Mullineaux and Butman, 1991). Further downstream, turbulence and shear stress decreased to lower, relatively constant values. Turbulence and shear stress tended to be higher in 10 cm s^{-1} than in 5 cm s^{-1} along-stream flow speeds, and were higher over the bluff and split plates

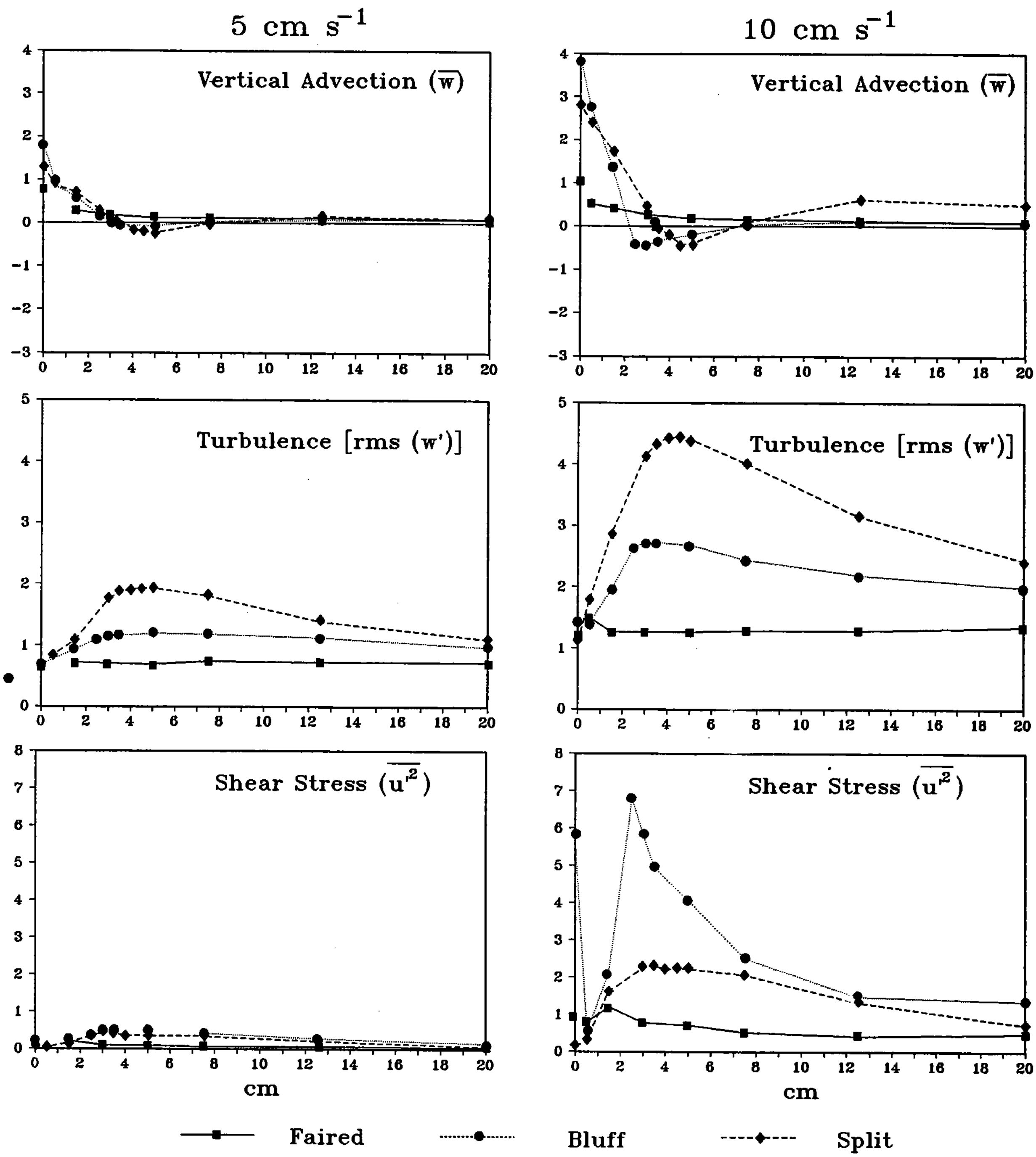

Figure 3. Boundary-layer flow characteristics calculated from 2-axis laser Doppler velocimeter measurements. Mean fluctuating flows were measured over faired, bluff, and split plates at along-stream velocities of 5 and 10 cm s^{-1} measured at 10 cm above flume bottom. Vertical (normal to the plate) advection ($\overline{w}$) and turbulence [rms(u')] were integrated over vertical profiles between 0.2 and 2.0 cm above the plate surface. Boundary shear stress (u'^2) was measured at 0.1 cm above each plate. Data symbols not connected by lines represent suspect measurements (see Results).

than over the faired plate.

The highest shear stresses occurred on the bluff plates in a region extending from 1-5 cm downstream of the leading edge; these were substantially higher than those over a similar region on the split plates. Reduced shear stress on the split plate, downstream of the splitter bar, was likely due to protection of the plate from incident flows. These patterns were intensified at the higher along-stream flow speed. Both turbulence and shear stress values decreased to a moderate, but constant level in the mid-plate regions of the split and bluff plates, although the values were consistently higher than over the faired plates.

Vertical advection away from the plate was high at the leading edge of both the bluff and split plates where flow separations formed, but decreased sharply (i.e., vertical advection toward the plate increased) as the flow reattached to the plates, 2 to 5 cm downstream. The reattachment position on both plates varied with changes in along-stream flow speeds. On the bluff plate at 5 cm s^{-1}, flow reattached 4.5 - 5.0 cm downstream from the leading edge, but at 10 cm s^{-1} the reattachment point was located between 3.5 and 4.5 cm downstream. Generally, the reattachment point on the bluff plates was located between 0.5 and 1.0 cm upstream from the reattachment point on the split plates in comparable along-stream flow speeds. Dye studies indicated that the downstream extent of the separation eddy increased with increasing flow speed up to a critical speed, where the separation eddy became unstable. The observation that reattachment in 10 cm s^{-1} flow was closer to the leading edge than in 5 cm s^{-1} flow suggested that at 10 cm s^{-1} the separation eddies became unsteady and appeared smaller because they were being shed more frequently (as in Ruderich and Fernholz, 1986). The reattachment point corresponded with the region of highest shear stress on both the split and bluff plates.

Flow visualizations with dye on bluff and faired plates corroborated the LDV measurements at higher flow speeds, and contributed insight into behavior of boundary-layer flows over plates in 2 cm s^{-1} along-stream flows. Dye injected along the leading edge of a bluff plate followed the contour of the plate in along-stream flows of 2.0 - 2.8 cm s^{-1}, outlining a boundary layer qualitatively similar to that over a faired plate, but with a higher boundary-layer growth rate. Visualizations at along-stream flows speeds between 5 and 13 cm s^{-1} indicated that a separation eddy formed and grew in height and length with increasing flow speed up to 9 cm s^{-1}. Separation eddies in faster flow speeds were unstable and were shed frequently.

Downstream flow variations were most pronounced in the region 0-8 cm from the leading edge of all three plate types, where the boundary layer was developing and flow separations occurred. Flow disturbances produced at the leading edge dissipated downstream, and the boundary layer at distances greater than 10 cm from the leading edge grew so slowly that a change in boundary-layer thickness was not noticeable on regions downstream from this point. Because of this qualitative difference, downstream variations in particle contact on the "leading edge" region only were compared to downstream variations in vertical (plate-ward) advection, turbulence and shear stress. In contrast, particle abundances on the "mid-plate" region (10-20 cm) were pooled and analyzed relative to along-stream flow speeds and particle fluxes. The flow in this region was considered "non-varying", although the boundary layer was still developing slightly.

3.2 Particle Concentrations in the Flume

Preliminary measurements indicated that particles were well-distributed throughout the flume during experimental runs, so subsequent particle concentration measurements were taken at plate height in the section of the flume where the plates were placed. Particle concentrations in the flume were consistent between replicate runs and, with the exception of the first run, decreased only slightly (4.7 to 11.1 %) over the course of the three flow treatments (speed adjustments) within each run (Fig. 4). Mean particle concentrations, measured during each flow treatment (Table 1), were used to adjust corresponding particle abundance on the plates, so they could be compared between flow speeds and between replicates. All plate abundances were normalized to a mean flume particle concentration of 44.50 ml^{-1}.

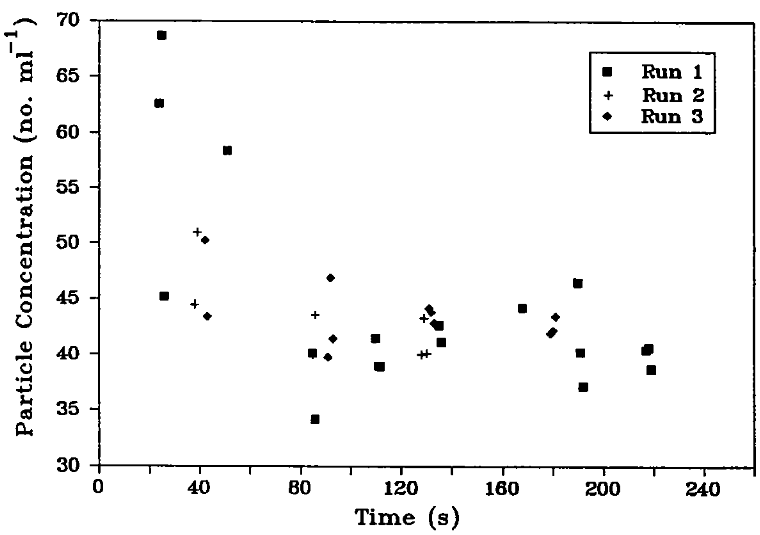

Figure 4. Particle concentrations in the flume during three replicate runs determined by counting number of spores per ml from pump samples drawn from Location B (Fig. 2). Mean numbers collected during each of the three flow speed treatments in each replicate run were used to normalize particle abundances on plates (Table 1).

3.3 Particle Contact Patterns

Particle accumulation on the plates in the leading edge regions was used as a measure of particle contact, since previous experiments had shown that erosion was negligible. Particle contact, normalized by particle concentration in the flume, varied downstream from the leading edge of all plates, and also varied slightly between plate types and flow speeds (Fig. 5).

Particle contact on the faired plate showed a strong pattern relative to the leading edge at all three flow speeds, with contact increasing with distance downstream in the leading edge region and becoming relatively constant in the mid-plate region (Fig. 5a). Contact near the

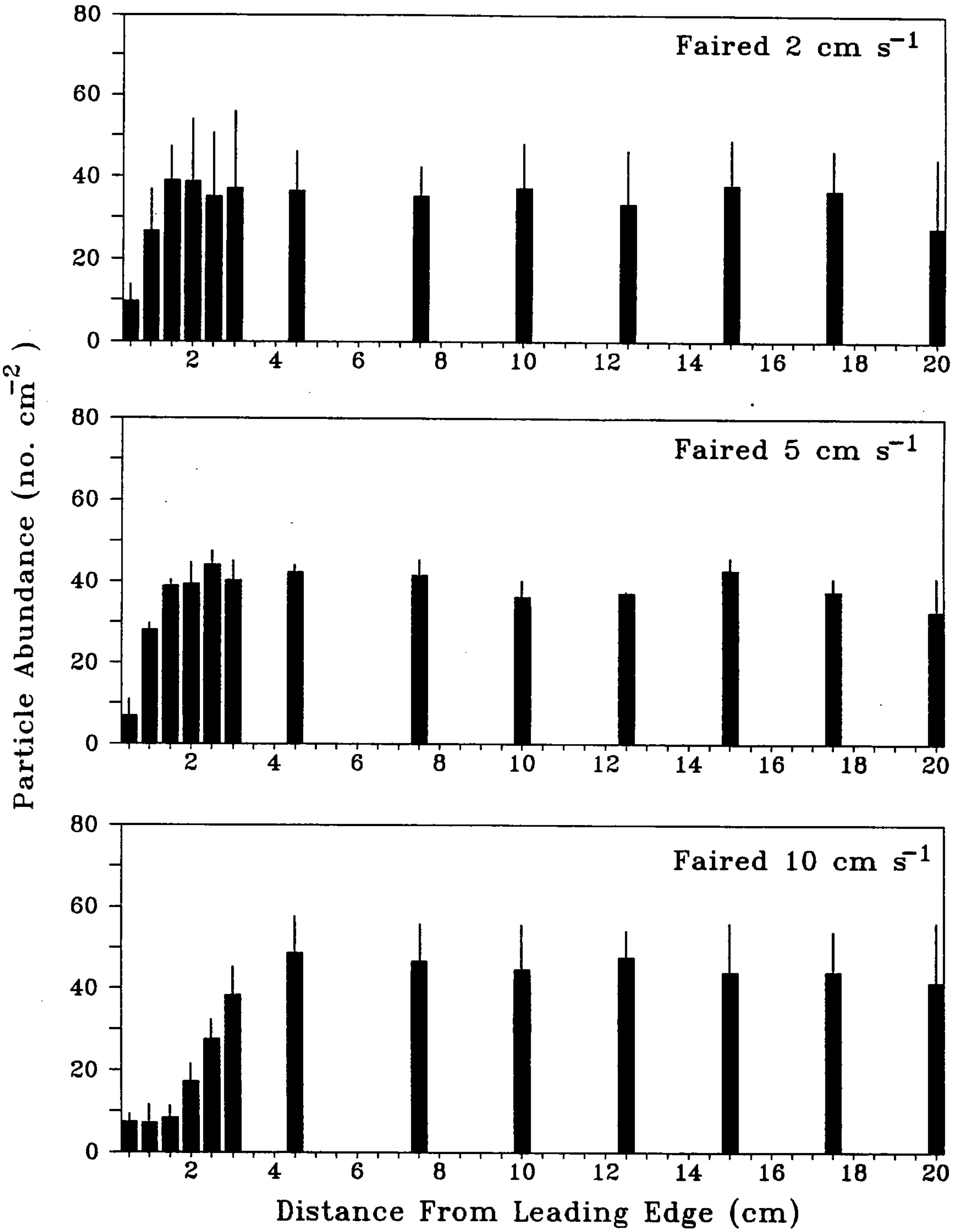

Figure 5a. Particle distribution (normalized by flume particle concentration) on faired plates at flume flow speeds of 2, 5, and 10 cm s^{-1}. Means and standard deviations are shown from three replicate flume runs. Values from 0-3 cm represent abundances in 0.5 cm intervals; values from 5-20 cm represent abundances in 1.0 cm intervals, centered at the marked distance.

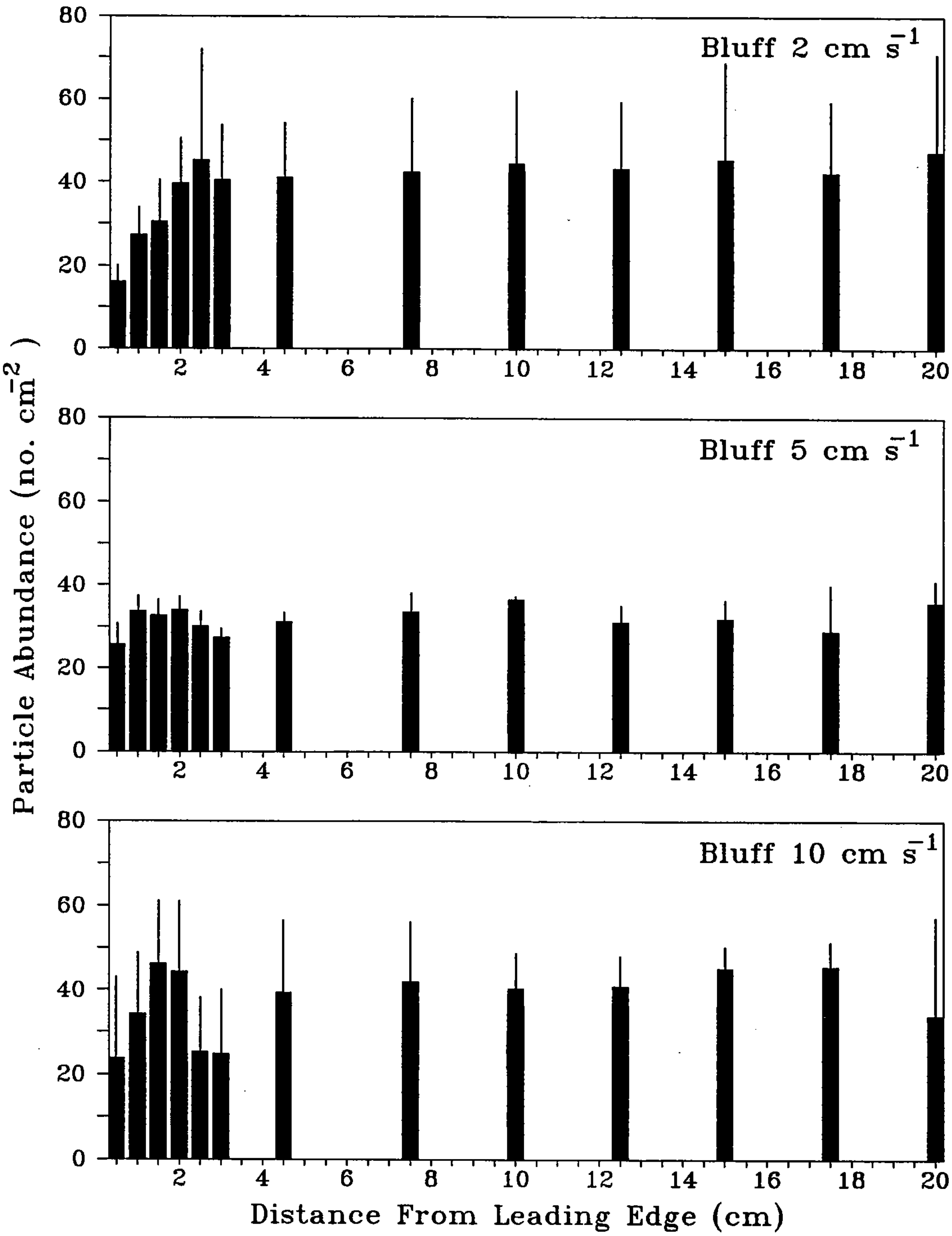

Figure 5b. Particle distribution (normalized by flume particle concentration) on bluff plates at flume flow speeds of 2, 5, and 10 cm s^{-1}. Means and standard deviations are shown from three replicate flume runs. Values from 0-3 cm represent abundances in 0.5 cm intervals; values from 5-20 cm represent abundances in 1.0 cm intervals, centered at the marked distance.

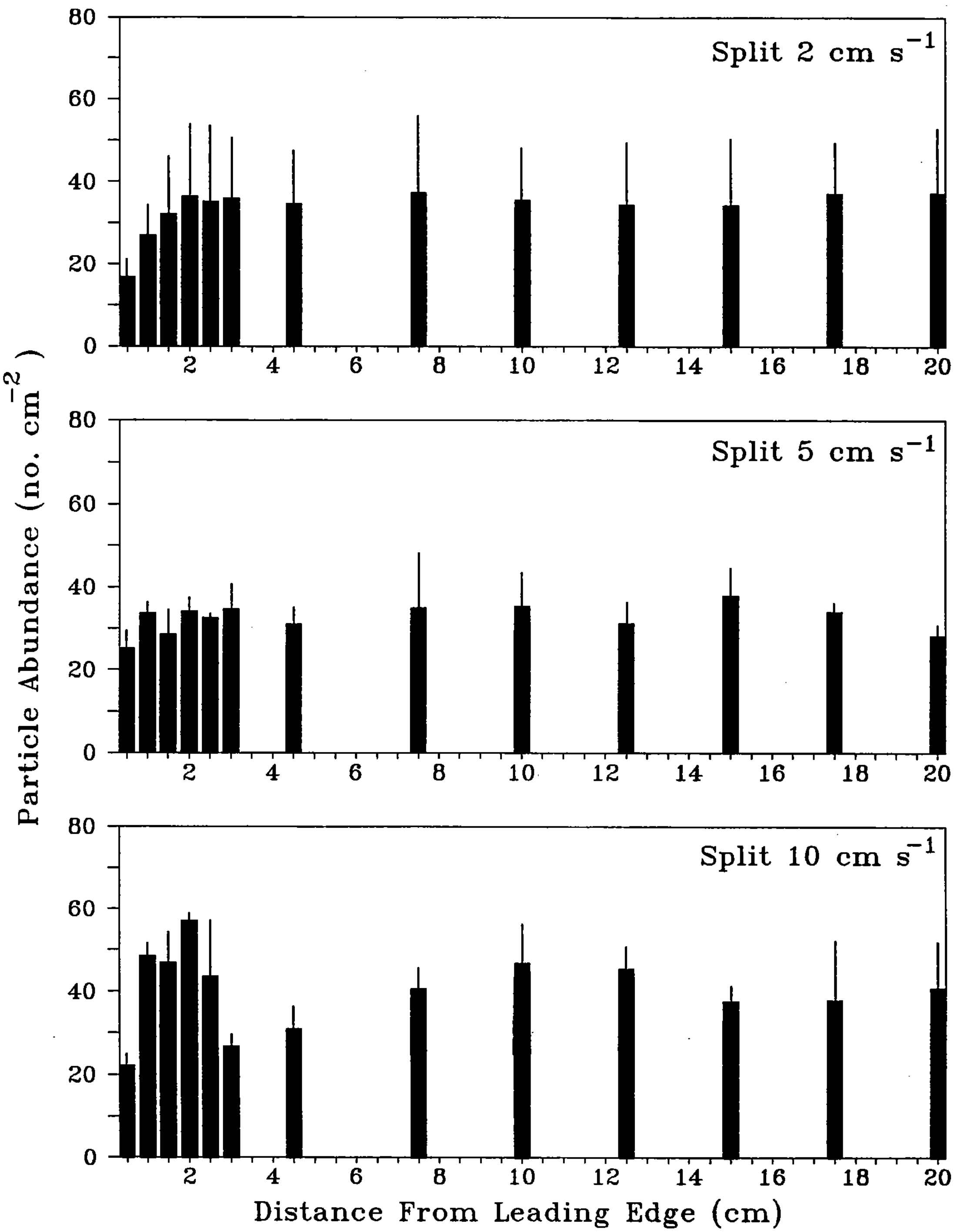

Figure 5c. Particle distribution (normalized by flume particle concentration) on split plates at flume flow speeds of 2, 5, and 10 cm s^{-1}. Means and standard deviations are shown from three replicate flume runs. Values from 0-3 cm represent abundances in 0.5 cm intervals; values from 5-20 cm represent abundances in 1.0 cm intervals, centered at the marked distance.

leading edge of plates in 2 cm s^{-1} and 5 cm s^{-1} flows was reduced only in the 0-1 cm bands, whereas contact on the plates in 10 cm s^{-1} flows was reduced throughout the 0-3 cm bands. Because the flow characteristics of turbulence, vertical advection and shear stress all decreased with distance from the leading edge at 5 cm s^{-1} and 10 cm s^{-1}, contact was negatively correlated (Kendall's τ correlation coefficient, $p < 0.05$) with all three flow characteristics (Table 2).

Flume Flow Speed	2 cm s^{-1} (no. ml^{-1})	5 cm s^{-1} (no. ml^{-1})	10 cm s^{-1} (no. ml^{-1})
Replicate #1	38.69	42.65	58.71
Replicate #2	41.13	41.77	46.20
Replicate #3	42.51	45.19	43.61

Table 1. Mean particle concentrations the flume for each flow speed treatment during each of three replicate runs. Means were calculated from particle concentrations measured in at least three pump samples (Fig. 4), except for Replicate #2 at 5 cm s^{-1} (n=2). These means were used to normalize particle contact data to a standard flume concentration of particles (arbitrarily chosen to be the grand mean of 44.50 particles ml^{-1}).

Plate Treatment and Flow Speed	Vertical Advection	Turbulence	Shear Stress
Faired			
5 cm s^{-1}	-0.714 *	-0.643 *	-0.714 *
10 cm s^{-1}	-0.857 *	-1.000 *	-0.857 *
Bluff			
5 cm s^{-1}	0.000	0.071	-0.214
10 cm s^{-1}	0.143	-0.143	-0.500 *
Split			
5 cm s^{-1}	-0.500 *	0.429	0.429
10 cm s^{-1}	0.214	-0.286	-0.214

* $P < 0.05$

Table 2. Nonparametric correlation (Kendall's τ) between positions of particle contact and flow characteristics on three plate treatments. Values ranked from eight positions downstream from the leading edge. Particle contact ranks were assigned to the average of three replicate runs at each flow speed. Ranks for the flow characteristics were assigned to mean values from 4-min sampling intervals.