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Field assessment of sediment trap efficiency under varying flow conditions

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ABSTRACT

Knowledge of the collection efficiency of sediment traps, particularly under conditions of varying current speed, is presently more a matter of hope than confidence. We report here on a field experiment designed to determine, for a particular trap geometry, the effect of current speed and particle fall velocity on the collection efficiency of a moored trap relative to the presumably unbiased efficiency of an identical drifting trap. The experiment was performed in a deep estuarine tidal passage where a smoothly varying unidirectional flow and a spatially homogenous particle population mimicked laboratory flume conditions. A multiple-sample sediment trap integrated to a current meter partitioned the mass flux collected by the moored trap into one of four chambers according to the following speed intervals: <12, 12–<30, 30–<50, and ≥50 cm/s. The magnitude and particle characteristics of the flux collected at <12 cm/s were indistinguishable from those simultaneously collected by drifting traps. At higher speeds, the relative efficiency of the moored trap ranged between 1% and 24% and the mean size and density of the trapped particles increased. These results support predictions based on laboratory studies that collection efficiency decreases with an increase in the trap Reynolds number or a decrease in particle fall velocity. The study demonstrates that consideration must be given to scaling both trap diameter and aspect ratio according to the expected flow conditions, and that knowledge of flow conditions at the trap mouth is necessary to properly interpret the flux data.

1. Introduction

The collection efficiency of sediment traps has been extensively studied, with varying degrees of success, in a variety of laboratory and field investigations. As Butman *et al.* (1986) point out, most of the reported tests cover only a narrow range of flow and particle types and are therefore uncharacteristic of most natural conditions. Based on low-Reynolds-number ($R_e \leq 2 \times 10^4$; current speed $\lesssim$10 cm/s) flume and field experiments (e.g., Lau, 1979; Hargrave and Burns, 1979; Bloesch and Burns, 1980; Gardner, 1980a,b; Blomqvist and Hakanson, 1981; Blomqvist and Kofoed, 1981; Lorenzen *et al.*, 1981; Butman, 1986), biased sampling associated with cylindrical traps having a height/depth (aspect) ratio $\gtrsim$3 and a diameter $\gtrsim$3 cm appears to be small, at least for particles with fall velocities of $\sim 10^{-2}$ to 10^{-1} cm/s and $4 \times 10^3 \leq$

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$R_e \leq 2 \times 10^4$ (Butman, 1986). Significant changes in trapping efficiency have been detected for cylinders in environments with a very low Reynolds number, however, with a factor of two decrease in efficiency over a factor of two increase in Reynolds number ($2–4 \times 10^{-3}$), as demonstrated in the laboratory flume study of Butman (1986).

The performance of traps of any type in the relatively high and variable speed flows that typify many natural environments remains uncertain because of the difficulty in setting up reliable test conditions. Flume studies are constrained by problems in meeting dynamic-scaling criteria for the required high flow speeds (see Butman, 1986) and the difficulty in measuring or calculating a "true" flux with which to compare the trap results. Quantitative field studies are inherently difficult because of natural variability in the flow regime, particle type, and particle concentration, and because of uncertainty in measuring unbiased flux estimates for comparison to the trap collections. For example, Gardner *et al.* (1983) examined trapping efficiency in a benthic boundary layer with high current speeds but found that resuspension masked the effect of current variability on trap efficiency.

Following Butman's (1986) systematic flume study of the effects of trap Reynolds number on trap collection efficiency, it is important to determine if the pattern of trap biases demonstrated in that study is repeated by traps collecting in the natural field environment. Such a field study must satisfy the following criteria to allow comparison with Butman's (1986) results: (1) Traps must be straight-sided cylinders with aspect ratios of ~3; (2) Traps must be held rigidly and vertically; (3) The flow regime must be relatively uniform (i.e., low or no vertical shear) and reasonably steady (i.e., speeds changing only gradually with time) without wave interference; (4) The trap collections must be separated for different flow-speed intervals; (5) Particles must have fall velocities between about 10^{-2} and 10^{-1} cm/s; and (6) Current speed must be continuously measured at or near the trap mouth. We describe in this paper a field experiment that closely fulfills these stringent conditions and thus offers some insight into the variability in efficiency of sediment traps in estuaries, continental shelves, and other environments with the potential of sustaining a high Reynolds-number flow. Our approach was to use a natural environment that has a relatively simple flow and particle environment, comparable to that in a laboratory flume, and to use a specially-constructed sediment trap with the ability to direct the vertical flux into different collection chambers on the basis of the observed current speed. The efficiency of the moored traps in the experiment was normalized against simultaneously-collected flux data from identically-dimensioned drifting traps.

2. The experiment

a. Sediment traps. Sediment traps were standard or modified Sequentially Sampling Sediment Traps, or S^3T, which collect up to 10 individual flux samples during a single deployment (Baker and Milburn, 1983). The trap is neither a true cylindrical nor

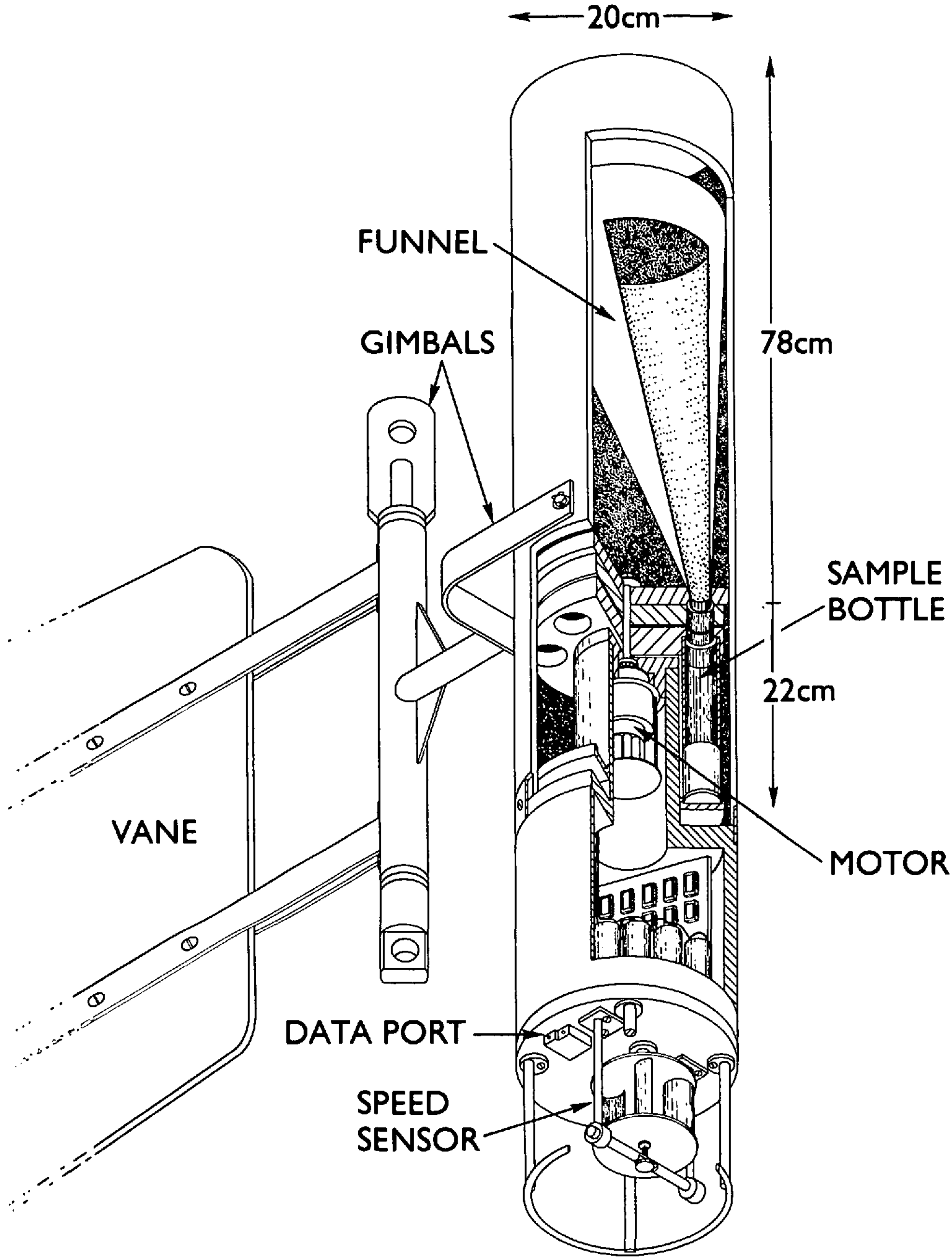

Figure 1. Schematic drawing of the sediment trap and mooring gimbals and vane used to keep the trap vertical and upcurrent of the mooring wire. The Flow-Actuated Sediment Trap was created by adding a Savonious rotor on the trap bottom to measure current speed and control the rotation of the sample chambers.

funnel shape, being 20 cm in diameter with a 64-cm-deep asymmetric funnel set 14 cm below the unbaffled mouth of the trap (Fig. 1). The funnel has a minimum slope of 73° and directs the flux into a 22-cm-deep collection tube. All flux calculations in this paper are based on the mouth area (314 cm^2) of the trap. Several studies (Hargrave and Burns, 1979; Gardner, 1980a,b; Butman, 1986) have categorized funnel traps as less efficient than cylinder traps, but in the tested traps the funnel sides typically extended up to the mouth and had a gentler slope than in the present case.

Butman *et al.* (1986) define particle collection efficiency, E, as the net deposition of particles onto the trap bottom divided by the total flux of particles settling through the mouth, so that

$$E = \frac{C_i WA_b - \phi_b A_b}{C_o WA_m} \tag{1}$$

where C_i and C_o are the mass concentration of particles inside and outside the trap, A_m and A_b are the area of the trap mouth and bottom, W is the particle fall velocity, and ϕ_b is the resuspended flux per unit area from the trap bottom. Although this definition is straightforward when applied to purely cylindrical traps, the practical difficulty both in defining A_b in a funnel trap (especially the design in Fig. 1) and in calculating the $\phi_b A_b$ term makes it difficult to determine the absolute efficiency of funnel traps. For an arbitrary trap geometry, Butman *et al.* (1986) also show that the relationship between E and the mass flux into and out of the trap by advection (Q) can be written

$$E = 1 + (C_o - C_i)Q/C_o W A_m. \tag{2}$$

Eq. 2 demonstrates that in the absence of advection all traps are unbiased collectors (i.e., the collected mass flux equals the mass flux settling through the trap mouth). This relationship suggests that relative trap efficiency can be determined by comparing trap performance in still water with trap performance at various current speeds, providing that other environmental factors remain unchanged.

Moored traps must remain vertical and rigidly held even under high current speeds to be properly compared with still water (drifting) traps. To insure a vertical orientation of the traps in this study, we attached them to the mooring line with a swivel and vane that kept the trap both upstream of the cable and vertical at inclinations of the mooring line up to 30°. The fixture points on the trap cylinder are at the center of the drag area, and a strong righting moment is achieved by the weight distribution. The potential for motion induced by the vortex street behind the trap is significantly reduced by the splitter effect of the vane (Hoerner, 1965). High frequency energy from cable strumming is damped by the large virtual mass of the trap and vane fixture that serves as a node point on the cable. Any remaining vibratory motions may aid in moving particles down the steep funnel walls.

In normal operation, the sample carousel in a S^3T holds 10 sample tubes that rotate under the collection funnel at preset intervals. For this experiment, we modified one

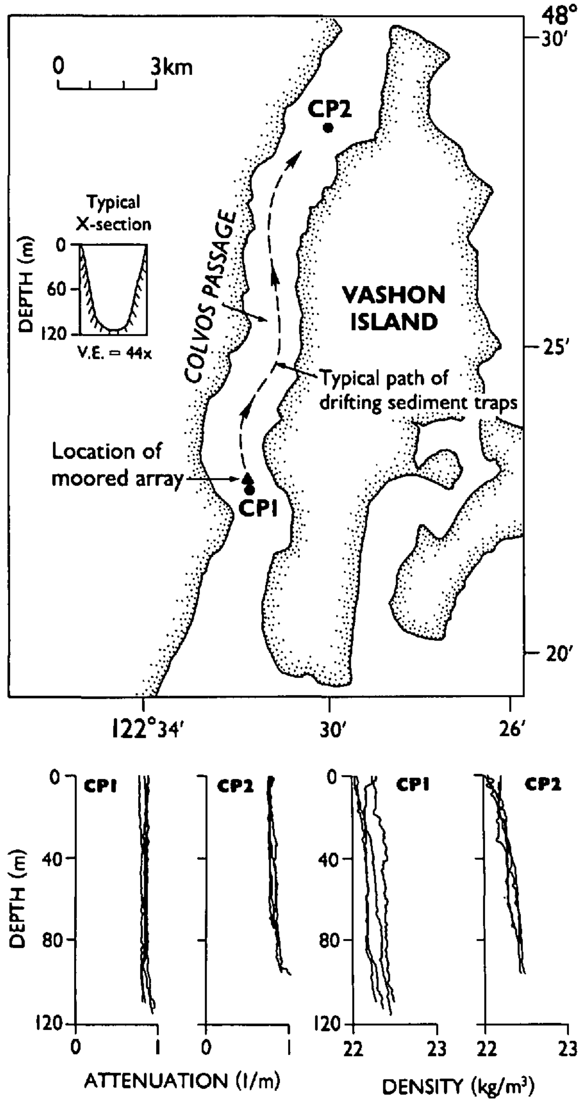

Figure 2. (A) Chart of Colvos Passage and surrounding waters. The net tidal flow around Vashon Island is clockwise. The triangle near the southern entrance to Colvos Passage marks the location of the mooring and the deployment site for the drifting sediment trap array. Inset shows a cross section of Colvos Passage at the mooring site. (B) Vertical profiles of light attenuation and density at the mooring site (station CP1) and at the northern end (station CP2) of Colvos Passage from four daily casts at each station between Aug. 11 and Aug. 15, 1984 (experiment 5). The light-attenuation value of particle free water is about 0.40 m^{-1}. Station locations are shown in Figure 2A. The water column and particle distribution throughout Colvos Passage were well-mixed and showed little variation in time or space.

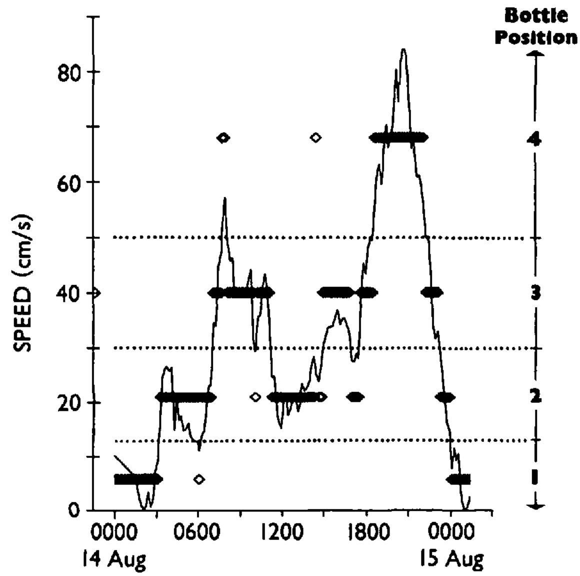

Figure 3. Unfiltered speed record compared to the sequence of FAST bottle positions for a typical tidal cycle. Each diamond symbol represents a 10-min collection period for a given bottle position.

trap by adding a Savonious rotor from an Aanderaa current meter to the bottom of the trap and changing the control logic from a time basis to a current-speed basis. The resulting Flow-Actuated Sediment Trap, or FAST, continually sampled the rotor revolutions, calculated a mean speed every 10 minutes, and positioned one of four collection tubes under the funnel according to the most recent speed. The carousel rotation required only a few seconds. Tube 1 collected for speeds of <12 cm/s, tube 2 for 12 – <30 cm/s, tube 3 for 30 – <50 cm/s, and tube 4 for ≥50 cm/s. The tube number, current speed, and time of day were recorded every 10 min in solid state memory. We recognized that the FAST would only successfully partition the flux if the current regime varied smoothly and relatively slowly, so a field site was required that would approximate the flow conditions of a laboratory flume.

b. Field site. Colvos Passage (Fig. 2A) is a 120-m-deep, 18.5 km by 1.75 km nearly linear channel in Puget Sound that is vertically well-mixed by a smoothly varying and essentially unidirectional tidal flow (Cannon *et al.*, 1979). Current speeds range from zero to >100 cm/s to the north. Figure 3 shows an unfiltered speed record from a typical tidal cycle together with the response of the FAST. In most instances a particular tube was continually open for at least 40 min as the current smoothly increased and decreased during the semi-diurnal tidal cycle.

The strong currents and unidirectional flow create a uniform hydrographic and particle regime in Colvos Passage. Vertical current shear is low, with the coefficient of variation between the mean speed at different depths typically <10% (Cannon *et al.*, 1979). Vertical and horizontal gradients of density and light attenuation (proportional to the particle concentration) are weak throughout Colvos Passage (Fig. 2B), indicating that both moored and drifting traps within the Passage will be exposed to a common physical and particle environment. Despite high current speeds, resuspension is a negligible source of particles because Colvos Passage is floored with sand and gravel (Roberts, 1974). Suspended matter in Colvos Passage is a mixture of detrital and biogenic particles with a wide range of settling speeds, although the great bulk of the particles have a settling speed of $<3 \times 10^{-2}$ cm/s (see below). Mean suspended mass concentration during the experiment was on the order of 1 mg/l.

c. Mooring configuration. The experiment used traps on both moored and drifting arrays (Fig. 4) to sample the vertical flux. The mooring consisted of a subsurface float, separate FAST and S^3T, and an Aanderaa current meter interfaced to a Sea Tech transmissometer. Traps on the mooring were held vertical and upcurrent of the mooring wire by means of a two-axis gimballed mounting (Baker and Milburn, 1983). The drifting array consisted of a pair of S^3Ts and a drogue suspended from a spar buoy. Most of the resistance of the drifting array was concentrated at the trap depth in order to minimize vertical slip. The drifting array occasionally carried an Aanderaa meter below the traps to record relative current speed. The drifting traps, which never experienced a speed >2 cm/s relative to the surrounding water and encountered no measurable wave motion, were intended to provide a "stillwater" measure of the vertical particle flux in Colvos Passage for comparison to collections by the moored traps. The efficiency of the moored traps at various current speeds, relative to the drifting traps, allows for evaluation of the potential trap bias caused by a Reynolds-number effect.

d. Sampling strategy and methods. Six experiments, lasting from 3 to 14.6 days, were made during the spring and summer of 1985 (Table 1). No FAST data are available from experiments 1 and 4 because of mechanical or electronic problems. Drifting traps were used only during experiments 1, 5, and 6. A complete experiment consisted of a continuous FAST collection integrated over the entire deployment period; 6–10 samples, equally divided through the deployment period, from the moored S^3T; replicate samples at one hour intervals from the dual S^3Ts on the drifting array, which was deployed for 10-hr periods as often as logistically possible; and continuous velocity and light-attenuation records from immediately below the trap depth on the mooring. The mooring was always located at the same position in Colvos Passage (Fig. 2A), and each new deployment of the drifting array began at the site of the mooring. The drifting array normally floated north along the center of Colvos Passage, and its position was regularly checked to make sure it had not drifted ashore or been advected out of the north end of the channel.

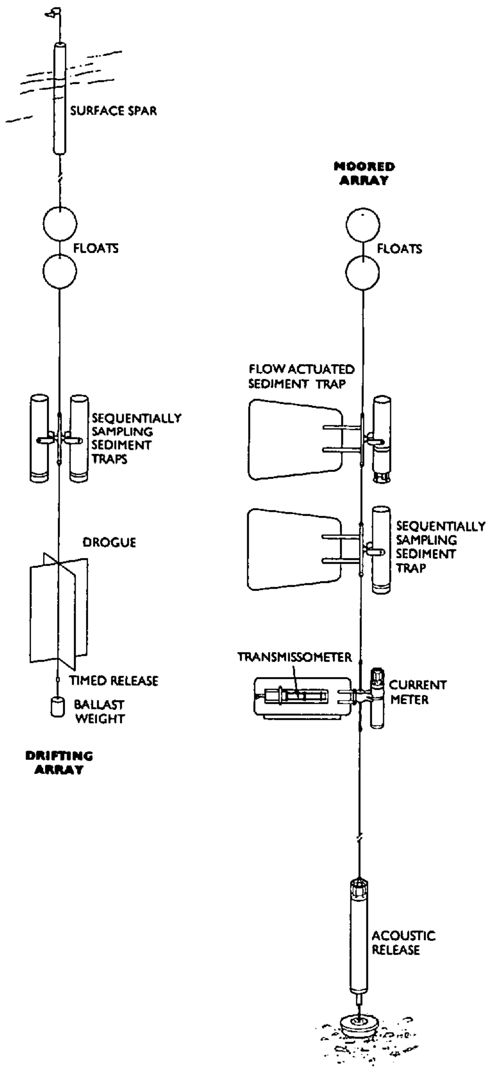

Figure 4. Mooring configurations for the moored and drifting arrays. Sediment traps were at a nominal depth of 40 m. A current meter was occasionally added to the drifting trap to monitor relative speed.

Sample tubes in all traps were filled before deployment with filtered seawater containing sodium-azide to retard biological activity. After recovery the tubes were stored cold and dark until processing. The contents of each tube from the moored traps were sized and then density fractionated. Trapped particles were gently washed through 250 μm, 125 μm, 64 μm, and 38 μm screens with care taken not to destroy aggregates such as fecal pellets. The <38 μm fraction was filtered through a 0.4 μm-pore-sized polycarbonate filter. Particles on each of the four screens were

Table 1. Summary of sediment trap fluxes and current speeds.

Experiment	Mean current speed (cm/s)	Trap	No. of samples	Mean flux ($g/m^2/d$)	Start date	End date
1	20.1	S^3T	6	2.0 ± 0.9	1600, 27 Mar	0500, 30 Mar
		DT_i^a	35	4.1 ± 2.4	1410, 26 Mar	1830, 29 Mar
		DT_p^a	4	2.7 ± 0.5	1410, 26 Mar	1830, 29 Mar
2	27.9	FAST	1	3.2	1326, 2 Apr	1550, 5 Apr
		S^3T	6	2.2 ± 0.7	1800, 2 Apr	1438, 5 Apr
3	22.4	FAST	1	2.9	1955, 25 Jul	0740, 7 Aug
5	32.1	FAST	1	1.9	1926, 11 Aug	0726, 16 Aug
		S^3T	9	2.9 ± 2.3	1955, 11 Aug	0755, 16 Aug
		DT_i^a	95	9.1 ± 5.6	1200, 11 Aug	0643, 16 Aug
		DT_p^a	10	11.0 ± 6.2	1200, 11 Aug	0643, 16 Aug
6	17.5	FAST	1	13.5	1602, 16 Aug	0546, 31 Aug
		S^3T	10	17.7 ± 16.3	1602, 16 Aug	0629, 31 Aug
		DT_i^a	61	18.7 ± 19.1	0800, 21 Aug	1800, 30 Aug
		DT_p^a	7	16.9 ± 11.5	0800, 21 Aug	1800, 30 Aug

[a]Each drifting trap array carried paired sediment traps. DT_i represents the mean flux calculated from each individually sampled tube during a given FAST deployment. DT_p represents the mean flux calculated from the fractionation data derived from tubes pooled from each drifting trap deployment during a given FAST deployment.

density separated using CCl_4 (ρ = 1.6 g/cm^3). The lower density fraction included fecal pellets, planktonic tests, and unidentifiable organic debris. The higher density fraction was largely mineral grains. The total mass in each tube was determined by summing all fractions. The replicate drifting traps were treated identically, except that the brief 1-hr sampling time of each tube necessitated combining one entire trap for the size and density fractionation procedures and using the other trap for individual mass flux calculations from each tube. No significant bias was found between the paired drifting traps (see Table 1).

3. Results

Experiments 5 and 6 covered the longest continuous time span, and the records of current speed, light attenuation, and particle flux during those deployments is shown in Figure 5. Mean current speed (Fig. 5A) during experiment 5 was 32.2 cm/s, almost twice the 17.5 cm/s mean during experiment 6. Light attenuation (Fig. 5B) showed considerable relative variation at tidal frequencies owing to the advection of turbid water from outside Colvos Passage on the ebb tide. There was no evidence of significant local resuspension. In absolute terms, however, the daily variation was rather small. Light-attenuation values can be converted to particulate concentrations from empirical calibration equations based on previous work in Puget Sound (Baker *et*

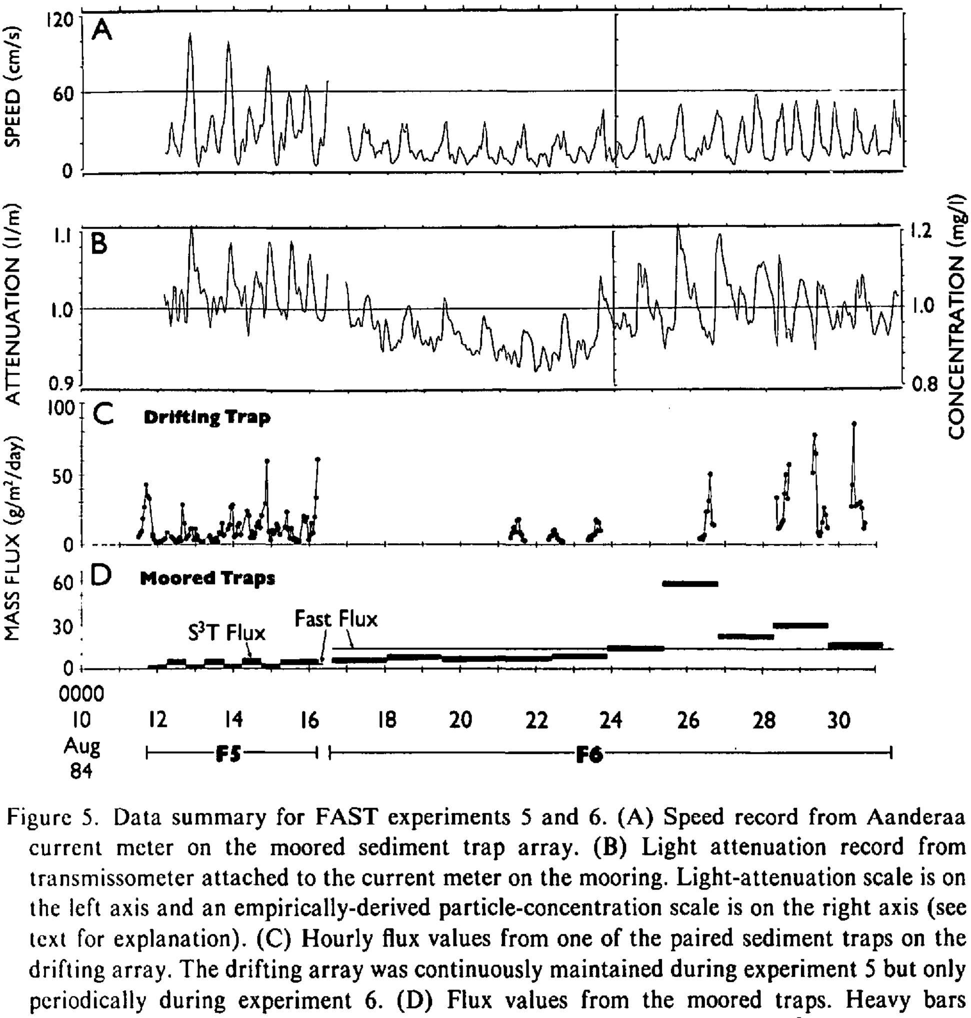

Figure 5. Data summary for FAST experiments 5 and 6. (A) Speed record from Aanderaa current meter on the moored sediment trap array. (B) Light attenuation record from transmissometer attached to the current meter on the mooring. Light-attenuation scale is on the left axis and an empirically-derived particle-concentration scale is on the right axis (see text for explanation). (C) Hourly flux values from one of the paired sediment traps on the drifting array. The drifting array was continuously maintained during experiment 5 but only periodically during experiment 6. (D) Flux values from the moored traps. Heavy bars represent the flux magnitude during discrete sampling intervals of each S³T (0.5 d during experiment 5 and 1.46 d during experiment 6). The single horizontal line extending throughout each experiment represents the mean total flux for each FAST deployment, calculated by summing the samples from each of the four speed intervals.

al., 1983; Baker, 1984). The daily variation in the particle concentration was ~0.2 mg/l or less about a background concentration of ~1.0 mg/l (see right hand axis of Fig. 5B). Variation of the long term mean was much smaller than that of the daily variation.

Hourly flux averages from the drifting traps (Fig. 5C) ranged from <1 to 85.6 g/m²/d and often varied by a factor of 20 or more over a few hours. Mean flux was 9.1 and 11.0 g/m²/d for the paired drifting traps during deployment 5, and 16.9 and 18.7 g/m²/d during deployment 6 (Table 1). Least-squares regressions of the hourly

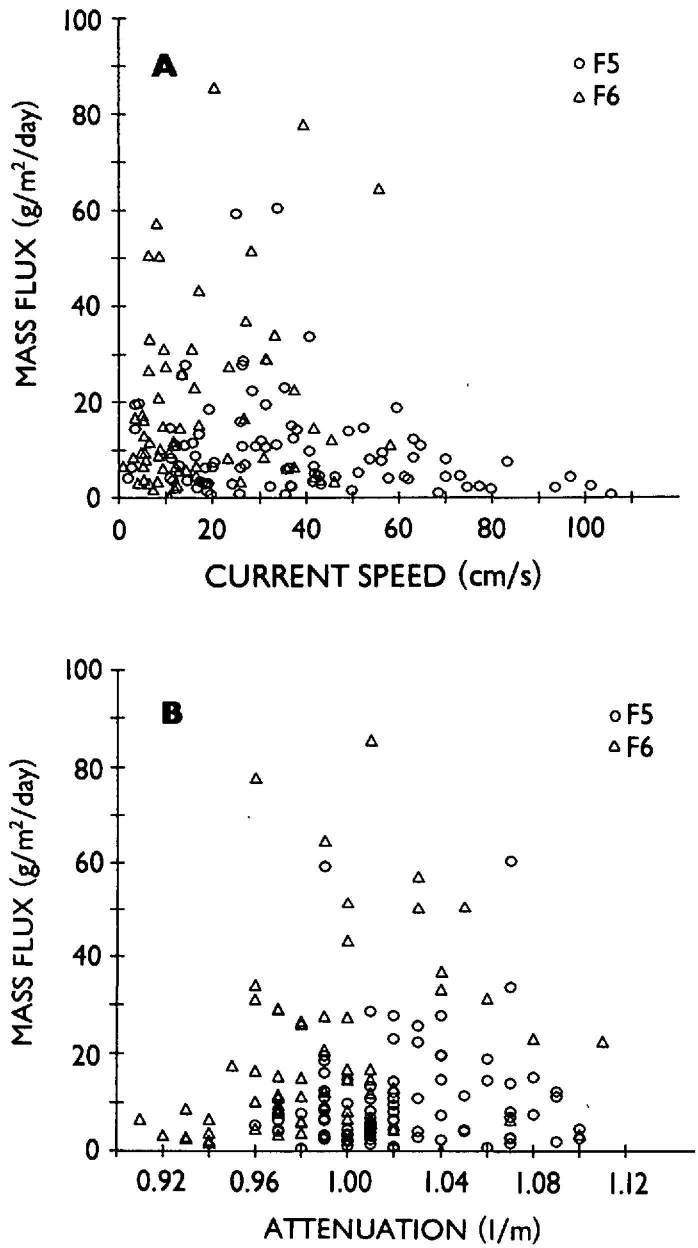

Figure 6. Scatter plots of hourly means of (A) current speed and (B) light attenuation at the mooring against mass flux into the drifting traps for experiments 5 and 6.

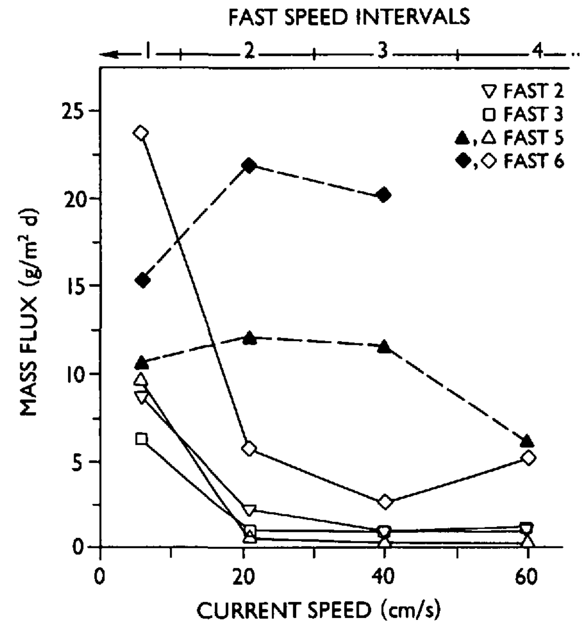

Figure 7. Mass flux collected during four deployments of the moored FAST suffered a sharp decrease with increasing current speed (open symbols), whereas the mean flux collected by the drifting trap over the same current speed intervals was essentially uniform (closed symbols). (Drifting trap data taken from Fig. 6A.)

drifting-trap flux against hourly averages of current speed and light attenuation at the mooring were not significant in either case (Fig. 6). Recalling that the light-attenuation and hydrographic profiles in Figure 2B describe Colvos Passage as a uniform water mass, the data in Figure 6 argue that the drifting-trap flux is decoupled from the absolute current speed and the ambient concentration of fine-grained particles in the water column. This conclusion is consistent with the abundant evidence that large, rare particles control the vertical flux mass flux (McCave, 1975). (No instances of high flux were observed for current speeds >70 cm/s, which might indicate a lowering of efficiency even for the drifting trap at very high speeds, perhaps caused by a delayed acceleration of the trap in response to a strongly accelerating flow. Since speeds >70 cm/s occurred during only ~2% of the experiment 5 and 6 records, however, the sample base for such conclusions is quite small.)

Flux into the moored traps (Fig. 5D) showed much less variability, perhaps because of the longer sampling intervals. During experiment 5, the S^3T flux over 0.5-day periods varied regularly between about 0.5 and 4.7 $g/m^2/d$ with a mean of 2.9 $g/m^2/d$, about one-third the mean flux recorded by the drifting traps over the same interval. During experiment 6, the S^3T flux ranged between 5.6 and 58.1 $g/m^2/d$ with a mean of 17.7 $g/m^2/d$, within the range sampled by the drifting traps (although note that the drifting traps sampled during only 20% of the total experiment). A doubling of the

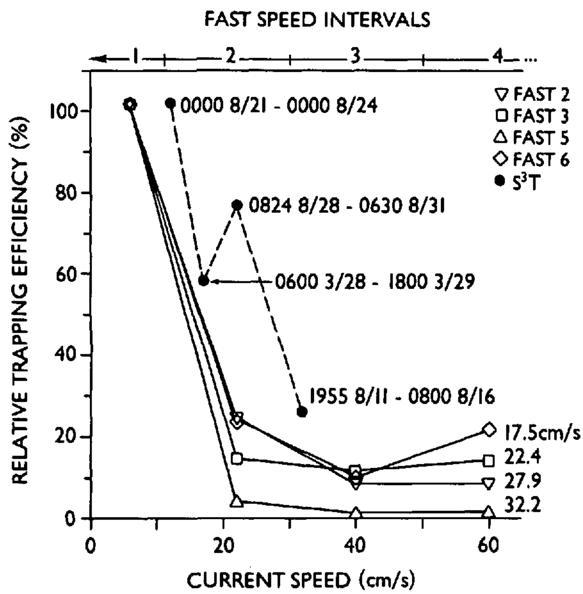

Figure 8. Relative collection efficiencies calculated by normalizing the flux from each FAST interval to the flux from the <12 cm/s interval (open symbols), and by normalizing flux from the standard moored trap to a simultaneous drifting trap deployment (closed symbols). The mean speed during each FAST deployment is also shown.

mean current speed during experiment 5 compared with experiment 6 thus appears to have decreased the efficiency of the moored traps by about a factor of three relative to the drifting traps.

The effect of current speed on the traps can be seen much more clearly in the FAST data. During experiments 5 and 6 the total mean flux into the FAST was not significantly different than into the S^3T (Fig. 5, Table 1), but the current-fractionated flux varied by as much as a factor of 70 (Fig. 7). Plots of the mass flux against the speed class for each of the successful FAST deployments shows a consistent trend of decreased trapping efficiency at current speeds >12 cm/s. This trend contrasts with a similar plot for the data from the drifting traps (taken from Fig. 6) showing that absolute current speed had little effect on the drifting trap flux except possibly at speeds >70 cm/s (Fig. 7).

Examination of Figure 7 reveals that agreement between moored and drifting traps was close at speeds <12 cm/s but became very poor at higher speeds; that is, the collection efficiency of the moored traps relative to the drifting traps decreased as the speed increased. If we assume that the flux at speeds <12 cm/s for all FAST deployments was equal to the drifting trap flux, then we can determine the relative collection efficiency of the moored traps by normalizing the flux from each FAST interval to that of the <12 cm/s interval (Fig. 8). Relative collection efficiencies at speeds >12 cm/s range from 1 to 24%, and the mean efficiency of a particular deployment decreases with an increase in the mean current speed.

Relative collection efficiencies can also be estimated from the ratio of standard moored trap flux to drifting trap flux during specific intervals when near-simultaneous data from both are available. There were four occasions when the moored S^3T sampling intervals closely matched the drifting trap deployments: 0600 March 28 to 1800 March 29, 1955 Aug. 11 to 0800 Aug. 16, 0000 Aug. 21 to 0000 Aug. 24, and 0824 Aug. 28 to 0630 Aug. 31. Plotting the relative collection efficiency of the trap against the mean current speed for each interval produces a trend that closely follows the FAST data (Fig. 8). Figure 8 also suggests that knowledge of the current speed during a sediment trap deployment may make it possible to evaluate the efficiency losses suffered by a particular trap design in high-Reynolds-number environments, thus allowing the calculation of more realistic flux magnitudes.

Since changes in the current speed affect the total mass flux, we should also expect changes in the size and density distribution of the trapped particles. Figure 9 summarizes these changes for FAST deployments 3, 5, and 6 (deployment 2 was too short to provide enough material for a reliable fractionation). The relative flux of particles with $\rho > 1.65$ g/cm^3 showed a pronounced shift from fine-grained particles at speeds <12 cm/s to particles with diameters >125 μm at speeds >50 cm/s. The relative flux of all size classes of particles with $\rho < 1.65$ g/cm^3 decreased as current speed increased. The similarity of the size/density distributions from the <12 cm/s FAST sample and the drifting traps reinforces the conclusion that the efficiency of the trap at low speeds is close to 1.

The uniformity of the particle size and density characteristics between the moored and drifting traps also supports our contention that because Colvos Passage is a homogeneous particle environment the moored and drifting traps were exposed to equivalent fluxes.

4. Discussion

The sediment trap analysis of Butman *et al.* (1986) evolved a set of three testable hypotheses concerning the relationship of trapping efficiency to trap Reynolds number, particle fall velocity, and trap aspect ratio. Under conditions where only one of these parameters is allowed to vary, the collection efficiency of cylinders will (1) decrease with increasing trap Reynolds number, (2) decrease with decreasing particle fall velocity, and (3) increase with increasing trap aspect ratio. Butman (1986) addressed the first and third of these hypotheses under laboratory conditions of low current speed (~10 cm/s) but emphasized that the results could not necessarily be generalized to different combinations of parameters or to field environments. Our experiment addressed hypotheses one and two under field conditions rather than laboratory conditions.

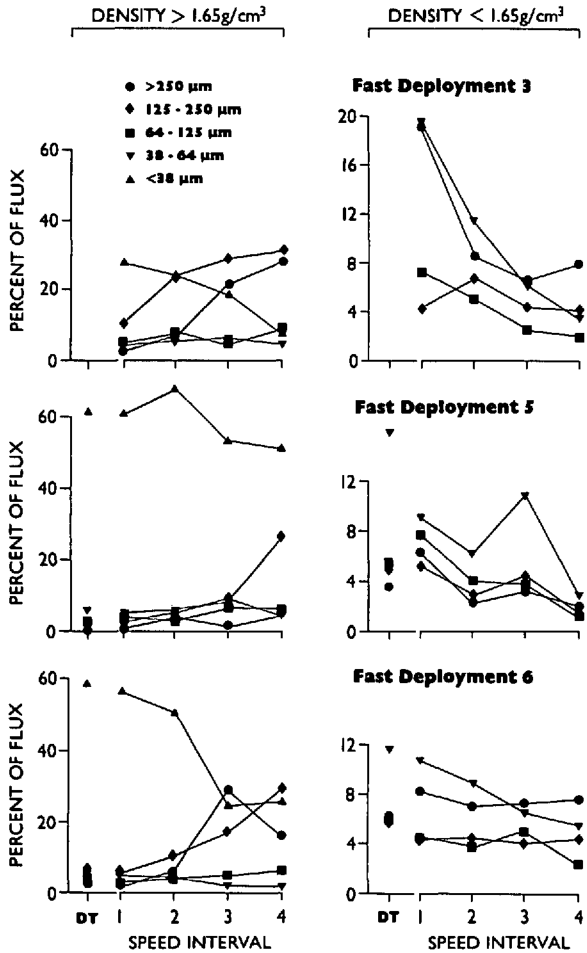

Figure 9. Size and density fractionation of the total flux collected by each speed interval of the FAST and by the simultaneously deployed drifting traps (DT). Within each density category, particles of larger size make up an increasingly larger fraction of the total flux as current speed increases. The size/density distribution of the trapped particles from the drifting traps closely matches the distribution in the lowest speed interval of the FAST.

a. Effect of trap Reynolds number. Trap Reynolds number (R_t) is a dimensionless parameter that relates the ratio of inertial ($u_f D$) to viscous (ν) forces in the flow and thus gauges the relative importance of eddy versus frictional effects:

$$R_t = \frac{u_f D}{\nu}$$

where u_f = horizontal flow speed at the trap mouth, D = trap diameter, and

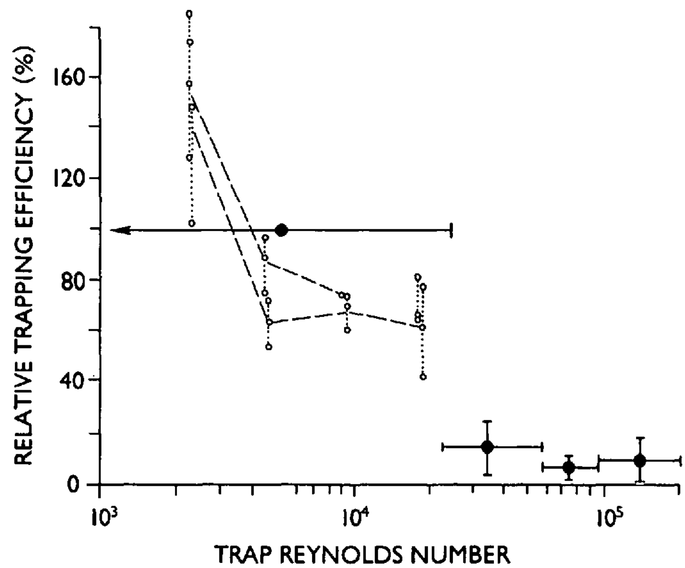

Figure 10. Relationship between trap Reynolds number and relative collection efficiency for the four FAST deployments (solid lines and symbols). Horizontal lines delineate the trap Reynolds number range for each speed interval; symbols and vertical lines mark the mean and standard deviation of the relative collection efficiency during each speed interval. We define the collection efficiency of the trap at speeds <12 cm/s to be 100% because of its agreement with the flux trapped by the drifting trap. Open symbols and dashed lines mark the results of a laboratory study by Butman (1986; Fig. 7). In that study the trap Reynolds number was varied by changing the diameter (but not the aspect ratio) of the trap in a constant flow field.

ν = kinematic fluid viscosity. R_t affects trap efficiency through changes in resuspension and particle aggregation; physical arguments (Butman *et al.*, 1986) and laboratory studies (Lau, 1979) suggest that trap efficiency decreases with increasing R_t. Unlike Butman's (1986) flume study, the FAST experiment studied the R_t effect by changing u_f rather than D. A plot of R_t against relative collection efficiency follows a decreasing trend as observed by Butman (1986), where relative efficiency $\simeq \sim 1$ for low R_t values and decreases substantially at greater R_t values (Fig. 10). We would not expect an exact agreement between the two studies because of the difference in trap aspect ratios and because our lowest R_t class covered the entire range of R_t values studied by Butman (1986), making it impossible to resolve changes in efficiency for $R_t < 2 \times 10^4$ to compare with her data. Furthermore, uncertainties about the magnitude of the "true" flux in either experiment means that only efficiency *differences* associated with changes in the Reynolds number can presently be evaluated. That is, the actual position of the curves of relative efficiency from both experiments could be shifted up or down depending on the value of the "true" flux. Despite these constraints, the present study and that of Butman (1986) indicate that under both field and laboratory conditions, and for two different trap geometries, an increase in R_t caused by variations in either u_f or D results in a significant decline in trap efficiency for a given aspect ratio.

From a practical point of view, a loss of trap efficiency at high current speeds can be alleviated by decreasing the trap diameter, since a decrease in either D or u_f will decrease R_t. For a trap with the aspect ratio and geometry of the one used in this study, collection efficiency decreases sharply above R_t values of $\sim 2.4 \times 10^4$ (or possibly lower), which corresponds to a diameter of 20 cm at 12 cm/s, 10 cm at 24 cm/s, and 5 cm at 48 cm/s. Since efficiency is also a function of aspect ratio, trap users should treat with caution the presently-ingrained assumption that a trap with an aspect ratio ≥ 3 will provide a "true" flux measurement under all conditions. Trap dimensions must be properly scaled for the environment in which they will be used.

We note that the results of an earlier field experiment by Blomqvist and Kofoed (1981), who found no consistent dependence of total flux on trap diameter for a fixed aspect ratio, appear not to agree with the conclusion of a direct relationship between R_t and trapping efficiency. Unfortunately, the results of the Blomqvist and Kofoed (1981) experiment cannot be generalized because of an absence of information about current flow or particle settling velocity, and because the traps were deployed near the sea floor in a shallow ($\sim$10 m) embayment where both resuspension and wave motion might have been influential. Under conditions of very low currents, for example, $R_t \rightarrow 0$ and variations in D (for a fixed aspect ratio) have little or no effect on the trapping efficiency (see also the discussion of trapping efficiency in §2a). Trap studies have advanced to the stage where new insights can only be achieved by carefully constrained experiments.

b. Effect of particle fall velocity. The dimensionless parameter u_f/W gauges the importance of the horizontal component of fluid velocity relative to vertical particle motion (W). As u_f/W increases, the ratio of horizontal to vertical particle transport increases, and eddies within a trap become more effective at capturing and removing particles, thereby decreasing trap efficiency (Butman *et al.*, 1986). For a given value of u_f, then, trapping efficiency should decrease with decreasing W. To test this hypothesis, we calculated a representative fall velocity for each class of particle size and density separated from the FAST samples. Fall velocity was calculated using the Stokes equation,

$$W = \frac{g(\rho_s - \rho)d^2}{18\eta}$$

where $g = 980$ cm/s^2, ρ_s = particle density, ρ = water density (1 g/cm^3), d = particle diameter, and η = dynamic viscosity (0.01 g/cm s). Particle diameter was set to the midpoint of each size class (or 400 μm for the >250 μm class and 15 μm for the <38 μm

Table 2. Calculated fall velocity (cm/s) for sediment trap size and density fractions.

	$d > 250\ \mu m$	125–250 μm	64–125 μm	38–64 μm	<38 μm
$\rho > 1.6\ g/cm^3$	11.7	2.6	0.65	0.19	0.016
$\rho < 1.6\ g/cm^3$	0.71	0.16	0.079	0.012	

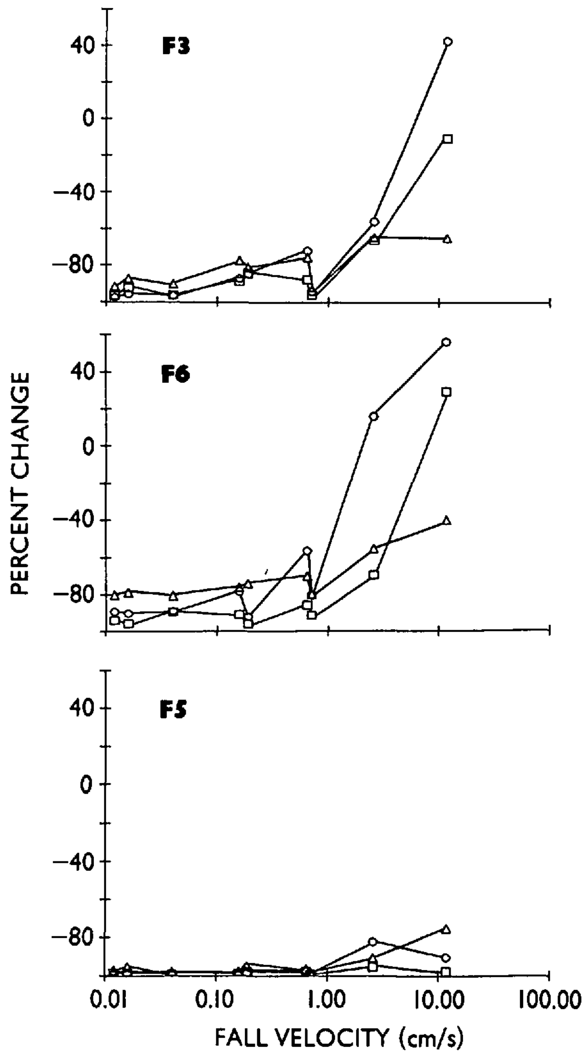

Figure 11. Percent flux change between the <12 cm/s speed interval and increasingly higher speed intervals as a function of particle fall velocity. For each particle category in Table 2, the percentage change was calculated as $(f_n - f_1)/f_1 \times 100$, where f_n = flux during speed interval 2(△), 3(□), or 4(O), and f_1 = flux during speed interval 1. Results for experiments with a similar current speed distribution (3 and 6) showed similar changes in collection efficiency, whereas the higher speeds during experiment 5 caused a proportionally greater flux decrease.

class); ρ to 2.65 g/cm^3 for the heavy fraction (mostly mineral grains) and 1.1 g/cm^3 for the light fraction (mostly organic debris). The computed fall velocity for each particle fraction is listed in Table 2. For FAST deployments 3, 5, and 6 we then compared the change in absolute flux between the <12 cm/s speed class and each of the other three speed classes (Fig. 11). Each deployment found a consistent trend of decreasing efficiency with decreasing fall velocity. For particles with $W < \sim 3$ cm/s, most of the efficiency decrease occurred between the <12 and the 12 – <30 cm/s samples, with additional flux decreases at higher speeds accounting for <10% of the total. The particle class with the highest fall velocity actually showed an absolute increase in flux as speed increased during deployments 3 and 6, a trend not observed during deployment 5 when currents were at their maximum.

5. Conclusions

The collection efficiency of moored sediment traps in a varying flow field is strongly dependent on the horizontal current speed at the trap mouth and the fall velocity of the suspended particles. The mass flux and the distribution of particle size and density collected at speeds <12 cm/s was indistinguishable from that collected in drifting traps deployed in an essentially identical particle and hydrographic environment. At higher speeds, mass flux into moored traps decreased sharply, declining by a factor of 70 at speeds >50 cm/s. These field experiments further generalize the conclusions of Butman's (1986) laboratory study by demonstrating that an increase in the trap Reynolds number caused by an increase in the current speed results in a decrease in relative trap efficiency. Our results also support the hypothesis of Butman *et al.* (1986) that collection efficiency decreases with decreasing particle fall velocity, and are the first results to rigorously test this hypothesis. Additional experiments covering ranges of current speed, trap diameter, and particle fall velocity not yet studied are needed to fully generalize these conclusions.

Drifting traps are the ideal device for sampling the vertical flux in environments with a high Reynolds number, but they are often impractical. This study suggests that it may be possible to evaluate the speed-biased results obtained with moored traps by comparing the mass flux into drifting and moored traps at several points over the range of expected speeds. The derived relationship may be expected to be a function of both the trap design and the suspended particle characteristics. Because the collection efficiency of a trap with a given aspect ratio is a function of the current speed and the mouth diameter, trap dimensions must be properly scaled for the environment in which they will be used.

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