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## **A sediment trap experiment in the Vema Channel to evaluate the effect of horizontal particle fluxes on measured vertical fluxes**

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### **ABSTRACT**

Sediment traps are used to measure fluxes and collect samples for studies in biology, chemistry and geology, yet we have much to learn about factors that influence particle collection rates. Toward this end, we deployed cylindrical sediment traps on five current meter moorings across the Vema Channel to field-test the effect of different horizontal particle fluxes on the collection rate of the traps— instruments intended for the collection of vertically settling particles. The asymmetric flow of Antarctic Bottom Water through the Vema Channel created an excellent natural flume environment in which there were vertical and lateral gradients in the distribution of both horizontal velocity and particle concentration and, therefore, the resulting horizontal flux. Horizontal effects were examined by comparing quantities of collected material (apparent vertical fluxes) with the horizontal fluxes of particles past each trap. We also looked for evidence of hydrodynamic biases by comparing and contrasting the composition of trap material based on particle size and the concentration of Al, Si, Ca, Mg, Mn, C<sub>org</sub> and CaCO<sub>3</sub>. Experimental inverted traps and traps with only side openings were deployed to test a hypothesis of how particles are collected in traps.

The vertical flux of surface-water particles should have been relatively uniform over the 45 km region of the mooring locations, so if horizontal transport contributed significantly to collection rates in traps, the calculated trap fluxes should be correlated positively with the horizontal flux. If the horizontal flow caused undertrapping, there should be a negative correlation with velocity or Reynolds number. The gross horizontal flux past different traps varied by a factor of 37, yet the quantity collected by the traps differed by only a factor of 1.4. The calculated horizontal fluxes were 2–4 orders of magnitude larger than the measured apparent vertical fluxes. Mean velocities past the traps ranged from 1–22 cm s<sup>-1</sup> (Reynolds numbers of 3,500–43,000 for these traps with a diameter of 30.5 cm and an aspect ratio of ~3) and showed no statistically significant relationship to the apparent vertical flux. We conclude that at current speeds measured in a very large portion of the world's oceans, vertical fluxes measured with moored, cylindrical traps should exhibit little effect from horizontal currents.

### **1. Introduction**

Sediment traps are widely used and important instruments in biogeochemical studies. However, since the earliest attempts to calibrate sediment traps in a recirculating flume, there have been questions about whether the material collected in a trap is a true qualitative

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and quantitative measure of the vertical flux of particles, or if the material is influenced by the horizontal flux of particles past the trap (Peck, 1972; Gardner, 1977a, 1980a; Hargrave and Burns, 1979; Butman, 1986). The importance of this question is heightened upon realizing that the currents experienced in the natural environment ( $1 - >50 \text{ cm sec}^{-1}$ ) are orders of magnitude faster than the settling velocity of most particles in water ( $\sim 10^{-4}$  to  $10^0 \text{ cm s}^{-1}$ ). Therefore, most particles are not collected in a trap by passive settling; they enter in trap-generated eddies that plunge into the trap and settle from the entrained fluid (Gardner, 1980a). As a result, the "trapping process" occurs primarily via fluid exchange between the eddies entering the trap and the tranquil water in the lower portion of the trap in which the particles have time to settle.

As summarized in the US.GOFS Report No. 10 (1989), the two basic questions about the use of traps are:

- (1) Can traps yield an unbiased, quantitative measure of the total gravitational flux of particles through a horizontal plane in a given environment?
- (2) Do traps yield samples that are quantitatively unbiased with respect to chemical, mineralogical and biological composition of settling material?

Field experiments with traps have yielded fluxes that appear to be internally consistent and reasonable when tested against other parameters, e.g., sediment accumulation rates (Soutar *et al.*, 1977; Dymond *et al.*, 1981; Gardner *et al.*, 1985), fluxes of appropriate radionuclides (Anderson *et al.*, 1983; Bacon *et al.*, 1985; Biscaye *et al.*, 1988; Biscaye and Anderson, 1994), and seasonal variations (Deuser and Ross, 1980; Honjo, 1982; Deuser, 1986, 1987).

Experiments in flumes and in small bodies of water (Gardner, 1977a, 1980a, b; Hargrave and Burns, 1979; Butman, 1986) combined with dimensional analysis (Butman *et al.*, 1986) have shown that the important variables in determining the collection efficiency of a trap are: (1) the trap aspect ratio,  $A = H/D$ , where  $H$  is the trap height and  $D$  is the inside trap diameter at the trap mouth; (2) the trap Reynolds number,  $R_t = uD/\nu$ , where  $u$  is the horizontal flow at the trap mouth and  $\nu$  is kinematic viscosity; and (3) the ratio of flow speed to particle fall velocity. These investigators also found that trap geometry dramatically affects collection rate: small-mouthed, wide-bodied traps overcollect particles; cone-shaped traps tend to undercollect particles; cylindrical traps are recommended whenever possible since their collection area is well defined under conditions ranging from quiescent to turbulent; and axial symmetry of a trap is desirable because of the omnidirectional currents in the natural environment.

Dimensional analysis allows the use of scale models to accurately test the hydrodynamic behavior of full-scale objects, similar to that of planes and cars in wind tunnels. Experiments with scale-model traps in flumes or tanks have the advantage of allowing control of the variables to test for their individual effects on trapping efficiency. However, the drawbacks of flumes are: (1) when critical erosion velocities at the flume bed are exceeded, there will not be a net downward flux of particles, and resuspended particles will

have more than one opportunity to be collected in the traps; (2) the large scale of eddies and internal waves present in the ocean cannot be duplicated in the flume; and (3) it is difficult, if not impossible, to replicate or to scale the complex range of particle sizes and densities that exist in natural environments and their change with time in the trapping process, e.g., the breakup of aggregates upon encountering trap-induced turbulence. Therefore, we sought an opportunity to field test sediment traps in an area over which the vertical flux could be expected to be uniform, but within which horizontal particle fluxes covered a wide range, so we could test the hypothesis that the horizontal flux of particles does not alter the vertical flux of particles measured with cylindrical sediment traps. The Vema Channel in the South Atlantic Ocean served as a suitable setting for this experiment.

The Vema Channel is a deep-ocean passage with a sill depth of  $\sim 4550$  m (Johnson, 1984) that cuts through the Rio Grande Rise—a major topographic barrier running approximately east-west between the mid-ocean ridge and the South American continent, and which separates the Argentine Basin to the south from the Brazil Basin to the north. The channel is  $\sim 400$  km long with a main channel at  $\sim 39^{\circ}30'W$  through which Antarctic Bottom Water (AABW) flows northward (Fig. 1), carrying a significant annual flux of particulate matter from the Argentine to the Brazil Basin (Biscaye and Eittem, 1977; Richardson *et al.*, 1987). Since the Vema Channel is the major northward passage for AABW in the South Atlantic, it was expected that flow would be fairly unidirectional within the channel which would thus approximate a large flume.

Previous hydrographic sections across the channel had revealed an asymmetry in the flow and in the distribution of particulate matter (PM) within the channel (Johnson *et al.*, 1976). These asymmetries offered the opportunity to deploy traps at several different locations that would span a wide range of horizontal fluxes of PM (product of velocity and PM concentration). The 45-km horizontal distance over which the traps were deployed was insignificant compared to the horizontal currents, so it seemed reasonable to expect that the vertical flux of particles from surface waters to a depth of  $>4000$  m would be nearly uniform, especially when averaged over the deployment period of 11 months. There was also the possibility, however, that vertical fluxes could be affected within the channel by resuspension of sediment from the channel walls and floor. The processes that might influence the trap include: (1) the large horizontal vs. the small vertical flux of particles past the trap (Gardner, 1980a, b; Yund *et al.*, 1991; Gust *et al.*, 1992; Buesseler *et al.*, 1994); (2) resuspension of bottom sediment (Gardner, 1977a; Bloesch, 1982; Eadie *et al.*, 1984; Gardner *et al.*, 1983b, 1985; Richardson and Hollister, 1987; Walsh *et al.*, 1988; Monaco *et al.*, 1990; White, 1990); and (3) hydrodynamic effects of trap-induced turbulence (Gardner, 1977a, 1980a; Hargrave and Burns, 1979; Butman, 1986; Butman *et al.*, 1986; Baker *et al.*, 1988; Hawley, 1988; U.S. GOFS Report No. 10, 1989). We tested the combined effects of these processes on traps set in the Vema Channel.

Although we cannot evaluate separately all the potential nonvertical processes, we interpret a correlation between the quantity of material trapped and the calculated horizontal flux as a measure of the influence of horizontal processes.

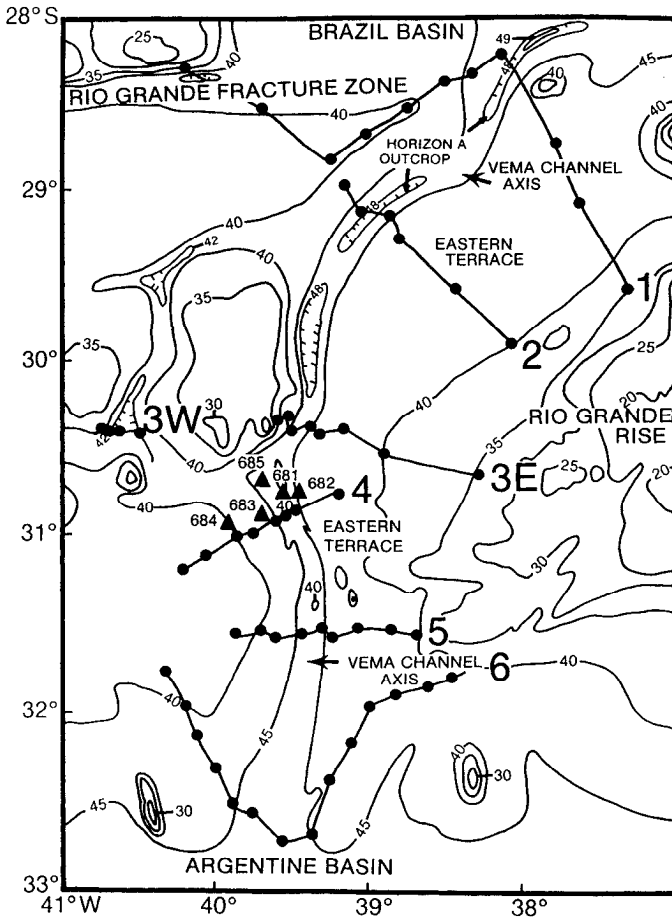


Figure 1. Bathymetry of the Vema Channel region after Johnson (1984). Hydrographic lines where particulate matter (PM) sections and geostrophic calculations were made are shown and numbered 1–6 (see Hogg *et al.*, 1982 and Richardson *et al.*, 1987). Station locations are indicated by dots. Trap/current meter mooring locations near Section 4 are given by triangles and were located south of the branching of the channel which occurs between sections 4 and 3.

## 2. Methods

In an attempt to obtain a better estimate of the transport of AABW through the Vema Channel, Hogg *et al.* (1982) deployed 4 current meter moorings across the channel (along Section 4, Fig. 1), and one mooring to the north to test for downstream coherence in January 1979. The moorings included 13 current meters and 17 sediment traps. Sediment traps were attached to the moorings, generally within 5 m of the current meters (Fig. 2). Recording long-term nephelometers (LTN) (Thorndike, 1975; Gardner *et al.*, 1984) were deployed at three locations on the moorings within 18 m of the current meters (Fig. 2).

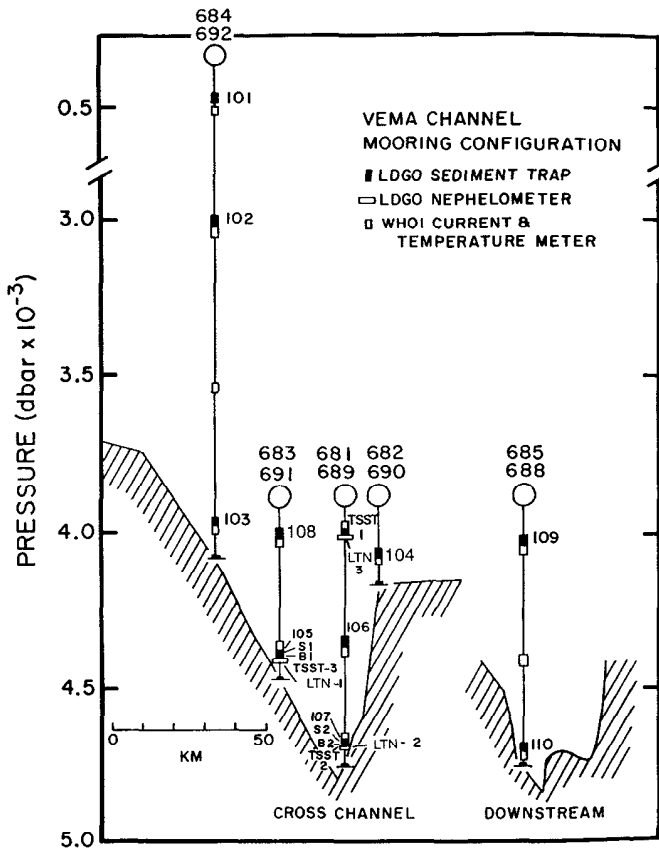


Figure 2. Vema Channel mooring configuration. Mooring locations are shown in Figure 1. The numbers at the top of the moorings (e.g. 684/692) are for the initial and subsequent redeployment, respectively. The “standard” cylindrical traps (Fig. 3) are numbered 101–110. S1 and S2 are the traps with holes only on the side of the traps (Fig. 3), and B1 and B2 are the traps with a hole only in the bottom of the trap (Fig. 3). The three time-series sediment traps (TSST) did not function properly, so the limited data are not reported here.

Soon after the mooring deployment cruise, it was discovered that the batteries of the acoustic releases were potentially defective. A rescue mission was quickly organized and in March 1980, all 5 moorings were recovered and reset for 12 months after changing batteries, data tapes, LTN film and trap sample cups. The redeployed moorings were given a second number designation (Fig. 2).

#### a. Particulate matter (PM) concentration

During the initial deployment cruise, 29 CTD profiles were made on which 19 nephelometer profiles were obtained. Mid-way through the second mooring-deployment period a hydrographic survey cruise was conducted during which sixty-seven CTD

stations, comprising six hydrographic sections, were made across the Vema Channel (Fig. 1). An LDEO-Thorndike nephelometer (Thorndike, 1975) was used on the hydrocasts for simultaneous measurement of PM. The nephelometer measures low-angle forward scattering (Thorndike, 1975) and integrates the signal from particles of all sizes, but, like transmissometers, most of the signal comes from small particles (Gardner *et al.*, 1984). Particle concentrations measured with nephelometers or transmissometers or filtered from water bottles are often referred to as “suspended” particulate matter (SPM), and particles sampled by sediment traps are termed “sinking” particles. However, because some aggregates have very low densities, they may settle slowly (Asper, 1987; Diercks and Asper, 1997). Even small particles settle, and contribute to the sinking flux, so the boundary between “suspended” and “sinking” particles is not so easily drawn based on size. Furthermore, outside of actively mixing boundary layers there is no force that “suspends” particles in the ocean. The density difference between seawater and small organic particles or large aggregates may be so small that they settle slowly or not at all, but this is a matter of buoyancy, not suspension, and it can affect particles of all sizes. Therefore, we should not refer to small particles as “suspended” and large particles as “settling.” All particles are simply “particulate matter” and should be referred to as PM rather than SPM.

The nephelometer signal was calibrated by filtering the entire contents (including the particles that had settled below the spigots, Gardner, 1977b) of at least eight 30-l Niskin bottles per cast and regressing light scattering versus PM concentration (Richardson *et al.*, 1987). Thus, both small and large particles and aggregates collected in the Niskin bottles were included in the calibration.

Three long-term nephelometers (LTN) deployed on the moorings measured light scattering once every four hours using a strobed light source. The light scattering versus PM concentration calibration obtained for the profiling nephelometers in this region was used for the LTNs. Transverse asymmetry in previously measured distributions of PM and velocity in the channel (Johnson *et al.*, 1976) led to the placement of the LTNs in regimes of different currents and PM concentrations. LTN 1 was ~80 m above the seafloor on mooring No. 683/691 in the western section of the channel (Fig. 2) where previous nephelometer profiles showed a gradual increase in PM from the clear-water minimum at about 1500 m above bottom (mab) to the seafloor (Johnson *et al.*, 1976). LTN 2 was ~90 m above the seafloor on mooring 681/689 in the deeper eastern section of the channel where nephelometer profiles had shown more intense nepheloid layers in the bottom ~500 m. LTN 3 was on the same mooring, but ~750 m above the seafloor, well above the high concentration regions of the nepheloid layer.

#### *b. Trap design*

*i. Standard traps.* Ten “standard” LDEO traps were deployed at different locations across the channel (101–110 in Fig. 2). These “standard” traps were PVC cylinders 30.5 cm in diameter and 90 cm high, yielding an aspect ratio (height/width) of about 3 (Fig. 3). The

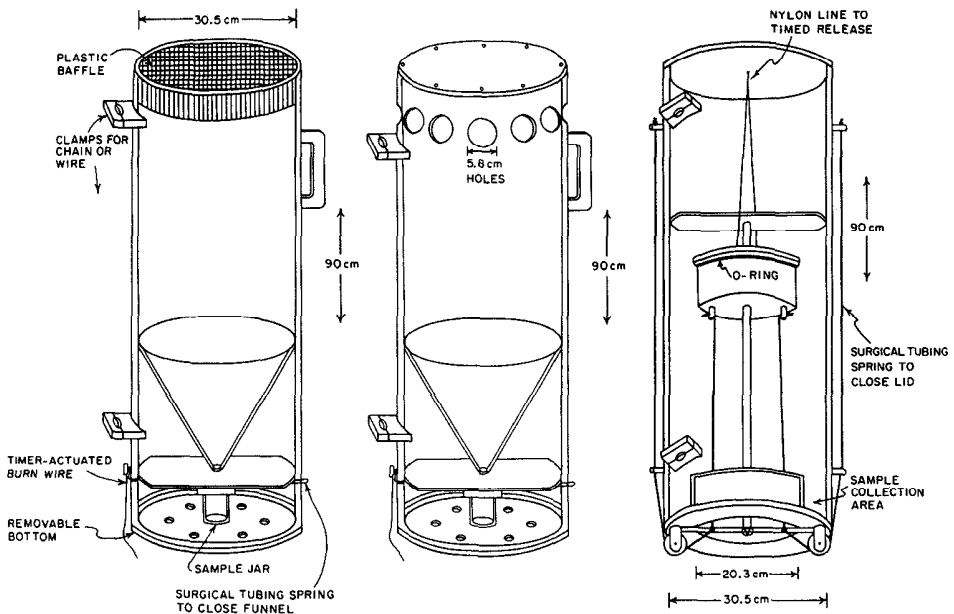


Figure 3. The “standard” (101–110), side-hole (S1, S2) and bottom-hole (B1, B2) traps tested in this experiment.

aspect ratio of the cylindrical portion at the top of the trap was about 2. At the top of the trap was a baffle composed of a 1 cm square plastic grid, 5 cm deep. Inside the cylinder was a funnel with a 3 cm opening that emptied into a sample jar 8.3 cm wide, 12 cm deep. This configuration made it very difficult for any sample to be resuspended during deployment or recovery. The closing mechanism was a PVC “tongue” between the bottom of the funnel and the sample bottle that was pulled from the open to a closed position by stretched latex tubing which acted as a spring when the tongue was released by a burn-wire triggered from an Oceanic Instrument Systems timer.

Each sample jar contained a small glass vial filled with NaCl and mercuric chloride. Salt and poison diffused through a 0.6  $\mu\text{m}$  Nucleopore filter beneath the vial lid, which had three 6-mm holes. The salt was to increase slightly the density of the fluid in the sample jar in order to inhibit resuspension of sample and diffusion of the mercuric chloride. The mercuric chloride acted as a poison for swimmers to prevent them from grazing on the trap sample, and to prevent microbial degradation (Gardner *et al.*, 1983a; Knauer *et al.*, 1984; Lee *et al.*, 1992).

*ii. Experimental traps.* Three experimental traps were designed and deployed. The first had solid tops with holes only around the upper perimeter of the trap (Fig. 3) and were deployed at S1 and S2 (Fig. 2). The intent was not to measure horizontal flux, but to test the hypothesis of Gardner (1980a, b) that traps collect particles through a process of fluid



exchange of advected water and subsequent settling of entrained particles, rather than simply collecting vertically settling particles; i.e. the closed top excluded all particles and they could enter only through the holes in the side of the cylinder. The overall dimensions of these traps were identical to the standard traps. To relate the mass of particles collected with these side-hole traps with our standard cylindrical traps, the cross-sectional area of the cylinder was used to calculate a "flux" (Table 1). Had we used the sum of the area of the holes in the sides of the trap for calculations, the calculated flux would have been 2.3 times greater. The side-hole design would ostensibly enhance the trapping of horizontally-transported particles and discriminate against vertically falling particles.

The second trap design had an opening only in the bottom of the trap to completely preclude particles that were settling strictly vertically (Fig. 3). These traps (B1 and B2 in Fig. 2) further test the concept of trapping by fluid exchange. Particles collected in the 10-cm wide annular area (374 cm<sup>2</sup>) at the bottom of the trap could enter the trap only by upward fluid exchange through the 20.3 cm hole (323.6 cm<sup>2</sup>) and subsequent settling in the outer annular area at the bottom of the trap.

Finally, a third design of three time-series sediment traps (TSST) with eight sample cups (similar to Jannasch *et al.*, 1980) was also deployed. Unfortunately these traps did not function properly, and their data are not reported here.

### c. Sample processing and analysis

The samples were refrigerated upon retrieval of the traps, returned to the laboratory, wet-sieved at 1 mm, and wet-split into subsamples with a precision, four-compartment, rotating sample splitter. Seven subsamples from each trap were filtered, washed and dried and used in the determination of the total flux. The coefficient of variation of total flux (standard deviation/mean) for all traps ranged between 6% and 18%. Splits were used to estimate the total flux of material <1 mm and to obtain replicate determinations of carbonate content (by weight loss after acidification) and organic carbon and nitrogen content (with a Carlo-Erba CHN analyzer). One quarter of each "standard" trap sample was digested in HNO<sub>3</sub> and analyzed for concentrations of acid soluble Al, Si, Ca, Mg and Mn using standard Atomic Absorption techniques. The insoluble portion was fused with LiBO<sub>2</sub>, dissolved in HF, HCl and KOH and analyzed in the same manner. Other splits were gently wet-sieved for size fractions (>250 μm, 125–250 μm, 63–125 μm, 20–63 μm) with each fraction being filtered onto a separate Millipore filter for weight determination and counting of individual large particles using light microscopy. Each filter was examined using reflected light and counts were made of fecal pellets, foraminifera and radiolarians, but the latter two are not reported here. For filters with low particle density the entire filter was counted, while for filters with high particle density, two sweeps at right angles were made across the diameter of the filter and appropriate corrections applied to obtain the total flux of each particle type. The accuracy of the particle counts is within a factor of two after combining the splitting and counting errors.

Table 1. Measured vertical fluxes, organic carbon and carbonate fluxes measured in all traps in the Vema Channel.

Trap #	Meters above bottom	Depth (m)	Deploy. time (days)	Measured flux ( $\text{mg m}^{-2}\text{d}^{-1}$ )	Std. dev. flux ( $\text{mg m}^{-2}\text{d}^{-1}$ )	<i>n</i>	Horizontal flux ( $\text{mg m}^{-2}\text{d}^{-1}$ )	Reynolds number	Org C		CaCO <sub>3</sub>		C <sub>org</sub> /CaCO <sub>3</sub> Molar ratio	
									% of flux	Flux ( $\text{mg m}^{-2}\text{d}^{-1}$ )	C/N molar	% of flux		Flux ( $\text{mg m}^{-2}\text{d}^{-1}$ )
Traps above the nepheloid layer														
101	3524	504	209.0	21.7*	4.0	7			12.0	2.6	6.9	71	15.4	1.3
102	1024	2985	210.0	41.4	5.2	7	10,400	5,800	5.7	2.3	8.0	72	29.8	0.6
Traps in the nepheloid layer, but above the bottom mixed layer														
108	455	3929	209.4	52.0	4.7	7	73,400	22,800	4.5	2.4	8.7	53	27.7	0.7
105	94	4290	210.7	39.5	6.5	7	181,400	3,400	2.9	1.1	9.1	51	20.2	0.5
B1	89	4295	210.7	106.1***	16.8	6			2.7	2.9	7.7	5	4.9	4.8
106	400	4256	211.3	56.2	7.4	7	382,400	43,800	3.1	1.7	8.5	35	19.4	0.7
104	105	3996	211.2	46.0	3.0	7	21,600	4,200	4.1	1.9	8.4	67	31.0	0.5
109	709	3928	213.6	40.9	5.8	7	42,300	18,800	3.9	1.6	8.4	57	23.1	0.5
Traps in the bottom mixed layer														
107	94	4562	211.3	76.8	4.9	7	575,400	43,800	2.3	1.8	8.6	11	8.7	1.6
B2	90	4566	211.3	41.5**	1.5	6			2.0	0.8	9.7	18	7.5	0.9
S2	92	4564	211.3	47.2***	2.1	6			3.0	1.4	10.0	19	9.1	1.2
110	53	4584	213.6	107.9	9.0	7	101,100	23,600	2.8	3.1	7.8	23	25.2	1.0

\*Some sample may have been lost during recovery and processing.

\*\*Based on area of trap opening at bottom,  $D = 20.3$  cm.

\*\*\*Based on inside trap diameter—same as “standard” traps. Multiply by 2.3 if using the total area of side holes.

### 3. Results

The distribution of temperature and velocity (Hogg *et al.*, 1982) and PM (Fig. 4) showed an asymmetry across the Channel similar to that observed by Johnson *et al.* (1976). Both velocity and PM values were greater in the central to eastern portion of the channel, and as a result, the horizontal PM flux was much larger in that region. The horizontal flux and standard deviation of PM were determined in two ways: quasi-synoptic “snapshot” sections and time-series. “Snapshot” estimates of flux (Fig. 5) were made by combining geostrophic velocity sections made during the trap deployment with sections of PM from the calibrated nephelometer profiles (Fig. 4). Time-series determinations were made by multiplying the current velocities times PM concentrations from calibrated LTN data (Fig. 5). Unfortunately the LTN and adjacent current meter did not always function properly simultaneously. Time-series calculations of the horizontal flux past the traps were made by applying the current multiplied by either (1) the PM from the corresponding LTN, if available, or (2) by a mean PM concentration estimated from the sections. Where a current meter malfunctioned but the LTN recorded data properly, an average speed was estimated from the geostrophic sections and nearby current meters and multiplied by the LTN PM values to obtain horizontal PM flux (Fig. 5). The current meter near trap 101 failed (Fig. 2) and the flux from that trap was also questionable, so our analysis will focus

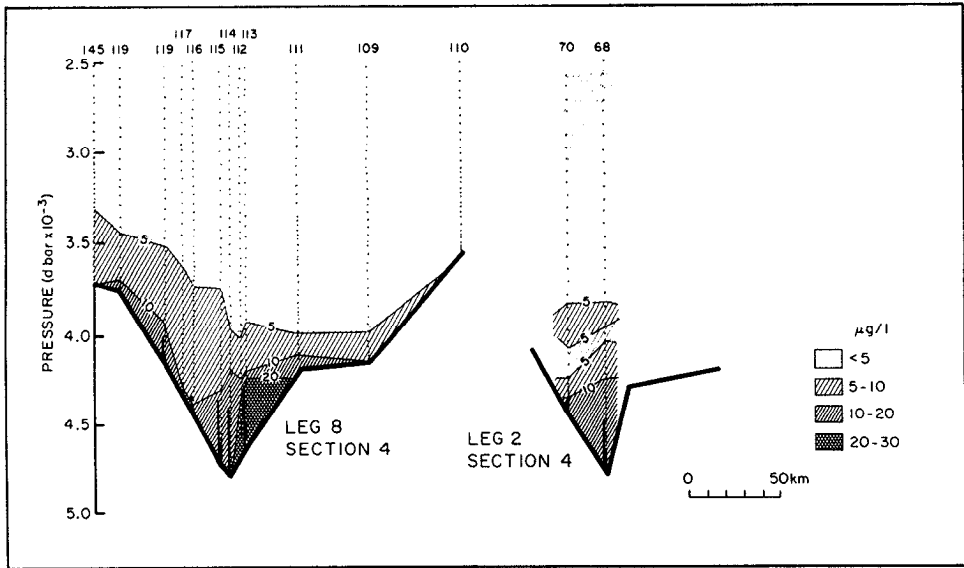


Figure 4. Section of particulate matter (PM) concentration ( $\mu\text{g l}^{-1}$ ) across the mooring line (Section 4, Figure 1) based on the calibrated nephelometer profiles (numbers across top are cast numbers) from the deployment cruise (Leg 2, Oct. 1979) and during a cruise in the middle of the deployment (Leg 8, June, 1980). Solid vertical lines show height of the bottom mixed layer (determined by the temperature warming by  $1\text{ m}^{\circ}\text{C}$  from the bottom value). Note by comparison with Figure 2 that all traps except 101 and 102 are within the nepheloid layer where particle concentrations increase toward the bottom. Only traps 107 and 110 are in the bottom mixed layer.

on the deep traps and flow. Calculations from the time-series data (current meters and LTN) yielded a higher horizontal flux than the quasi-synoptic calculation from the hydrographic section.

Because of the unexpected turnaround of moorings, quantitative samples were obtained from only four traps of the first deployment, so we have considered here only the trap samples from the second deployment.

On the second deployment all timers appeared to have closed the traps properly. However, the funnel in trap 101 was twisted upon recovery and a part of the closing mechanism was broken, presenting the possibility that the sample represented a minimum flux. Also, trap 103 contained so little material that either the trap must have closed early or most of the sample was lost during recovery. The other standard traps were recovered intact and were considered to contain excellent samples. Of the two traps with holes in the sides, only the S2 sample was collected intact. Sample was collected from both inverted traps (B1 and B2), but some sample was lost from B2 on mooring recovery.

All traps except 101 and 102 were in the nepheloid layer of the channel where PM concentrations were higher due to resuspended sediment. As a result, we can expect fluxes in these traps to be increased by the settling of resuspended material (Gardner *et al.*, 1983b,

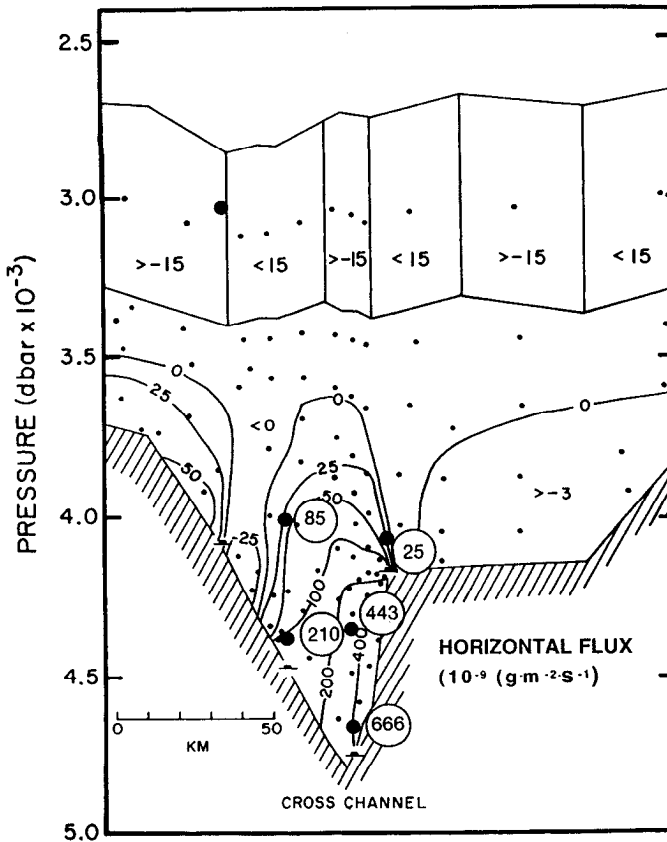


Figure 5. Horizontal flux of PM through Section 4 at the mooring transect (Fig. 1). Calculations were made by two methods. The first multiplied geostrophic transport times PM concentrations averaged over areas of the small dots. The isopleths of flux in  $10^{-9} \text{ g cm}^{-2} \text{ s}^{-1}$  are drawn for these data. The second estimates of horizontal flux were determined from the time-series measurements made at the current meter and LTNs at the large points (from Richardson *et al.*, 1988). Note the general agreement between the two methods.

1985; Gardner and Richardson, 1992). We had intended for all traps to be above any bottom mixed layer (BML), but after the hydrographic data were analyzed we found that the BML engulfed the two bottom traps on moorings in the axis of the channel at least some of the time (Traps 107 and 110; Fig. 2; see Hogg *et al.*, 1982; Fig. 4). Mixing within the BML changes the dynamics of particle settling and may increase the flux measured by traps (Gardner and Richardson, 1992).

#### a. Trap fluxes and chemical composition

The total flux measured by each “standard” trap (101–110, Table 1) is plotted in a section across the Vema Channel (Fig. 6a) and the calculated horizontal flux is displayed

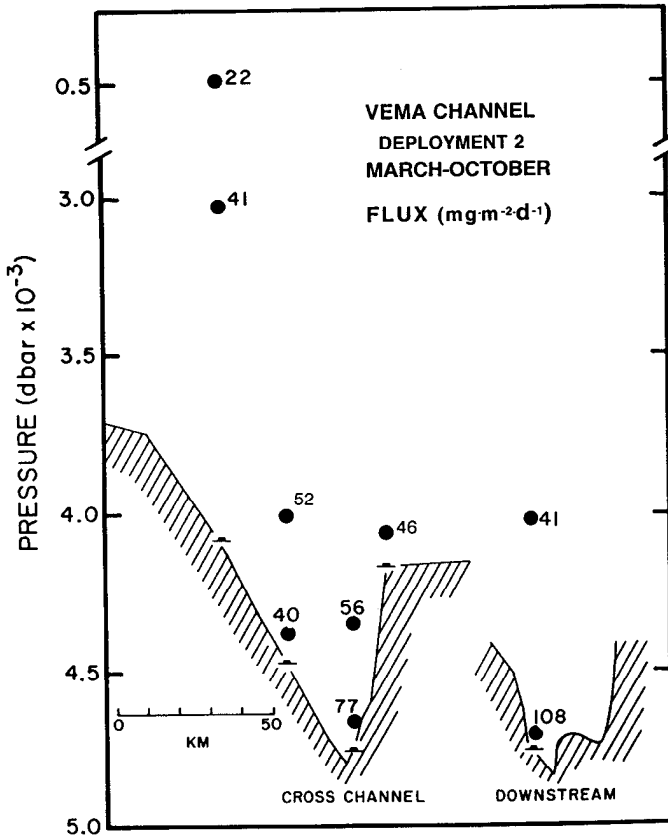


Figure 6. (a) Total mass flux collected by sediment traps. Some material may have been lost from the top-most trap (trap 101; See Fig. 2 and text). (b) Mass flux corrected for aluminosilicate material resulting from resuspension/advection. This does not correct for the flux of non-aluminosilicate material (e.g. opal) that might also have been resuspended and collected by the traps.

across the same section (Fig. 5). Compared with the order-of-magnitude variability in the horizontal flux of PM past the traps, the variability in the measured vertical flux below 3 km is insignificant.

The composition of trap material was consistent with its predominantly biogenic debris: calcium carbonate, organic carbon and opaline silica. As expected, all trap samples contained a significant percentage of Ca (Table 2). The portion of trap sample that was calcium carbonate was >70% in traps above the nepheloid layer, 35–67% in traps within the nepheloid layer but above the BML, and 11–23% in BML traps (Table 1). The same trend was observed in the percentages of organic carbon (Table 1). The amount (mg) of acid-soluble Si (mostly siliceous opal) was very uniform for all traps except trap 101 (depth = 0.5 km; 3.5 km above the bottom) which had a much higher percentage acid-

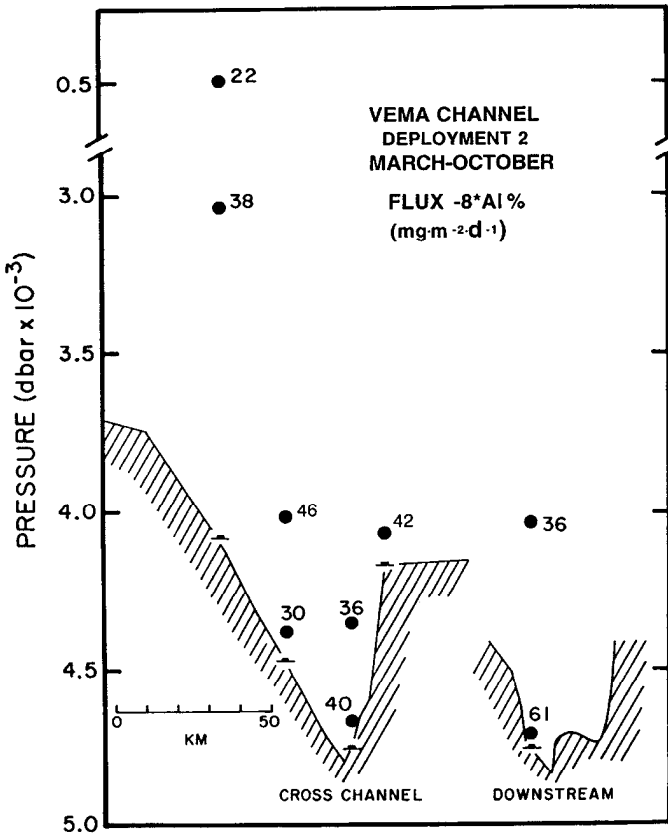


Figure 6. (Continued)

soluble Si (Table 2). The percentage of Al increased with depth from 0.18% (trap 101) to more than 6% (trap 107; Table 2).

We corrected the trap fluxes for the resuspended material using the percent Al. The rationale for this is that bottom sediments in this region are predominantly aluminosilicate minerals since it is well below the local carbonate compensation depth (Biscaye *et al.*, 1976; Thunell, 1982), and bottom sediments seldom contain as much as 1% organic carbon (Premuzic, 1980). An estimate of the aluminosilicate abundance in the trap samples is typically obtained by multiplying the %Al in each sample (Table 2) times 8 (Boström *et al.*, 1973). Subtracting this amount of aluminosilicate mass from the total trap fluxes gave a maximum estimate of the non-resuspended flux of material (Fig. 6b). We did not correct for any siliceous opal material that might have been resuspended; therefore, the estimate of the non-resuspended flux may be slightly high. Removing the estimated contribution of aluminosilicates from the trap fluxes had little effect on the flux in traps well off the bottom, but decreased the flux in near-bottom traps by 25–50% (Fig. 6b).

Table 2. Chemical composition of trap material.

Trap #	Meters above bottom	Total flux mg m <sup>-2</sup> d <sup>-1</sup>	mg sed in 1/4 split	Al		Soluble Si		Total Si		Ca		Mg		Mn		Sum*		
				mg	% Al	mg	% Si	mg	% Si	mg	% Ca	mg	% Ca	mg	% Ca		mg	% Sol.
Traps above the nepheloid layer																		
101	3524	21.7	75.93	0.1	0.18	0.1	10.14	1.41	1.86	18	24.06	24	0.20	0.26	0.01	0.10	44	64%
102	1024	41.4	160.15	1.2	0.77	0.2	3.87	6.26	3.91	43	26.81	29	0.51	0.32	0.08	0.05	96	77%
Traps in the nepheloid layer, but above the bottom mixed layer																		
108	455	52.0	215.14	3.1	1.43	0.3	2.50	10.50	4.88	46	21.56	24	0.89	0.41	0.14	0.06	97	71%
105	94	39.5	130.48	4.1	3.16	0.3	2.00	13.34	10.2	28	21.08	28	1.10	0.84	0.14	0.11	94	89%
106	400	56.2	215.73	9.5	4.39	0.2	0.71	31.90	14.8	31	14.43	22	3.95	1.83	0.32	0.15	93	88%
104	105	46.0	185.21	2.1	1.12	0.2	2.52	9.36	5.05	49	26.30	29	0.55	0.30	0.14	0.07	95	80%
109	709	40.9	142.66	2.1	1.43	0.3	3.75	7.60	5.33	45	31.33	35	0.74	0.52	0.11	0.07	94	96%
Traps in the bottom mixed layer																		
107	94	76.8	325.54	20	6.05	0.2	0.42	57.23	17.6	22	6.81	13	4.42	1.36	0.60	0.18	93	85%
110	53	107.9	408.00	22	5.39	0.2	0.36	68.33	16.8	41	10.00	18	4.75	1.16	0.72	0.18	94	86%

\*Sum is 8\*Al + 2.14\*(Soluble Si) + (In Soluble Si) + 2.49\*Ca + Mg + Mn.

\*\*This is the % Ca after removing the aluminosilicates.

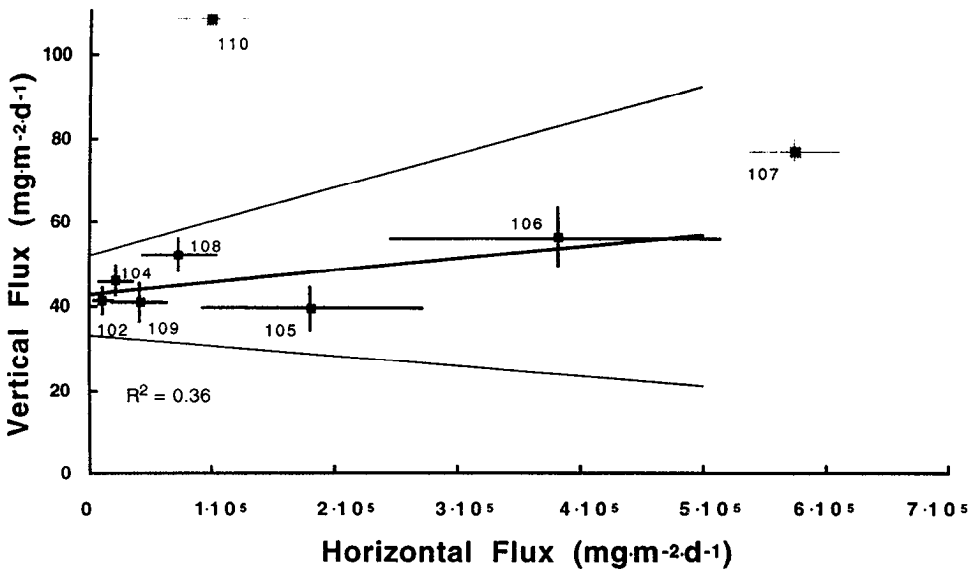


Figure 7. Total vertical flux measured by each trap versus the horizontal flux past the trap. Trap numbers are indicated for each point (see Fig. 2). Fluxes for traps 107 and 110 are high because they were in the BML. Error bars are one standard deviation for the vertical flux (based on measurements of several sample splits) and horizontal flux based on variations in current speed and PM concentration from nephelometers. The heavy line is the least squares regression of the non-BML traps. The upper and lower boundaries of the 95% confidence interval of the regression are given by the thin lines.

#### b. Vertical fluxes versus horizontal fluxes and trap Reynolds number

The horizontal flux of particulate matter past traps deeper than 3 km and above the BML varied by a factor of 37, while the vertical flux measured by those traps varied by a factor of only 1.4 (Fig. 7). The two traps with the highest vertical flux (107 and 110) were located within the bottom mixed layer (Figs. 2 and 4), and were eliminated from statistical correlations. Although a linear regression of the non-BML trap fluxes shows a slightly positive slope, the 95% confidence intervals show that a positive slope is not statistically significant (Fig. 7). The horizontal flux was between 250 and 7,500 times the vertical flux for the six deep non-BML traps, so these data indicate that the traps were very inefficient collectors of the horizontal flux of particles.

As discussed in the Introduction, dimensional analysis allows the comparison of hydrodynamic measurements on traps of different dimensions. Mean velocities in the Vema Channel ranged from 1.7 to 21.9 cm s<sup>-1</sup>, yielding mean trap Reynolds numbers ( $R_t$ ) from 3,500 to 45,000 based on a trap diameter of 30.5 cm and a kinematic viscosity of 0.015 cm<sup>2</sup> s<sup>-1</sup> (Fig. 8). Excluding the BML traps there is a slightly positive slope to the regression between vertical trap flux and  $R_t$ , but in this case the zero slope of the regression falls just outside the 95% confidence interval, so the case for an  $R_t$  dependence of the vertical flux over the range of  $R_t$  measured is rather weak.



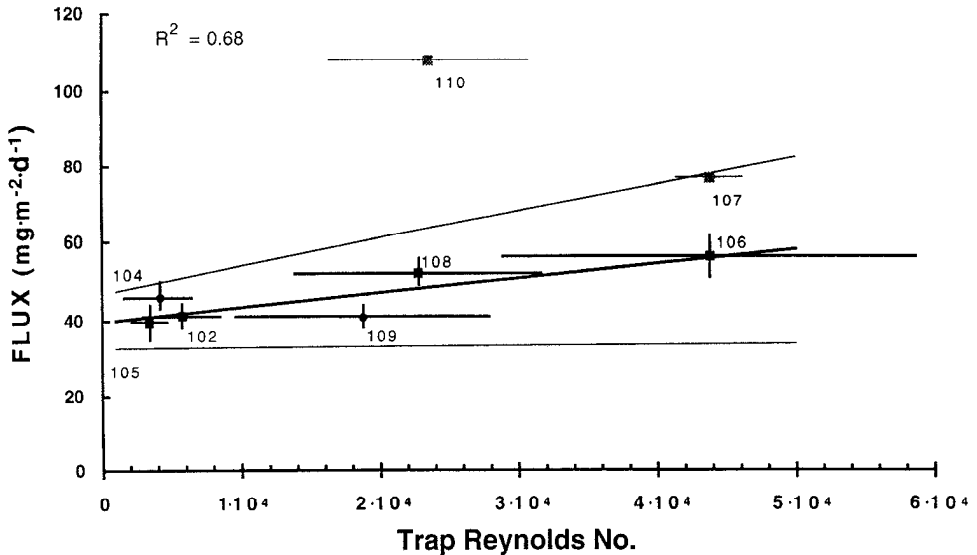


Figure 8. Total vertical flux collected by each trap versus trap Reynolds number ( $R_t$ ). Trap numbers are indicated for each point. Error bars are one standard deviation for the vertical flux and  $R_t$ . The heavy line is the least squares regression of the non-BML traps. The upper and lower boundaries of the 95% confidence interval of the regression are given by the thin lines.

### c. Particle size distribution in traps

We examined the composition and texture of material collected in the different traps to assess similarities and differences in particle sizes. Wet sieving for particle size is not a precise measurement and should not be construed to indicate the size distribution of particles entering the trap. Nevertheless, by handling all samples identically, this method provides a rough estimate of inter-trap similarity of particle sizes. A second reason for size separation is that it helps in counting specific particle types. Replicate analyses of wet-sieved samples from the same traps suggested the coefficient of variation was  $< \pm 10\%$ . The percentage of sample  $> 63 \mu\text{m}$  was similar for all standard traps except for the trap at 500 m (trap 101) and the bottom trap in the main channel (trap 107; Fig. 9a). The high percentage of large particles in the 500 m trap was consistent with similar analyses in the North Atlantic showing that, in the upper water column, the settling material is high in organic carbon and presumably is carried in large, cohesive aggregates that are not broken up upon entering the trap or in the sieving process as easily as the organic-poor clay aggregates near the seafloor (Gardner and Richardson, 1992). The percentage of particles  $> 63 \mu\text{m}$  in the bottom trap in the BML was anomalously small (18%), presumably reflecting the collection of small, resuspended particles, consistent with previous studies (Gardner *et al.*, 1983b, 1985; Gardner and Richardson, 1992).

The size distribution of material from the near-bottom, deep trap in the main channel (trap 107) and the adjacent side-hole (S2) and bottom-hole (B2) traps were all quite similar

(Table 3). The organic carbon and carbonate contents were also similar, though trap 107 had a much larger total flux (Table 1). These traps were all in the BML where there was a high-concentration nepheloid layer, abundant in small particles. We surmise that these small particles move closely with the flow of water. In this well-mixed zone the particles statistically have multiple opportunities to be collected in all three varieties of traps and so dominate the trapped flux in the BML. In sharp contrast, the particles in trap 105 (above the BML) were much larger than those in the adjacent bottom-hole trap (B1), and the carbonate content was also much larger. In general, the non-standard trap samples and traps in the BML had lower percentages of calcium carbonate (Table 1). It appears that the flux in the region above the BML is dominated by large, vertically-settling, carbonate-rich particles that were not carried upward into the bottom-opening trap. Thus, even though settling particles enter a trap through a process of fluid exchange, large carbonate particles (e.g. forams) or carbonate containing particles (e.g. fecal pellets) have a tendency to be excluded from traps without a free exchange at the top.

Specific types of fecal pellets can be identified in trap samples and there has been much speculation about the sources of different types of pellets in traps (Honjo, 1978; Uerrey and Knauer, 1981). We identified a particular dark gray fecal pellet in the size fraction  $>250\ \mu\text{m}$  that was abundant in all samples. The data of Komar *et al.* (1981) suggest the fall velocity of a pellet  $250\ \mu\text{m}$  long and  $100\text{--}150\ \mu\text{m}$  wide would be  $0.2\text{--}0.3\ \text{cm s}^{-1}$  ( $170\text{--}260\ \text{m d}^{-1}$ ). A section of the flux of these pellets at each trap showed a variation of less than a factor of three with no trend of higher fluxes where the current velocities were higher, even for the two traps within the BML (Fig. 9b). The lack of variability in flux suggests that the collection of large, rapidly settling particles is minimally influenced by horizontal processes.

#### 4. Discussion

##### *a. Theoretical predictions vs. field studies*

The ultimate goal in testing and calibrating sediment traps is to determine whether they collect a quantitatively and qualitatively unbiased sample of particles settling through the water column. From theoretical predictions and field studies, trapping efficiency has been related to several dimensionless parameters, allowing the prediction of conditions when some traps will over- or undercollect.

Two important dimensionless parameters in trap analysis are the Reynolds number ( $R_t = uD/v$ ) and aspect ratio ( $A$ ). Changing trap mouth diameter ( $D$ ) changes both of these parameters simultaneously. One parameter must be held constant while varying the others to systematically test for the evidence between each parameter and trapping efficiency. Most experiments have failed to do this, so it is difficult to know whether observed changes in efficiency are related to  $R_t$  or  $A$ . The third important dimensionless variable identified by Butman *et al.* (1986) was  $u/w$ , a dimensionless velocity ratio, where  $u$  is the horizontal approach velocity outside the trap and  $w$  is the particle settling velocity in still water. Based

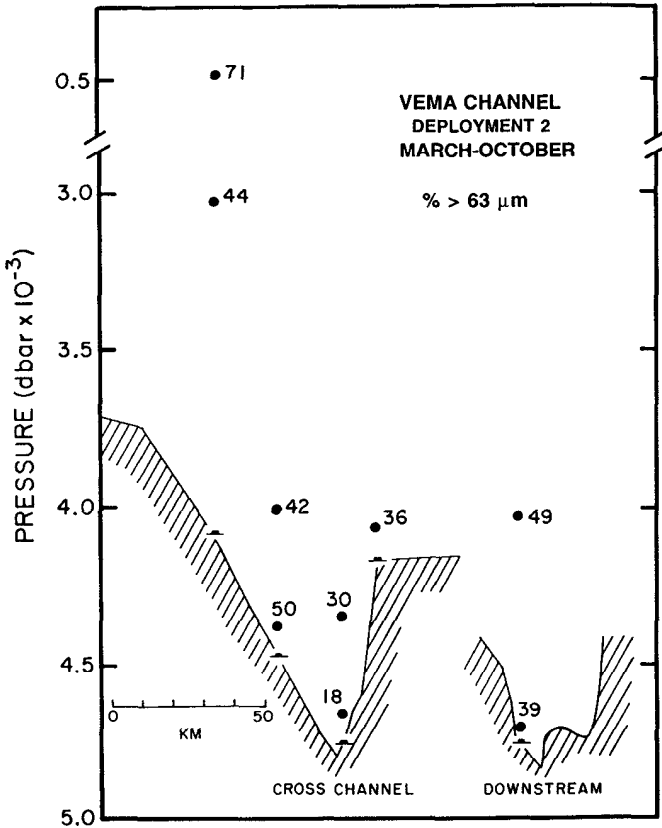


Figure 9. (a) Percentage of material in traps  $>63 \mu\text{m}$  in the second deployment. (b) Flux of dark gray fecal pellets collected in the traps.

on their dimensional analysis, Butman *et al.* (1986) predicted that, for fixed values of the other two parameters, the collection efficiency of cylinders (for  $A > 1$ ) was expected to:

- (1) decrease over some range of increasing  $R_t$ ,
- (2) decrease over some range of increasing  $u/w$ , and
- (3) increase over some range of increasing  $A$ .

Several studies have shown that collection efficiency increases over some range of increasing  $A$  (Gardner, 1977a, 1980; Hargrave and Burns, 1979; Bloesch and Burns, 1980; Blomqvist and Kofoed, 1981; Butman, 1986). The mechanism by which particles are retained inside of traps increases particle retention until  $A$  is sufficiently large, after which the dynamics of particle retention are constant. It appears to be related to the presence of a tranquil layer at the trap bottom (Gardner, 1980b). Hawley (1988) quantified the thickness of the tranquil layer as a function of  $A$  and  $R_t$ , and found that it ceased to exist at  $R_t > 6,000$  for  $A = 3$ . Hawley also described an upward spiraling secondary type of circulation in the

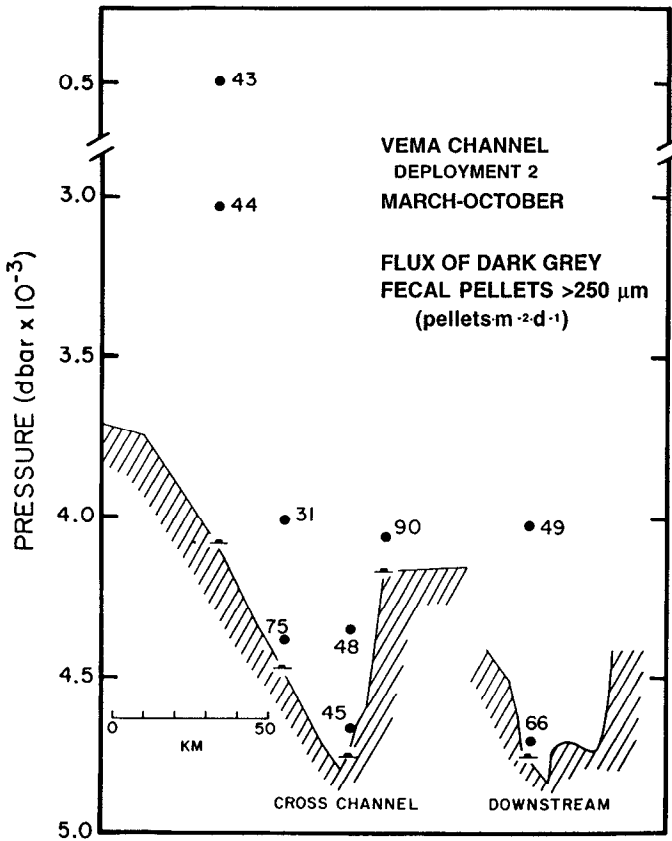


Figure 9. (Continued)

trap that he termed upwelling (noted also by von Bröckel, personal communication, 1977 and by Gardner, 1985) and carefully noted its onset as a function of  $R_t$ . For  $A = 3$ , upwelling began sporadically at  $R_t = 3,500$ . In our field study, both  $D$  and  $A$  were constant. Only  $u$  changed, but that in turn changed the dimensionless variable  $u/w$ . In the location where these traps were deployed, there was no reason to expect that  $w$  increased proportionately with  $u$  to keep  $u/w$  constant. If anything, the mean  $w$  decreased as more fine-grained particles were encountered in the nepheloid layer.

Butman (1986) conducted trapping efficiency experiments in a flume as a function of  $R_t$ .  $R_t$  was increased by increasing the diameter of cylindrical traps, while holding  $A$  and velocity constant. Dimensionally this is the same as increasing  $R_t$  by increasing velocity. However, in predicting trap efficiency one is predicting the behavior of particles within a turbulent flow, which can vary with  $u$ , so this hypothesis should be verified by empirical tests before being universally applied.

In Butman's study, collection efficiency decreased by a factor of 2 when  $R_t$  was increased from 2,000 to 5,000 and then leveled off for  $R_t$  up to 20,000 (Fig. 10a). One caveat about this result is that the decrease in efficiency was seen only in the smallest cylinder, whose

Table 3. Percentage of material in each size class of trap and sediment.

Trap	<20 $\mu\text{m}$	20–63 $\mu\text{m}$	63–125 $\mu\text{m}$	125–250 $\mu\text{m}$	>250 $\mu\text{m}$
Traps above the nepheloid layer					
101	17	15	15	14	39
102	28	29	15	13	15
Traps in the nepheloid layer, but above the bottom mixed layer					
108	42	13	15	11	19
105	30	17	11	12	30
B1	46	28	10	9	7
106	40	30	13	8	9
104	44	21	12	11	11
109	32	19	16	23	10
Traps in the bottom mixed layer					
107	60	23	5	4	8
B2	58	26	6	8	2
S2	68	14	8	6	4
110	23	28	18	12	18
Core gc-08	87.4	8.6	2.6	1.1	0.3

The five size fractions are an average of 2 measurements using Millipore filters.

The >63  $\mu\text{m}$  data plotted in Figure 9a are the averages of 3 measurements.

Traps 105 and B1 and traps 107, B2 and S2, respectively, were moored 2 m apart in the vertical.

diameter was 1.8 cm. In the field study of Blomqvist and Kofoed (1981), their data in Figure 6b indicate that cylinders smaller than 3–4 cm in diameter were biased collectors relative to larger diameter cylinders ( $D = 4.5\text{--}31$  cm,  $A = 8$ ) tested on a given deployment. The small cylinders overcollected organic-rich particles and undertrapped mineral matter (i.e. high density material), contrary to theoretical prediction (2) listed above, suggesting that some trapping mechanism may be peculiar to cylinders with very small diameters. The narrow cylinders undercollected inorganic particles, with the result that the net flux varied by less than 50% among traps over the diameter range of 1–31 cm (Fig. 10b). Blomqvist and Kofoed (1981) suggested that with narrow traps, higher-density particles were being centrifugally spun out of trap-generated eddies and beyond the downstream trap wall rather than being carried into the trap, whereas the low-density organic matter remained in the eddies and was carried into the trap and collected. They made no particle size analysis of their trapped material to confirm their hypothesis, nor did they have any independent measures of the absolute flux of particles for comparison with their measured fluxes.

The results of a novel field study by Baker *et al.* (1988) agreed with Butman *et al.*'s (1986) theoretical prediction that relative trapping efficiency decreases over some range of increasing  $R_r$ . They compared fluxes in moored and drifting traps over intervals of several

currents speeds ( $<12$ ,  $12\text{--}30$ ,  $30\text{--}50$ , and  $>50$   $\text{cm s}^{-1}$ ). No absolute measurements of vertical flux were made; fluxes were normalized to the flux calculated from the drifting trap. The measured flux in the moored trap was observed to decrease as current speed (and thus  $R_t$ ) increased (Fig. 10a).  $R_t$  ranged from  $<24,000$  to  $>100,000$ , and the trapping efficiency decreased by 75% between the  $R_t$  ranges of  $<24,000$  and  $24,000\text{--}60,000$ . Baker *et al.* (1988) could not resolve efficiency changes for  $R_t$  of  $<24,000$ , nor could they determine the  $R_t$  at which efficiency decreased between the wide bounds of 24,000 and 60,000. The traps drifting with the water showed neither of these trends during corresponding collection periods, but the differential flow past the drifting traps was small.

Our open ocean study showed no systematic decrease in trapping efficiency over the  $R_t$  range of 3500–43,000 (Fig. 8). Perhaps it was in the higher end of the 24,000–60,000 range of Baker *et al.* (1988) where trapping efficiency decreased sharply. Furthermore, the Baker *et al.* (1988) data extended to a much higher  $R_t$  than our data (Fig. 10). We cannot rule out the possibility of a decrease in trapping efficiency at higher  $R_t$ . The time scale of our experiment was also much longer than that of Baker *et al.* (1988) making it possible that we averaged out some trends or events which might have been observed had our time-series traps functioned properly.

As noted above, in the field study of Blomqvist and Kofoed (1981) little change ( $<50\%$ ) in total trapping efficiency was observed for traps with diameters of 1–31 cm when  $A$  was held constant at 8. Flow was not measured during the experiments, so we cannot accurately plot efficiency versus  $R_t$ . However, numerous current measurements made at other times in the sheltered, tideless bay have shown that currents were low and normally below  $10$   $\text{cm s}^{-1}$  (Blomqvist, personal communication, 1988), so we can constrain the range of  $R_t$  within an order of magnitude by assuming the velocity was between  $1$   $\text{cm s}^{-1}$  ( $R_t = 100\text{--}3100$ ) and  $10$   $\text{cm s}^{-1}$  ( $R_t = 1000\text{--}31,000$ ). A rough comparison of the data of Blomqvist and Kofoed (1981; Fig. 10b herein) with data of Baker *et al.* (1988) and Butman (1986; Fig. 10a herein) shows little variation over the range of  $R_t$  in Butman's lab experiments, nor in the overlapping interval in Baker *et al.*'s experiments or the Vema Channel experiment (Fig. 10c). However, Blomqvist and Kofoed's aspect ratio of 8 was much larger than those used in the other experiments (e.g., in Butman, 1986,  $A = 3$ ; in Baker *et al.*, 1988,  $A = 3.9$ ; in our study,  $A = 3$  or less). Also, there was no attempt to determine the true vertical flux by some independent method in any of the field experiments. Butman's fluxes were normalized to an estimated flux based on the product of settling velocity and concentration of glass beads in her flume studies.

A further complication to a comparison of the results of Butman (1986), Blomqvist and Kofoed (1981), Baker *et al.* (1988) and our study is the fact that cylinders were used in the first two studies, a steep-walled (minimum slope =  $73^\circ$ ), canted, asymmetric funnel ( $A = 3.9$ ) placed inside a cylinder was used by Baker *et al.* (1988), and a symmetrical funnel was at the bottom of a cylinder in our study. Another difference is that Butman (1986) used a specific range of glass beads of a constant density, whereas the other studies were in the natural environment. This will be addressed later, but it underscores the need

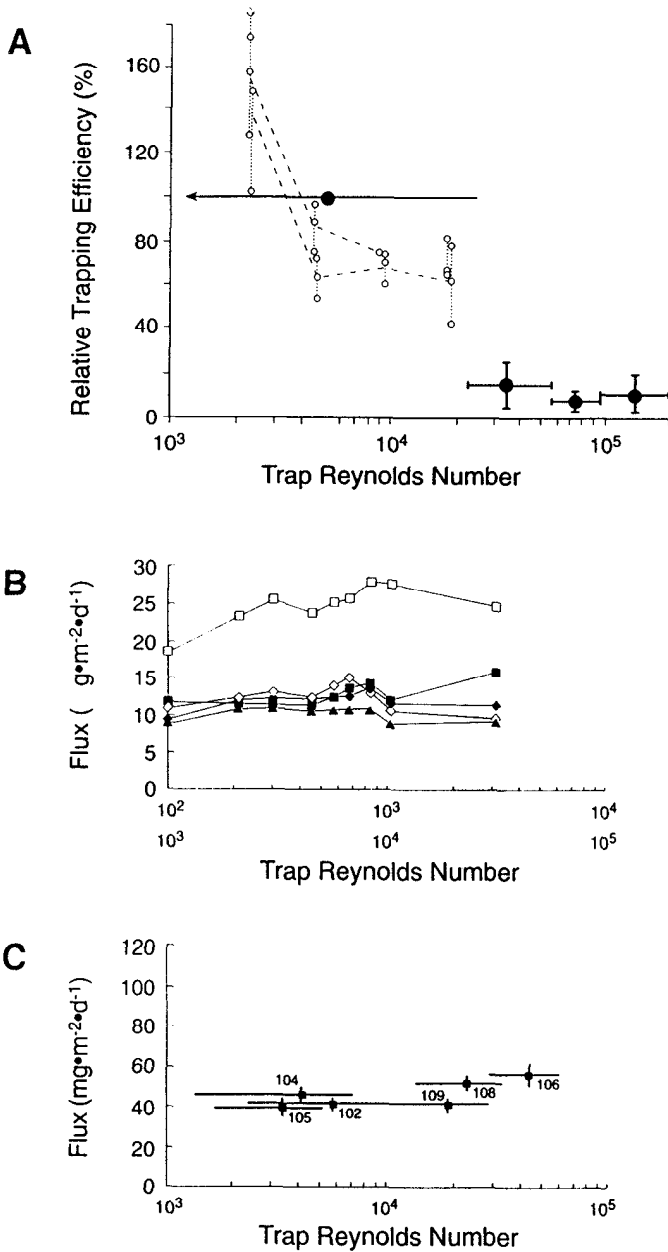


Figure 10

for systematic studies of  $A$  and  $R_t$  effects using the specific trap designs that are used in the field. Nevertheless, these are important and encouraging results for ocean trapping since the  $R_t$  in our Vema Channel study corresponded to a velocity of about 22 cm s<sup>-1</sup>, and currents in deep water are generally <22 cm s<sup>-1</sup>.

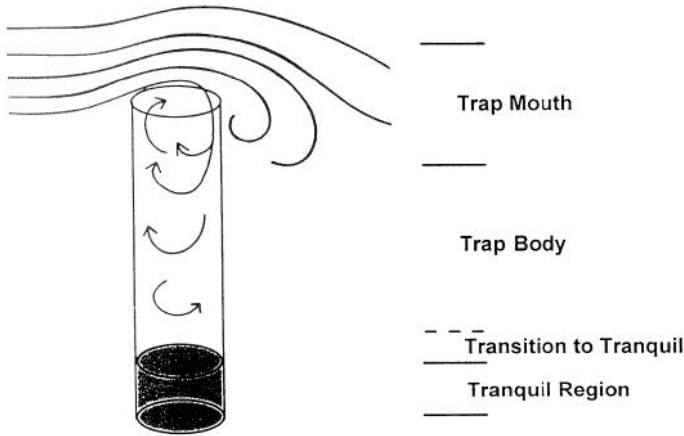


Figure 11. Flow lines around and in a cylindrical sediment trap. Eddies are generated at the top of the trap and may plunge into the downstream end of the trap or outside of the trap. Eddies decrease with depth in the trap and may cause a reverse circulation deeper in the body of the trap. If the trap aspect ratio is adequate, there is a transition zone to the tranquil region at the bottom of the trap where particles settle undisturbed by trap-induced circulation.

#### b. Nature of particle trapping mechanism

Flow visualization studies show there are three regions of importance in understanding how particles are collected in cylindrical traps (Fig. 11): (1) at the trap mouth where eddies are generated; (2) in the central region of the trap; and (3) in the bottom, tranquil region of the trap (when it is present) (Gardner, 1977, 1980a, b, 1985; Butman, 1986; Hawley, 1988).

Figure 10. (a) Relative collection efficiency versus trap Reynolds number ( $R_t$ ) for the laboratory study by Butman (1986; Fig. 6b) (open symbols and dashed lines), and the field study of Baker *et al.* (1988) (solid lines and symbols). In the Butman (1986) study fluxes were normalized to an estimated flux based on the product of settling velocity and concentration of glass beads in the flume.  $R_t$  was increased by increasing the diameter of the traps while velocity and aspect ratio ( $A = 3$ ) were held constant. In the Baker *et al.* (1988) data, horizontal lines delineate the  $R_t$  range for each speed interval; symbols and vertical lines mark the mean and standard deviation of the relative collection efficiency during each speed interval for four deployments. They assumed the collection efficiency of the trap at speeds  $< 12 \text{ cm s}^{-1}$  to be 100% because of its agreement with the flux measured by the drifting trap (from Baker *et al.*, 1988). (b) Particle flux versus  $R_t$  for five consecutive field experiments by Blomqvist and Kofoed (1981). Experiments lasted 12–30 days and used cylinders with different diameters (which create a range of  $R_t$ 's for each experiment, as in Butman, 1986) but a constant aspect ratio of 8. Currents were not measured concurrently, but numerous current measurements at other times were between  $1\text{--}10 \text{ cm s}^{-1}$  (Blomqvist, personal communication, 1988), constraining  $R_t$  to within one order of magnitude. Fluxes were generally constant to slightly positive for a given deployment, suggesting that fluxes measured by cylindrical traps are not influenced significantly by  $R_t$  over a range possibly from as small as 100 to as much as 31,000. (c) Flux versus  $R_t$  from our study (See Fig. 8).



*i. Trap mouth.* Traps obstruct flow, causing water to accelerate around the trap. Acceleration of the flow over the top of an open trap results in decreased pressure in that region, which draws water out of the trap at its leading (upstream) edge, and water enters at the downstream side (Fig. 11). Even at very low velocities or  $R_t$ , eddies develop. Depending on the geometry and  $R_t$ , the eddies can spin off into the downstream flow, plunge completely into the downstream end of the trap opening, or break on the downstream edge of the trap, with only a portion of the water entering the trap. The regions where fluid enters and leaves the trap are not always equal in area, which implies that velocities normal to the plane of the trap must be variable to maintain conservation of mass.

Do these eddies cause preferential selection of particles entering the trap based on size or density? If so, what is the effect of flow conditions as represented by  $R_t$  and  $u/w$ ? For the slowly settling particles, which dominate the mass of particulate matter in the ocean, particle inertia relative to the mean or turbulent flow is negligible, so particles will follow streamlines very closely and little particle discrimination should occur. As particle size and settling velocity increase, however, particle paths begin to deviate from streamlines. There is evidence that the average fall velocity of particles collected in traps is on the order of  $100 \text{ m d}^{-1}$  (Deuser and Ross, 1980; Honjo, 1982; Deuser, 1986, 1987) and is likely to be in the form of large aggregates (1 mm or greater; Asper, 1987), in which case further theoretical and empirical evaluation is needed to determine the size and density of particles that no longer follow streamlines and might experience sorting (see Soo, 1967; Tooby *et al.*, 1977; Butman *et al.*, 1986). This may be one of the biggest drawbacks of flume calibrations that don't use full-sized traps, because, although it is possible to scale the shape of traps to be hydrodynamically similar to full size traps in the field, it may not be possible to simultaneously scale the particles with the dimensionless parameter  $u/w$  in order to have the particles behave similarly in the lab and field. For example, to obtain the same  $R_t$  in the flume as in the field requires a larger  $u$  to compensate for the scaled-down trap, which in turn may increase the chance of sorting within eddies of particles which have the same  $w$ . Maintaining  $u/w$  constant requires particles with an increased  $w$ . So while it is possible to scale the flow around and within traps, it is difficult to simultaneously scale or predict the behavior of particles within the trap-generated turbulence.

Laboratory studies (Murray, 1970; Jobson and Sayre, 1970) have shown that the gravitational settling velocity of particles may be affected by turbulence. Fung (1993) showed that in the surface layer the largest decrease in settling velocity with increased turbulence was for small, low-density particles, but even then, the effect was minimal. Mixing within the surface layer decreases the rate at which particles leave the layer (Lande and Wood, 1987; Kerr and Kuiper, 1997). Turbulence and mixing are most likely in surface- and bottom-mixed layers where significant turbulent energy is introduced or dissipated. There is, however, no evidence that oceanic turbulence away from boundaries will alter the mean gravitational settling velocity of particles, especially the rapidly settling particles and aggregates which are responsible for most of the particle flux.

The trap-induced flow overwhelms turbulence in the environment unless the scale of

natural eddies has vertical structure on the order of the size of the trap (i.e. if a passing eddy imposed large positive and negative vertical velocities on the flow field). In nearly all cases the average current speed in the flow approaching the mouth of the trap is the important flow variable to use in dimensional analysis to predict the flow structure and particle trapping characteristics of a given trap.

*ii. Central region of trap.* The flow within a trap depends on the geometry of the trap. The mean depth of penetration of an eddy at the top of the trap is a function of trap diameter and  $R_t$  (Gardner, 1980a; Butman *et al.*, 1986; Hawley, 1988) and the degree of turbulence in this primary cell is much greater than in the approaching fluid outside the trap. Beneath this primary cell a complete or partial counter-rotating secondary cell may develop (depending on  $R_t$ ), from which fluid parcels break off intermittently and move deeper into the trap. What combination of parameters result in the transfer of particles from the primary eddies to this transition zone and deeper? Is the retention of particles here based on their  $w$ , on the vertical velocity of water, on residence time in the trap, or geometry (especially aspect ratio) of the trap? It is clear that only a small percentage of the particles entering the trap remain in the trap: the horizontal fluxes were two to nearly four orders of magnitude greater than the measured vertical fluxes (Fig. 7).

*iii. Bottom of trap.* Particles are transferred from the body of the trap to the tranquil region through fluid exchange or gravitational settling. Hawley (1988) quantified the thickness of the tranquil region as a function of  $R_t$  and aspect ratio ( $A$ ). Particles can be resuspended from this zone if  $R_t$  is large enough or  $A$  is small enough to let strong eddies scour the bottom, or if cyclonic upwelling at high  $R_t$  lifts particles up from the bottom. Deep collection tubes and brines protect particles from resuspension, but the addition of brine can also change  $A$  and decrease the collection efficiency (Gardner and Zhang, 1997). Baker *et al.* (1988), observed a large decrease in trap efficiency at high  $R_t$ , despite the use of brines and very deep collection tubes, which argues that the decrease in flux at high  $R_t$  is not due to resuspension from the bottom of the trap, but results from biasing in step 1 (centrifugal separation in eddies entering the trap), step 2 (low residence time for low- $w$  particles to settle in the central region of the trap), or step 3 (the transfer of particles to the bottom tranquil zone).

### *c. Flow around funnels and cylinders*

In meteorological studies Nipher (1878) found that placing a funnel (45° angle) around a cylindrical rain gauge effectively reduced the updraft at the leading edge of the cylinder. Rain gauges with the Nipher shield accurately measured rainfall as velocity increased (Kurtyka, 1953). One might argue that in water, funnel traps divert updrafts in the same way and therefore make effective collectors. The difference is that when funnels are used as traps, the whole funnel area is used in flux calculations rather than just a cylindrical area inside the funnel.

*Dye studies.* To further our understanding of trap dynamics, flow lines were traced using dye in models of our standard trap (Fig. 3) and the Baker *et al.* (1988) trap in a racetrack flume 60 cm wide with a water depth of 50 cm. Velocities tested were 5 and 10 cm s<sup>-1</sup>. The trap models were 8.9 cm wide and 26.7 cm tall with a funnel in the bottom third of the trap. In addition, flow was observed within this cylinder without a funnel. For the Baker trap model, a symmetric funnel was inserted into the “standard” trap model.

Of the designs tested, the simple cylinder had the most tranquil flow near the bottom of the trap. Our standard trap model showed penetration of the dye down into the funnel region, but the motion of the eddies quickly decreased in the funnel region. This was due partially to the increase in surface area drag per unit volume of water but mostly was due to the rapidly decreasing space into which the eddies were constricted in the closed-ended funnel.

In our model of the Baker trap, the inner funnel had an “aspect” ratio (height of funnel walls to width at top of funnel) of about 2.3 compared to ~3.9 for Baker’s trap. Both our model and Baker’s trap had steeper funnels than the funnel traps tested previously by Gardner (1980) or Butman (1986) where flow was reported as vigorous throughout the funnel. In our Baker model the eddies still plunged into the downstream end of the trap, but about halfway down the eddies quickly slowed and split into a slow upward flow and a downward reverse flow cell below the surface cell as reported earlier in high-aspect ratio cylinders (Gardner, 1985; Hawley, 1988). Water at the bottom of the trap moved very slowly. Thus, the flow in cylinders with a funnel at the bottom is dependent upon the steepness of the funnel walls, but there can be a tranquil region at the bottom in which particles can settle.

#### *d. Experimental traps to test collection biases*

Trap-induced turbulence can potentially render the calculated vertical flux inaccurate or bias the size frequency spectrum of trapped particles or both. That is, even if some traps collect particles at a rate equivalent to the downward vertical flux, the collected samples may not be representative in composition or hydrodynamic size to those particles responsible for the vertical flux. The correct vertical mass flux could fortuitously result from an overtrapping of small particles and an undertrapping of large particles or vice versa. A particle size biasing has been observed and was related to different trap geometries in both flume and field work (Gardner, 1980a, b; Baker *et al.*, 1988).

One of the reasons we deployed traps with openings only on the side or bottom was to test for this sort of size and compositional biasing, and indeed it occurred. The flux calculated from bottom-opening trap B1 was nearly 3 times the flux calculated for the standard trap near it (trap 105, Table 1). The material in the bottom-opening trap contained only one tenth the percentage of carbonate content (Table 1). The low carbonate was not an analytical problem as the C/N ratio was among the lowest values measured for the traps (Table 3). The bottom-opening trap had a much smaller percentage of large particles than the standard trap (Table 3).

These trends did not hold when comparing traps 107 and B2, where the flux of the bottom-opening trap was much less than the flux in the standard trap (Table 1) and the particle size distributions were quite similar in both traps (Table 3). However, a major difference between the environment of the two trap pairs was that 107 and B2 were in the BML as determined by both nephelometer and CTD profiles (Fig. 4; Hogg *et al.*, 1982; Richardson *et al.*, 1987), whereas traps 105 and B1 were above the BML. High concentrations of resuspended sediments in the BML typically result in higher fluxes of smaller particles ( $<63 \mu\text{m}$ ; Gardner and Richardson, 1992), as is also evident here where trap 107 in the BML collected nearly twice the flux of trap 105 and 83% of the particles collected were  $<63 \mu\text{m}$  compared to 47% in trap 105 (Table 3). We assume that the greater uniformity of particle composition and size distribution in traps in the BML (traps 107, B2 and S2) resulted from greater turbulence and, therefore, uniformity of the particles in the water and therefore, in the particles settling in the trap.

Positively buoyant particles have been collected in bottom-opening traps (Yayanos and Nevenzal, 1978; Simoneit *et al.*, 1986; Smith *et al.*, 1989). We noted an oily sheen on the water surface when we removed the top of the bottom-opening traps, but our traps were not designed to collect and recover rising particles.

#### *e. Comparisons with contradictory studies*

The hypothesis of Butman *et al.* (1986) and the findings of Baker *et al.* (1988) indicate that trap fluxes may decrease with increasing  $R_t$ . However, two investigators have reported a significant increase in trapping efficiency with increasing  $R_t$  (Yund *et al.*, 1991; Gust *et al.*, 1992, 1996), contrary to previous studies, and these differences should be addressed.

Yund *et al.* (1991) reported a several-fold increase in the collection rate of larvae in cylindrical traps as a function of horizontal velocity. There are several possible explanations. First, it appears that Yund *et al.* (1991) filled their traps with brine. At higher velocities they found a greater loss of brine and a greater collection of larvae. Gardner and Zhang (1997) have demonstrated that the addition of brine in cylindrical traps decreases the collection of particles. As the brine is eroded, the effective aspect ratio increases and the trap will collect more particles.

Second, their traps were deployed 1 m above bottom in a shallow (3–5 m) body of water, which means they were probably always in either the surface or bottom boundary layer of flow. Trap fluxes measured in boundary layers are suspect because the mixing and turbulence maintains particles in suspension, allowing multiple opportunities for particles to be collected in the traps. Once particles enter the trap and are in a semi-tranquil portion of the trap, they will sink, which does not simulate their settling velocity in a turbulent boundary layer.

Third, Yund *et al.* (1991) acknowledge that their collections may scale with horizontal flux if the particles do not follow the flow in eddies as described in Tooby *et al.* (1977). Large particles may be preferentially spun into the trap. This leads to the fourth explanation of why their results might differ significantly from those of Gardner (1980a), Butman

(1986) and Baker *et al.* (1988). Their material was predominantly larvae that were much larger ( $d = 1\text{--}1.2$  mm long) and settled much more rapidly ( $w = 0.29\text{--}0.97$  cm s<sup>-1</sup>) than the particles of Gardner (1980a; all <63 μm; 95% <25 μm) or Butman (1986:  $d = 25$  and 46 μm,  $w = 0.01\text{--}0.3$  cm s<sup>-1</sup>). Oceanic trap samples are routinely sieved at 1 mm and that component generally comprises <5–10% of the total sample (Honjo *et al.*, 1992), although this is not necessarily a measure of the size distribution at the time the particles originally entered the trap. Thus, even if Yund *et al.*'s (1991) results are correct, they may have little bearing on the use of traps to collect the vertical flux of particles outside of boundary layers in most oceanic conditions.

In other work, Gust *et al.* (1992) deployed pairs of floating trap arrays that used different-sized drogues so that the flow past the top of the traps was different and ranged from 7.8 to 37.3 cm sec<sup>-1</sup> ( $R_t = 48,000\text{--}229,000$ ). In all cases the traps with the higher velocity past the trap collected more material. Their interpretation was that flux increased with  $R_t$  or with the horizontal flux of material moving past the trap. This is contrary to the results of our study and to the results of Baker *et al.* (1988), which showed no change or a large decrease in flux over the same range of increasing  $R_t$  in a marine environment. Note, however, that the traps used by Gust were funnels, whereas Baker *et al.* (1988) and our study used cylinders with different types of funnels inside. Gust *et al.* (1992) reported vigorous flow near the bottom of funnel traps, contrary to our flume observations of funnels. The height to width ratio of their funnel, however, was only 1.8 compared with 3.9 for the traps of Baker *et al.* (1988), so the eddies were not constricted as rapidly in the traps used by Gust. In addition, the baffles in traps used by Gust *et al.* were 10 cm in diameter, which does little to dampen the flow. The addition of baffles (1 × 1 × 5 cm) to our standard trap models decreased the flow within the traps, and appeared to decrease the size of eddies entering the trap. Baffles with large diameters do not reduce the internal circulation as much as do baffles with a small diameter (Gardner, 1980a, b).

Another important characteristic of the traps tested by Gust *et al.* (1992) was that they were surface tethered and experienced vertical motions up to 0.5 m with a 10 s period. Obviously the traps were not isolated from vertical wave motion, which certainly changed the flow dynamics and particle collection processes within the traps. Vertical motion was not a factor with our traps in Vema Channel, and was not discussed as an issue by Baker *et al.* (1988).

Still another possible explanation for the Gust *et al.* (1992) observation of flux increasing with increasing speed is that tilted cylindrical traps have been shown to collect more than upright traps (Gardner, 1985). Since all the Gust traps were attached to surface flotation, an increase in the drogue area at depth should also cause an increase in the tilt experienced by the traps. They did not report the tilt data for specific trap experiments, only the general statement that none of their traps had more than a 5° tilt. Gardner (1985) demonstrated that a tilt of only 5° could increase by 25% the flux measured by cylinders with an aspect ratio of 5, and larger tilts could increase the flux by as much as 300%. No tests of this sort have been made with funnels, so while we cannot directly extrapolate the results from cylinders to funnels, our experience observing flows within funnels and

cylinders suggest a larger change in flow dynamics within funnels than within cylinders when both are tilted.

Gust *et al.* (1996) have also conducted freshwater flume experiments and present what they feel is further evidence that the flux collected by cylindrical traps is proportional to the flow past the trap. The manner in which they conducted their experiments, however, was very different from the natural environment or from previous flume studies in which particles were mixed into the system and allowed to enter the traps as they would in the field (Gardner, 1977a, 1980; Hargrave and Burns, 1979; Butman, 1986). Instead of allowing the particles to enter the trap naturally as part of the turbulent flow generated by traps, Gust *et al.* inserted a tube below the baffles at the downstream side of the trap through which they pumped water containing a constant concentration of glass beads or crushed walnut shells. They carefully matched the velocity in the tube with the fluid velocity inside the trap, so that as they increased the flow past the trap in different experiments, they increased the flow of water and beads in the tube. A plot of their data showed that the mass of particles collected in the trap was linearly related to the rate at which they fed particles into the trap and they interpreted this to mean that trapping efficiency is a function of flow velocity. A more straightforward interpretation is that the more particles you inject into a trap the more particles the trap collects. A fatal flaw in their methodology was that it completely bypassed the first of three major steps in the trap collection process as outlined in the next section.

They also showed a linear relationship between the mass of particles collected and the concentration of particles fed into the trap. Their inference was that this was evidence for a bias in trap collections. Actually, this relationship should be expected as long as the size and density distributions of particles, and the resulting settling velocities, were constant. As concentration increased, the flux increased proportionately because there was more material to settle. To find otherwise would suggest that traps are biased collectors. It is likewise to be expected, as shown in their data, that for a given particle concentration, the flux will also increase as the settling velocity of particles increases.

#### *f. Other comments*

Although we have compared the results of flume and field experiments as a function of  $R_t$  (Fig. 10) the unavoidable fact is that none of these traps had identical geometries. When we built the traps for this experiment in the Vema Channel in early 1979, it was proposed that cylinders with an aspect ratio of about 3 would accurately measure the vertical flux (Gardner, 1980a, b), and this was later confirmed by Butman (1986). The later work of Hawley (1988) showing the  $R_t$  at which the tranquil layer at the bottom of the cylindrical trap disappears suggests that larger aspect ratios are needed than had been previously anticipated at higher  $R_t$ . Bloesch and Burns (1980, their Table 2) presented data from trap collections in Lake Erie suggesting that trap aspect ratios of greater than 5 should be used with cylinders. Zhang *et al.* (1994) found identical collection rates in cylinders with aspect ratios of 5 and 10 in a turbulent shelf environment.

Our Vema Channel data show relatively uniform fluxes collected with our traps over a

wide range of  $R_t$  and horizontal particle fluxes. The “standard” Vema Channel traps were also tested during the Sediment Trap Intercomparison Experiment (STIE; Honjo *et al.*, 1992) and yielded fluxes very similar to those registered by other cylindrical traps and large funnels. For future work, however, we encourage the use of cylinders with an aspect ratio of 5 or greater (excluding any region filled with brine).

While it is tempting to extrapolate these data to the collection efficiency of surface-tethered traps, one must use extreme caution. Gust *et al.* (1994) have documented that wave motion is transferred to the floating traps if they are not decoupled by using a section of stretchable mooring line. High-frequency pumping (period = 10 sec) is likely to have an effect on collection efficiencies. What needs to be determined conclusively is whether the typical floating trap deployments have been affected in this way, as Gust *et al.* (1994) did not report adding flotation to compensate for the added weight of their instrument pressure cases when they tested floating trap arrays. If the standard surface-tethered traps are not sufficiently decoupled from surface waves, that might account for some of the low carbon fluxes reported by Michaels *et al.* (1994).

It is not enough to understand flow in traps; we must understand the behavior of particles within the flow. This is why we chose to test the effect of horizontal processes on trap fluxes in the natural environment. Another problem with natural particles is that aggregates are likely to be broken up as they encounter shear zones at the trap mouth and within the trap, but we have no idea to what degree. How does this affect their behavior in traps? Calibration tests need to use particles that are appropriately scaled to those found in the ocean. In addition to measuring the relative fluxes by different types of traps or in different environments, we also need better methods to determine true vertical fluxes independently. The use of radionuclides seems to hold the best hope in combination with measurements of accumulation rates of labile components in the sediments (Anderson *et al.*, 1983; Bacon *et al.*, 1985; Biscaye *et al.*, 1988; Biscaye and Anderson, 1994).

## 5. Conclusions

Sediment traps are valuable tools for measuring the vertical flux of particles in aquatic environments and collecting samples for various analyses. The results of this experiment suggest that the flux measured by cylindrical traps have little dependence on trap Reynolds numbers over the range from 3,500–43,000. For our “standard” traps (diameter = 30.5 cm), that corresponds to an upper velocity of 22 cm s<sup>-1</sup>. This is encouraging news for the use of traps in the open ocean, where the physical conditions are generally within this range. Furthermore, our data show that the fluxes measured by traps in the ocean are not a proportional measure of the horizontal flux of particles past the traps. These results are also consistent with those of Baker *et al.* (1988), but not with the flume experiments of Yund *et al.* (1991) or Gust *et al.* (1996). The latter two experiments employed methods that were very different from methods of other investigators and this likely biased their results. Lack of agreement may also result from the fact that, while it is possible to dynamically scale the flow around trap models in a flume, the behavior of complex oceanic particles and

aggregates within the flow around traps is not yet fully understood and is best studied *in-situ*, because these factors are not easily represented by scaling.

We still need improved methods to determine absolute vertical fluxes of particles, and improved understanding of the present method we use—sediment traps. We believe the results from our Vema Channel experiment constitute a step in that direction. At present, however, results from properly designed traps used within an appropriate range of ocean-dynamic conditions, appear to be sufficiently internally consistent and reasonable when tested against other parameters, (e.g., sediment accumulation rates, fluxes of appropriate radionuclides, seasonality) that these measurements should not be abandoned, as some have suggested, but used and intercompared with appropriate caution. It must be recognized that there are physical conditions outside of which cylindrical traps do not collect a quantitatively and qualitatively accurate vertical flux. In any case, there appear to be no other means extant or on the horizon for the long-term collection of settling marine particles, the samples of which provide the only possibilities for analytical data on the range of biological, geochemical and geological variables affected by gravitational settling of particles throughout the water column of the world oceans.

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