INSTRUMENTS AND METHODS

The effect of tilt on sediment trap efficiency

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Abstract—Cylindrical traps with an aspect ratio of 5.2 were tilted from 0° to 70° upstream and downstream in the Hudson River with currents ranging between 2 and 62 cm s⁻¹. Particle flux in the tilted traps increased with tilt up to about 45° where overcollection reached a maximum factor of three but decreased beyond 45° when traps were tilted downstream. There was no discernible velocity effect on the total flux collected with tilted traps. In a recirculating flume, dye used as a water tracer revealed the existence of boundary layers within traps. The exchange of particles across the boundaries appears to play an important role in controlling the collection rate of particles and the conditions during which traps over- and under-collect particles. The tilt effect on traps is important, not only where high velocities can cause a mooring to lean, but also where high-frequency internal waves might pass either moored or freefloating traps since the vertical velocity component of an internal wave can cause an effective tilt of the traps.

INTRODUCTION

Several studies have been made to determine the effect of trap geometry and current velocity on the mass of particles collected in sediment traps (Peck, 1972; Gardner, 1977, 1980a, b; Hargrave and Burns, 1979; Blomqvist and Kofoed, 1981) and to compare trap fluxes with other methods of measuring sedimentation rates (Pennington, 1974; Gardner, 1977; Spencer et al., 1978; Reynolds, 1979; Dymond et al., 1981; Bruland et al., 1981; Lorenzen et al., 1981; Gardner et al., 1983). Reported in this paper are the results of testing another parameter that affects the collection rate of traps, i.e., tilt. The empirical observations also have provided further insight into the dynamics of the way in which particles are collected in traps. Although previous experiments have provided a sound rationale for using traps to measure the vertical flux of particles over a range of environmental conditions, the burgeoning use of sediment traps (Reynolds et al., 1980; Bloesch and Burns, 1980; Blomqvist and Hakanson, 1981) increases the necessity of understanding trap dynamics and determining any limitations to their use.

The intent of using sediment traps is to collect a sample of the particles settling through the water column. A question asked in designing and using traps is whether there are factors that cause the collection of particles at rates greater than, or less than, the rate at which they are settling across a horizontal plane. Undercollection could occur if water is flushed through the trap so quickly that particles do not have time to settle out, or if particles collected in the bottom of the trap were resuspended by turbulence, scour, or wave action and then carried out of the trap. Overcollection might be suspected since the mass of particles carried through a trap in moving water greatly exceeds the vertical flux of particles.

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Sediment traps are not analagous to rain gauges, which, to a first approximation, passively collect the droplets falling into the collector. The fall velocities of marine particles are generally orders of magnitude less than the water velocities encountered in lakes or in the ocean.

Hargrave and Burns (1979) related the collection rate to the cross-sectional area of the trap bottom and argued that cylinders should be used for sediment traps because the cross-sectional area of a cylinder remains constant; therefore the area used to calculate particle fluxes would be unambiguous. Using dimensional analysis they concluded that the most important hydrodynamic parameters affecting sedimentation rates were (1) Reynolds number, \( Re = ud/v \) (where \( u \) is the horizontal current velocity outside the trap, \( d \) is the trap diameter, and \( v \) is the kinematic viscosity of the water) and (2) the aspect ratio, \( h/d \) (where \( h \) is trap height). They, and also Bloesch and Burns (1980), emphasized the necessity of maintaining the same particle concentration inside and outside the trap so that mean settling rates would be the same in both places. Thus, an important condition was that the velocity be negligible at the trap bottom. Also it was assumed that particles entering the trap are not biased by size or density through any hydrodynamic sorting.

Gardner (1980a) suggested that sediment traps collect particles when fluid outside the trap is exchanged with fluid inside the trap and the new fluid stays in a tranquil area of the trap for a sufficient time to allow some of the particles to settle to the bottom of the trap. The collection rate was correlated with the residence time of particle-carrying fluid in the trap, which in turn is largely a function of trap geometry, notably the height to width ratio (aspect ratio) for cylinders.

Soutar et al. (1977) used honeycomb baffles at the top of traps to improve collection efficiency and suggested the honeycomb top was analogous to the seafloor across which particles would be deposited.

In a laboratory evaluation of sediment trap dynamics, dye was used to delineate streamlines around traps and to determine the length of time water would remain in different types of containers (Gardner, 1980a). The residence time of dyed water increased dramatically for cylinders when tilted downstream and decreased when tilted upstream. The tilting of short cylinders (aspect ratios <3 were tested) had a much greater effect on the fluid residence time than did Reynolds number; however at that time no experiments were conducted on the collection rate of particles using tilted traps. Subsequent field experiments with traps deployed in the ocean where currents were strong enough to tilt the moorings up to 40° (Gardner et al., 1983) necessitated empirical tests of the effect of tilting on sediment trap efficiency. In this paper it will be shown that while none of the above hypotheses about the trapping mechanism is completely correct, a combination of parts of each may be the best explanation.

**METHODS**

**Field experiments**

Only one design of sediment trap was tested—a polybutyrate cylinder with a 7.3 cm inside diameter, 0.3 cm wall, and aspect ratio of 5.2. Polybutyrate is commonly used for core liners and can be made into a very inexpensive trap by taping an end cap on the bottom. In the first series of experiments, the cylinders did not have baffles. In the second series, however, a honeycomb baffle of Hexcel Nomex R material (a nylon-type material with epoxy coating), with cells 1 cm in diameter, was placed in the upper 5 cm of the cylinder.

Experiments were conducted at the pier at Piermont, New York. Variations in current speed were large due to tides which move the water both upriver and downriver past the pier.
A dock extends out from the pier, and there are several 5-m sections where the flow is unobstructed by pilings. Traps were strapped to thin bars on a rigid frame to minimize flow obstruction and to maintain fixed tilt angles. Eight traps were deployed across the current during each experiment; they were spaced three diameters apart at four different angles, thus providing replication of each angle used during an experiment. Two traps were always kept vertical, and three experiments with all traps vertical were used to check for uniformity of sedimentation across the test region. Trapping rates of tilted traps were normalized to collection rates of vertical traps. Normalizing the collection rates allows comparison, not only between traps within a single experiment, but also between results from all experiments conducted at the dock since parameters such as flow velocity, particle concentration, and fall velocity vary between experiments.

As sedimentation rates were large, traps only had to be deployed for 45 to 60 min to collect an easily measurable amount of particulate matter. Minimizing deployment times was important because current speed and direction changed rapidly at this site and it was important to ensure that the flow was perpendicular to the line of traps throughout the experiments to maintain the flow in the same plane as the tilted traps. Water samples taken once or twice during each experiment were filtered for particle concentration.

A current meter with a continuous readout at the surface was attached rigidly to a pipe at the depth of the traps. Current speed and direction were monitored every 5 to 10 min and experiments were terminated early if the direction changed. Upon recovery the traps were righted and allowed to settle for 5 to 10 min before the supernatant water was siphoned off. Samples were wet-sieved through a 63-μm screen and the two size fractions were washed through separate precombusted glass-fiber filters and rinsed with distilled water. After drying in an oven at 60°C, the samples were desiccated for 2 h before weighing. The samples were then ashed at 500°C and reweighed to determine organic matter content by weight loss.

Laboratory experiments

After the tilting experiments had been completed in the field, flow past two sizes of baffled cylinders (diameters of 7.3 and 3.8 cm; aspect ratio = 5) was observed in a recirculating flume. Cylinders were placed vertically and at tilts of 25°, 45°, and 70° upstream and downstream, while fluorescent dye was released upstream and inside the cylinders to observe fluid motions at velocities from 12 to 31 cm s⁻¹. Several shapes of containers that were tested in both upright and tilted positions were filled with dyed water to observe fluid motions and the development of steady-state boundaries.

The effect of gimbaling a sediment trap was tested by suspending a cylinder (3.8 x 19 cm) by an axle through the center and exposing it to flow velocities of 12 and 20 cm⁻¹. Three cases tested were (1) with both ends of the cylinder open, (2) only the top open, and (3) the top open and a weight at the bottom of the cylinder.

RESULTS

Field experiments

Although experiments in the river provided natural particles and allowed the use of larger traps than could be used in a flume, other parameters such as current speed and direction could not be controlled. During the 29 experiments conducted, the velocity ranged from <2 to 62 cm s⁻¹. Even during 1-h deployments the velocity had a considerable range (e.g. 2 to 10 cm s⁻¹ during one experiment and 15 to 36 cm s⁻¹ during another). Two velocity ranges, of
Fig. 1. Normalized flux collected in cylinders with baffles (aspect ratio = 5.2) tilted upstream and downstream. Flux in each trap is normalized to the average flux in two vertical cylinders during each experiment. Numbers refer to experiments; dots indicate single trap; bars indicate range of two replicate traps; dashed bars, velocities of 0 to 15 cm s\(^{-1}\) and solid bars of 15 to 62 cm s\(^{-1}\).

15 cm s\(^{-1}\) and 15 to 62 cm s\(^{-1}\) have been used for the results; the division is near the expected threshold velocity (as measured 1 m above the bottom) for resuspension of sediment from the river (SOUTHARD et al., 1971). Current direction also was variable and there were only seven experiments where the direction varied by <5° from normal to the line of traps. Only data from the seven experiments (all of these were from traps with baffles at the top) are plotted in Figs 1 and 2. The other experiments, which showed identical trends, but slightly more scatter, were eliminated because changing current direction alters the tilt angle tested. Although these experiments do not prove that vertical traps are collecting the absolute vertical flux of particles, it was encouraging that variation between traps in each of three experiments where all traps were vertical was very small ($\bar{S}/\bar{x} = 0.05$ for each experiment).

The major result of the tests was that the vertical flux of particles in cylindrical traps increased when the traps were tilted, even at small angles from the vertical, either upstream or downstream (Fig. 1). There was no obvious difference in the degree of enhanced trapping of the total flux of material at high (15 to 62 cm s\(^{-1}\)) vs low (<15 cm s\(^{-1}\)) velocities. The trapping enhancement increased to a maximum of 250 to 300% by 40 to 45° tilt, after which the enhancement decreased. Baffled traps tilted upstream did not decrease in flux beyond 45° (tests were made only to 60°). However, traps without baffling did decrease in flux beyond the 45° upstream tilt; at 75° the flux was <70% of that measured by vertical traps (data not shown in figures).
When the trapping rate of particles either more than, or less than, 63 μm is normalized by the trapping rate of the same size particles in the vertical traps, the same trend of enhanced trapping with tilt is observed, but enhancement for fine particles is greater than for coarse particles. The relative enhancement in particle size collection quantified by the ratio of the trapping enhancement for particles <63 μm : >63 μm is shown in Fig. 2. For a tilt of 30° downstream, the preference for small particles is not significant but can be large beyond 30°, particularly at velocities >15 cm s⁻¹ (experiments 18 and 19). Tilting cylinders upstream seems to enhance the relative collection of small particles at lower angles, but the effect at angles >30° is less than when cylinders are tilted downstream.

No statistically significant trend could be observed in the organic matter content of the particles as a function of tilt as might be expected if there were hydrodynamic sorting and biased collection of low- or high-density particles. In general, the organic content of particles >63μm was twice as high as for particles <63 μm, where percentages ranged from 13 to 28% and 7 to 15%, respectively, for most samples.

Particle fall velocity—the most important parameter in this discussion—is determined by coupling particle size with particle density. As it was not practical to measure the fall velocity of the particles, size was taken as a quick measurement of the nature of particles in the trap.

Laboratory experiments

The main features of the generalized flow around and within containers is described as follows.

In Fig. 3 the flow is from left to right and once inside the trap the fluid usually descends along the downstream side. One exception is shown in Fig. 3a, where the eddies moved to the upstream side of the trap after they entered. The region where fluid enters the containers is
Fig. 3. Distribution of dye (stippled regions) released inside sediment traps held vertical or tilted 15° for 10 to 20 min. Flow is from left to right at 5 to 10 cm s⁻¹. Eddies enter the downstream portion of the opening and descend the same side of the trap except where eddies moved to the upstream side (a). The region of the trap opening from which fluid is accepted changes with trap tilt as shown in the plan view diagrams of the trap openings above (a) and (b), but is highly dependent upon trap geometry. To enter the vertical container, fluid had to approach 0.5 to 2.0 cm below the trap (a). For the tilted container, fluid had to approach from 0 to 1 cm below the trap top (b). Mercury (Hg) used to anchor some traps in the flume (a and b) changed the internal trap geometry.

changed by tilting. With the exception of funnel-shaped containers (Fig. 3j–l), only fluid that approaches the trap from below the opening makes its way into the trap by slipping into the boundary layer along the outside wall of the trap. Looking at the trap opening from above, indicated by circles above traps (Fig. 3a and b), one can see an average area where eddies plunge into the trap with a fairly regular period but variable intensity, and an area where fluid leaves. Tilting the trap (Fig. 3b) changes the average area where fluid enters and exits the opening of the trap.

The development of boundary layers in containers with restricted openings was observed in the flume, though not all possible conditions were tested. In most cases tilting a narrow-necked bottle had little effect on the boundary layer that developed (Fig. 3d and e), whereas
tilting radically changed the boundary layer when the geometry of the bottle was changed by removing the top of the bottle (Fig. 3a and b). The residence time of fluid in a cylinder with an aspect ratio of 1 was about 30 s when tilted 15° into a 5 cm s⁻¹ current, 2 to 3 min when the cylinder was vertical, and, when tilted 15° downstream, a boundary layer developed within the trap and still existed after 20 min (Fig. 3g to i). Had this trap been tested for particle retention when tilted upstream, it would likely have had a very low flux. When a funnel was tilted 22° upstream, the flow within the funnel reversed direction completely (Fig. 3k). The flow was not changed significantly when the funnel was tilted 22° downstream. The addition of baffles (1 × 1 cm) inside the top of the funnel decreased the internal flow in all cases.

Flow around and within a cylinder with an aspect ratio of 5 was similar for both traps tested (diameters of 3.8 and 7.6 cm); therefore data for the smaller trap is presented in Fig. 4.

Fig. 4. Streamlines of flow around and inside cylinders (3.8 × 19 cm) held vertical and tilted 25° in a current of 12 cm s⁻¹ (a to c) and 31 cm s⁻¹ (d to f), and tilted 70° in a current of 20 cm s⁻¹ (g to h). Tilting upstream did not change the general pattern of flow. Tilting downstream produced an eddy that flowed in the opposite direction from that of eddies at the top of cylinders held vertical or tilted upstream, as a result of different pressure and flow fields outside the trap.
Table 1. Depth of penetration (cm) of eddies in cylinders 3.8 cm in diameter and 19 cm high, held vertical or tilted at several velocities and Reynolds numbers

<table>
<thead>
<tr>
<th>Velocity (cm s⁻¹)</th>
<th>Reynolds (Vd/v)</th>
<th>Tilt angle</th>
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<tr>
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<tr>
<td>12</td>
<td>4600</td>
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<td>22</td>
<td>8400</td>
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<td>31</td>
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<td>20</td>
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and Table 1. The general flow in vertical cylinders contained eddies penetrating in the downstream side of the cylinder to a depth that increased with current speed (Fig. 4b and e). Depths in Table 1 are those of consistent eddy penetration; occasionally eddies penetrated more deeply, or deep eddies moved across the trap, struck the wall, and a reverse eddy occurred deeper in the trap. A third-dimensional rotating component of the inner flow about the axis of the cylinder could not be portrayed in Fig. 4. At 12 and 22 cm s⁻¹ there was a tranquil region at the bottom of the cylinder, but at 31 cm s⁻¹, only the bottom corners were tranquil at all times (Table 2; Fig. 4e).

When the cylinders were tilted upstream, the general flow was similar to the flow in vertical traps, but the depth of eddy penetration decreased with increasing tilt (Fig. 4a, d and g; Table 1). Reverse eddies at mid-depth occurred more regularly in the cylinders tilted into the current. In all cases the depth of eddy penetration increased with speed and the thickness of the tranquil region at the bottom decreased with speed. When the cylinder was tilted 70° into the current, a boundary layer was established near the opening and eddies could penetrate only about 2 cm, but occasionally the boundary broke down and eddies penetrated to about 5 cm.

The general flow differed significantly in cylinders tilted downstream (Fig. 4c, f and h) in that the eddies at the top of the trap flowed in a direction opposite to that of the eddies in cylinders that were vertical or tilted upstream. There still was an accelerated flow over the top of the trap, but the water moving around the cylinder was sucked backwards into an eddy at the top of the cylinder. This caused a very high shear zone between the eddy and the accelerated flow over the top of the cylinder. The rotating flow about the axis of the cylinder was particularly strong and there was an occasional reverse eddy below the main eddy as in cylinders that were vertical or tilted upstream.

The gimbaled cylinder oscillated upstream and downstream with a constant period in a flow of 12 cm s⁻¹. The degree of rotation was usually about 40° in both directions, but sometimes was as low as 10°. With the bottom of the cylinder closed, the period of oscillation was less regular and the degree of rotation was generally about 10° to 20°, but sometimes was as high as 40°. Lowering the center of gravity by adding 19 g (wet wt) of lead to the bottom of the cylinder (wet wt 13 g) limited the oscillations to 2° to 3° upstream. At 20 cm s⁻¹ the tilt was only 1° to 2° upstream.
Table 2. Thickness of tranquil zone (cm) at bottom of cylinders 3.8 cm in diameter and 19 cm high, held vertical or tilted at several velocities and Reynolds numbers

<table>
<thead>
<tr>
<th>Velocity (cm s⁻¹)</th>
<th>Reynolds (Vd/v)</th>
<th>Tilt angle</th>
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<th>25° Upstream</th>
<th>25° Downstream</th>
<th>45° Upstream</th>
<th>45° Downstream</th>
<th>70° Upstream</th>
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* Tranquil in bottom corners only.

DISCUSSION

Two important requirements for efficient sediment traps are to (1) have a tranquil region in the bottom of the trap (Gardner, 1980a) and (2) maintain the same particle concentrations in the tranquil areas in the bottom of the trap as in the water outside the trap (Hargrave and Burns, 1979). The latter criterion enables the sedimentation rate to be the same both inside and outside the trap since the mean settling velocities of particles outside the trap are unaltered by the main flow. It also obviates the need to determine the precise motion of particles within eddies and turbulence as they enter a trap (Soo, 1967, Chapter 2; Tooby et al., 1977). Figures 3 and 4 show the complexity of flow at the tops of traps held vertical or tilted (25°, 45° or 70°).

The results of Soo (1967) and Tooby et al. (1977) suggested that only particles >1000 μm are likely to deviate from the stream lines within an eddy and thereby cause biases in the size of particles collected in sediment traps. Blomqvist and Kofoed (1981) tested cylindrical traps of different sizes and found evidence of particle biasing based on chemical composition if traps were <4.5 cm in diameter.

What is the cause of the increased flux with tilt? The flux of particles collected in a sediment trap is calculated using the horizontal area of the trap opening, or, as suggested by Hargrave and Burns (1979), by the cross-sectional area of the base of the trap since that is where final sedimentation occurs. If a trap is tilted, the base area where sedimentation occurs could be inferred to be the horizontal cross-sectional area of the tilted cylinder. This would account for the increase in flux regardless of tilt direction. As a cylinder is tilted, the increase in area is a secant function starting at 0° and increasing to a maximum where the cross section intersects the bottom of the cylinder. For the traps used here that would occur at 80°. The secant relationship would predict a minimal increase in flux with tilts <10° and a maximum flux at 80°. The increase in flux with increasing tilt in these experiments, however, does not fit a secant curve. The data fit a sine function of the form:

\[ F_T = F(1 + 1.4 \sin \theta), \]

where \( F_T \) is the flux in a tilted cylinder, \( F \) is the flux in a vertical cylinder, and \( \theta \) is the degree of tilt from the vertical. With a least-squares fit of the data to the dashed curve in Fig. 1, there is a 1 s.d. of ±0.34.
In the flume experiments cylinders with a large aspect ratio (≈5) developed an area of constant eddy penetration at the top of the cylinder and a tranquil region at the bottom separated by a region of moderate motion regardless of tilt direction (Fig. 4). Might the three-dimensional surface either below the area of eddy penetration or at the top of the tranquil region be the area of importance for deposition rather than the cross section of the trap? Unfortunately, the surface area of the boundary above the tranquil region is very similar to the cross section of the cylinder and therefore does not fit a sine function. The depth of penetration of eddies into the cylinder decreased with tilt, but the surface area remained similar at different tilts. The question then becomes whether the rate of exchange of particles across the boundary maintains identical concentrations both inside and outside the trap.

Consider, first, deposition of particles across the boundary of a flat plate. For flow along a flat plate, a boundary layer theory has been defined with a viscous sublayer close to the plate where the flow is predominantly viscous and a buffer or transition layer between the viscous layer and the region further from the wall where inertial forces dominate. In the uppermost layer the velocity increases exponentially away from the plate until the main stream velocity is reached (HINZE, 1975). Particles settling to the plate must first pass through the boundary. Particles with rapid settling velocities fall through the boundary with only slight modification of their trajectory. Particles with low settling velocities are highly influenced by fluid motion and are probably carried into the viscous sublayer by the burst and sweep cycles described by CORINO and BROADKEY (1969) after which the particles settle to the sediment surface as described by EINSTEIN (1968).

Inside a sediment trap the boundaries across which sedimentation occurs may not be along the rigid walls or floor of the trap, but rather across the curved boundaries between the eddies and the tranquil region at the bottom of the trap where the velocity approaches zero. There is not a sufficient distance from the point where the water enters the trap to the start of the tranquil layer to set up a well-developed boundary; however, the way in which particles enter the tranquil region appears very similar. The water entering the trap does so in an eddy, and since the motion is turbulent and the velocity field around a trap is not constant, the eddies differ in strength and therefore depth of penetration. An eddy or part of an eddy occasionally penetrates the ‘buffer’ layer and sometimes penetrates the tranquil zone (roughly equivalent to the viscous sublayer, but much thicker) and causes an exchange of water. Particles in the incoming water now have time to settle out before surrounding water is moved out of the trap. The flux of particles across the boundary becomes dependent not only upon the area of the boundary layer, but also the flow rate along the boundary-layer surface. If the flow rate is too high, the boundary may act as a filter and pull too many particles out of the water. The largest particles, with fall velocities >1 cm s⁻¹, are not affected to any extent by the eddies and can enter the trap independent of fluid motions, but such particles constitute only a few percent of the particles collected in traps.

The development of a tranquil region within a cylindrical trap depends on aspect ratio, direction of tilt, and Reynolds number. From Fig. 3g–i it is obvious that the aspect ratio must be <1 for vertical traps or traps tilted upstream, while for traps tilted downstream at low Reynolds number, an aspect ratio of one may conceivably be adequate. Tranquil regions existed across the bottom of the cylinder for all conditions listed in Table 2 except for vertical and upstream-tilted cylinders at 31 cm s⁻¹ where the tranquil area was limited to the corners of the cylinder.

LAU (1979) studied the flow conditions necessary to move fluid out of the bottom of cylinders and found roughly, that if \( A > 9.17 \left( \log Re \right) - 30.8 \), where \( A \) is the aspect ratio and
Re is Reynolds number, the fluid will not come out of the very bottom of the trap. No data were obtained for \( A < 4.7 \). Although this equation could be used to predict when there is a permanent tranquil region at the bottom of the trap, it does not predict the ideal aspect ratio for a trap for two reasons. First it does not indicate when shear stresses at the bottom of the trap are sufficient to resuspend particles. Secondly, it does not quantify the conditions under which no deposition of particles will occur.

The evidence for the second statement comes from field experiments of HARGRAVE and BURNS (1979), GARDNER (1980b), BLOMQVIST and KOFOED (1981), and SMETACEK (1983), where the collection rate of cylindrical sediment traps as a function of aspect ratio consistently reached a maximum at aspect ratios of 3 to 5. At higher aspect ratios the collection rate remained relatively constant because sedimentation rates within the traps equalled sedimentation rates outside the traps and there was no resuspension of settled particles. The experiments of LAU (1979) predict that traps with much higher aspect ratios—possibly as high as 7 to 12—should have been used in the above experiments to have tranquil regions at the bottom. Therefore, deposition must still occur without an absolutely tranquil region at the bottom.

It was noted earlier that for tilts >30° there is an overcollection of particles <63 \( \mu \)m relative to particles > 63 \( \mu \)m. A problem in quantifying this effect is that particle size and shape may be altered substantially by the shearing motion within the eddies produced as water enters a trap. It long has been assumed that large particles (>63 \( \mu \)m) dominate the downward mass flux in the ocean (McCave, 1975). When particle size has been measured in traps, however, only 10 to 30% of the mass is >63 \( \mu \)m. Wet sieving is the most common way of sizing particles in trap samples, and, even when done gently, they may break up. Breakup of particles also may occur during or after collection in the trap. Many references have been made to the ubiquitous presence of marine snow in the ocean, and based on my own observations from submersibles, it is likely that the slightest contact with the edge of a sediment trap would cause marine snow to disintegrate. Therefore, marine snow, often several cm across, could be broken down to components <63 \( \mu \)m.

It has been suggested that the problem of differential flow past a trap would be eliminated if a trap could be perfectly coupled with the water motion by using free-floating sediment traps (STARESINIC et al., 1978). A perfect coupling, however, is virtually impossible, especially with traps at multiple depths. Even neutrally buoyant floats are not perfectly coupled with the water. Furthermore, drifting traps are not practical in all situations (e.g., long deployments or near-bottom measurements in topographically rough areas). STARESINIC et al. (1982) compared floating and moored traps and found that the moored traps usually, though not always, registered a lower flux, with the median value of the ratio of moored and floating trap fluxes falling between 0.4 and 1.0. Some of the difference may result from spatial separation in the region over which the floating and moored traps collect particles. If there is a bias in moored traps it is towards undercollection, but overall, the similarity in collection rates is encouraging.

Another possible reason why the floating traps collected more than the moored traps tested by STARESINIC et al. (1982) could be the differences experienced by the traps in the two different modes in what will be defined here as the effective tilt. A mooring does not have to lean for a trap to experience tilt. The passage of internal waves causes vertical motion past moored or drifting traps because the traps stay at nearly constant depth. The vertical component of flow causes the oncoming water to approach the trap at an angle, thus causing what is defined here as an effective tilt (Fig. 5). The effective tilt increases with wave amplitude and frequency and decreases with higher currents past the trap. This effect was considered by DYMOND et al. (1981) and found to be negligible for internal waves of diurnal frequency but, in the Panama Basin, internal waves with periods of about 40 min caused effective tilts of up
Fig. 5. Passing internal waves (dotted line—highly exaggerated) cause an 'effective' tilt angle (t) because of the vertical velocity vector (B) caused by orbital motion of water in an internal wave superimposed on a mean flow past a trap (A). The effect is likely to be significant only when wave amplitude is >20 m, period is <4 h, and mean velocities are <20 cm s⁻¹. The most likely location for such conditions is the pycnocline. Since t increases as A decreases, floating traps experience larger effective tilts than moored traps.

to 40° for floating traps in the thermocline (BISHOP and GARDNER, unpublished data). The thermocline is the region most affected by large-amplitude internal waves, and floating traps are likely to experience larger effective tilts than moored traps with the passing of internal waves because the horizontal flow is greater past moored traps than past floating traps at the same location.

Some workers have chosen to circumvent the tilt problem by hanging the traps from a line (ANDERSON, 1977) or gimballing them (BAKER and MILBURN, 1983). Traps suspended from a bar in high-velocity flows might have erratic oscillations due to vortex shedding from the trap or strumming from the suspending lines. The attachment points for a gimbaled trap must be symmetric so that the drag forces are equal above and below the pivot point as shown by BAKER and MILBURN (1983). The open end of the trap, however, changes the symmetry of drag forces and, like the model tested in the flume, the trap could oscillate up to 40° upstream and downstream in the current. The oscillations in the flume were reduced to only a few degrees by putting the center of gravity well below the center of pivot. Care must be taken to balance the drag and inertial forces when applying these results to full-scale traps since they will vary considerably with scale and trap design. Neither of these methods will avoid the problem of effective tilt caused by internal waves.

The increased collection rate of traps tilted either upstream or downstream must be considered in all trap experiments. If the currents are strong enough to make a mooring lean, a trap attached to the line will tilt downstream. If the tilt is >30°, particles <63 μm may experience preferential collection, though a tilt of this magnitude is likely to be rare. Passing internal waves can cause effective tilts in both the upstream and downstream direction. Tilt can be expected to affect the results from funnels and other non-cylindrical traps, but the magnitude of the effects requires further investigation.

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REFERENCES


REYNOLDS C. S. (1979) Seston sedimentation: experiments with Lycopodium spores in a closed system. Freshwater Biology, 9, 55–76.


