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A comparison of the quantity and composition of material caught in a neutrally buoyant versus surface-tethered sediment trap

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Abstract

The flux and composition of material caught using two different upper ocean sediment trap designs was compared at the Bermuda Atlantic Time-series Study site (BATS). The standard surface-tethered trap array at BATS was compared to a newly designed neutrally buoyant sediment trap (NBST). Both traps used identical cylindrical collection tubes. Of particular concern was the effect of horizontal flow on trap collection efficiency. In one experiment, mass, particulate organic carbon (POC) and particulate organic nitrogen (PON) fluxes were slightly lower (20–30%) in the NBST than in the standard BATS trap. In contrast, ^{234}Th and fecal pellet fluxes were up to a factor of two to three lower in the NBST. In a second experiment, mass and POC fluxes decreased significantly with depth in the BATS surface-tethered trap, but not in the NBST. Different brine treatments had no measurable effect on collection efficiencies. A striking observation was that the swimmer "flux" was much larger in the standard BATS traps than in the NBST. Overall, these results show that different components of the sinking flux can be collected with differing efficiencies, depending upon how traps are deployed in the ambient environment.

Keywords: Sediment trap; Thorium-234; Bermuda

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1. Introduction

The vertical distributions of many elements in the ocean are determined, to a large extent, by their transport on the large particles that settle out of the surface ocean to the seafloor. These sinking particles have a wide range of sources and characteristics and are thought to have settling rates ranging from < 1 to $> 1000\ \mathrm{m\,d^{-1}}$ (e.g. Fowler and Knauer, 1986). Evidence for transport associated with rapidly sinking particles was first obtained from indirect approaches, such as the observation of fallout radionuclides at the deep seafloor shortly after the early nuclear weapons tests (Osterberg et al., 1963). Similarly, water column radionuclide data could be explained only if vertical removal on a rapidly sinking particle phase was considered (Bhat et al., 1969; Bacon and Anderson, 1982; Coale and Bruland, 1987). Direct observations and in situ camera techniques have further contributed to our understanding of sinking particles by quantifying both particle abundances and sinking speeds (Billet et al., 1983; Honjo et al., 1984; Alldredge and Gotschalk, 1988; Gardner and Walsh, 1990; Diercks and Asper, 1997). However, in both the deep and shallow ocean, most of our information concerning sinking particles has been obtained from the deployment of sediment traps. Sediment traps are generically open cylinders or cones deployed in the water column as passive “rain gauges”. Traps are used to quantify not only the flux patterns with space, time and depth, but also to serve as collectors for sampling sinking particles for chemical and physical analysis.

Much of the current understanding of biogeochemical processes can be traced directly to data from sediment traps. For example, sediment traps provided some of the first direct evidence that the seasonal pattern of surface productivity can lead to a seasonal variation in the flux of organic matter to the seafloor (Deuser, 1986; Karl et al., 1991; Lohrenz et al., 1992). The pattern of sinking flux with depth determined by traps has been used to estimate the rates of vertical remineralization for a wide range of compounds (e.g. Martin et al., 1987). This trap-derived relationship between particle flux and depth is used to parameterize export in many biogeochemical models. Traps have been used as an estimate of new production, since the input of new nutrients into the euphotic zone must be balanced by losses over appropriate time and space scales (Eppley and Petersen, 1979; Pace et al., 1987; Knauer et al., 1990; Michaels et al., 1994). Furthermore, sediment traps have been used to explain the vertical distribution, and to estimate the removal rates of many trace elements in the oceans associated with biotic particles in surface waters (Livingston and Anderson, 1983; Martin and Knauer, 1984; Buat-Menard et al., 1989; Buesseler et al., 1990).

While traps are widely relied upon to serve as accurate “rain gauges” in the oceans, the absolute accuracy of traps has not been well documented in the field. By and large, the data from traps have been internally consistent and this consistency and the “reasonableness” of the results has been one of the strongest arguments that the data cannot be too far from the true particle flux. However, differences between radionuclide fluxes calculated from measured water column ^{234}Th inventories and measured trap ^{234}Th fluxes have suggested that traps can both overcollect and undercollect in the field by up to a factor of 10 in the upper ocean (Buesseler, 1991; Buesseler et al., 1994; Murray et al., 1996). Also troublesome are large between-trap variations in shallow particle fluxes observed when traps of different designs are deployed as part of the same experiment. For example, during the Equatorial Pacific Process Study, the Particulate Organic Carbon (POC) fluxes at 100 m of Murray et al. (1996) were more than 10 times higher than the POC flux measured in the same experiment at 105 m using a different trap design (Hernes et al., 1996). Finally, when trap-derived POC flux data are used to "close" C budgets at the major US Joint Global Ocean Flux Studies (JGOFS) time-series sites, these trap data either leave a substantial C imbalance (Bermuda Atlantic Time-Series site, BATS; Michaels et al., 1994) or close the C balance to within a factor of two (Hawaii Ocean Time-Series, HOT; Emerson et al., 1997), leaving unresolved the issue of trap accuracy.

Since the advent of sediment traps, there have been a variety of studies to evaluate the trap designs and field conditions for which traps can be used as unbiased collectors of sinking particles in the oceans (summarized in US JGOFS Planning Report #10, Knauer and Asper, 1989). These studies have focused primarily on hydrodynamical concerns (Gardner, 1980; Butman et al., 1986; Gust et al., 1992), artifacts related to the collection of non-sinking material (i.e. "swimmers" – Lee et al., 1988; Michaels et al., 1990; Steinberg et al., 1998), and the preservation of the sample once collected by a trap (Knauer et al., 1984; Wakeham et al., 1993; Kortzinger et al., 1994). Despite the passage of over 10 years, many of the problems debated at the 1988 US JGOFS Sediment Trap Workshop are still unresolved. Key field studies are lacking. Flow sensors are rarely placed on sediment traps. Free-drifting trap arrays still have traps at multiple depths, a situation that guarantees horizontal flow across the mouth of the trap at some or all depths. Swimmer removal methods and accuracy are poorly documented in most studies. An update on many of these trap accuracy issues can be found in a more recent JGOFS report by Gardner (1999).

In this paper, we report the results from a field comparison of two trap designs – the surface-tethered particle interceptor trap (PIT) used regularly at BATS, HOT and in most upper ocean sediment trapping programs, and a newly designed neutrally buoyant sediment trap (NBST – see Valdes et al., 1997; and Valdes and Price (1999) for details of NBST design and operation). We focus here on fluxes in the upper ocean only, since the likelihood of hydrodynamic bias would be greatest in the upper ocean where velocity shear is high. In the generic experiment, the PITs and NBSTs were deployed on the same cruise and at the same depths for roughly 3 d. We use these flux data to examine the relative collection efficiencies for different particle types using the NBST and PIT designs.

2. Study site and experimental design

All trap deployments were conducted in the Sargasso Sea at the BATS site (31°40′N, 64°10′W), where regular monthly sampling for biogeochemical parameters commenced in 1988 as part of US JGOFS (see Michaels and Knap, 1996 for overview). The standard BATS surface-tethered floating trap array follows the configuration of the MultiPIT design (Knauer et al., 1979), where multiple trap tubes (7.4 cm internal diameter $\times$ 62 cm length) can be mounted at each depth. Identical collection tubes (0.0039 m^2 collection area) were used in both the PIT and NBST designs. The standard PITs were hung at 150, 200 and 300 m. The NBSTs were programmed to float at 150, 200 or 300 m, and this was confirmed by on-board pressure sensors (Valdes and Price, 1999). Up to four trap tubes can be mounted on a single NBST, and therefore the between-tube flux variability can be examined on both trap designs. After deployment, NBSTs take 4–6 h to reach the sampling depth. After a pre-programmed sampling interval, the NBST collection tubes are closed prior to ascent to the surface. Details of NBST ballasting and deployment can be found in Valdes and Price (1999). Sample treatment for the PIT array followed standard BATS protocols (Knap et al., 1997), and the post-cruise analyses were similar for both the PITs and the NBSTs.

Of concern in this study was whether the relative trap collection efficiencies might be affected by hydrodynamical biases. Hence, horizontal flow at the depth of each PIT was measured using an Aanderra RCM style current meter hung 10 m below the trap, and data were stored as averages over 1 min intervals (flows ranged from <1 to 10 cm s^{-1}). Horizontal flow across the NBST is presumed to be negligible, since they are neutrally buoyant and only about 1.3 m in length (Valdes and Price, 1999). Thus the major difference between designs was in the lack of horizontal flow around the NBST, not in the aspect ratio or design of the sample collection tubes.

Also of interest, and specifically tested in the October experiment, was the possible secondary effect of hydrodynamical biases due to differences in the brine treatments used in the standard PIT and NBST deployments. High-density brine solutions are used in traps to isolate samples and poisons, which might be lost during deployment and recovery (Knauer and Asper, 1989). At BATS, the standard protocols call for filling each tube completely with pre-filtered water from the depth of the trap containing a solution of 2% formalin and 86 g l^{-1} NaCl. Upon deployment, the majority of the brine is flushed out of the top half of the PIT collection tubes, leaving a stable brine layer in the bottom of the tubes (Gust et al., 1996). Internal flow sensors (e.g. Gust et al., 1994, 1996) suggest that this process occurs within the first 6–8 h after deployment, and upon retrieval, the brine/water interface is still visible approximately 10–15 cm from the bottom of the tube. The NBST tubes were only partially filled with 500 ml brine, so that buoyancy would be constant. The hydrodynamical issue of concern is that the effective aspect ratio (height/diameter) of the collection tube will change as the brine layer erodes in the filled PIT tubes, and this can alter the collection efficiency independent of the other horizontal flow issues (e.g. Gardner and Zhang, 1997). Thus, tubes were also deployed on the surface-tethered array that had the same brine configuration as the NBST tubes, allowing for a direct comparison between the NBSTs and PITs and between the two brine configurations on the PIT array.

2.1. October experiment

During October 1997, two floating-trap arrays of the PIT design were deployed along with the NBST, and flux comparisons were made at 150 m (a second NBST targeted for 300 m failed to operate at the correct depth; Valdes and Price, 1999). On the standard BATS floating-trap array (traps at 150, 200 and 300 m) selected trap tubes were added with 500 ml of brine, identical to the NBST (sample = PIT 1A). In addition, the standard BATS brine protocols were followed on replicate tubes

(PIT 1B). This floating array was deployed on October 6, 1997 at 12 : 40 (local) and recovered 2.65 d later. On a second floating array, PITs were hung at 150 m and only the NBST brine treatment was used (PIT 2). PIT 2 was deployed on October 6 at 09 : 30 (local) and recovered 2.83 d later. The 150 m NBST was deployed on October 6 at 10 : 45 (local) and recovered 2.42 d later (NBST 3). Pressure sensors on the NBST indicated that its pre-programmed vertical position of 150 m was reached within 6 h and that it held this position within 10 m (Valdes and Price, 1999). During this experiment, both of the floating arrays and the start and stop positions of the NBST remained in close proximity (within 5–6 km), thus minimizing the possibility of complications due to the sampling of different water masses by the different trap designs.

Mean current speeds as measured on floating arrays 1 and 2 were low and similar, at 5.0 and 5.4 cm s^{-1}, respectively, with excursions up to 9 cm s^{-1}. Laboratory studies of trap hydrodynamics predict that traps of this aspect ratio are accurate at horizontal velocities of <15 cm s^{-1} (Gardner, 1980; Butman et al., 1986), disregarding possible tilt and vertical motion related to the trap flotation (Gust et al., 1994). This particular PIT deployment thus took place under what would generally be accepted to be favorable conditions.

2.2. June experiment

The 150 NBST was deployed on June 10, 1997, at 11 : 30 (local) for 2.39 d and the 225 m NBST at 10 : 00 (local) for 2.45 d. The standard PIT array with traps at 150, 200 and 300 m was deployed on June 10 at 09 : 00 (local) for 2.86 d. Only one tube on the NBST array was successfully analyzed for mass, POC and particulate organic nitrogen (PON), and the standard three tubes at each depth were analyzed from the PIT array. The NBST tubes were partially filled with 500 ml of 37.5 g l^{-1} NaCl and formalin brine, and the PIT tubes were filled with brine following BATS protocols, identical to PIT 1B in October. The mean horizontal flows on the PIT array were 4.1 cm s^{-1} (range 3–8 cm s^{-1}). As in October, these low velocities suggest that the June experiment was conducted under hydrodynamic conditions considered to be favorable. The NBST and PIT arrays were deployed within one mile of each other and were 20 km apart when recovered.

3. Anaytical methods

3.1. Sediment traps

Processing and elemental analysis of the trap samples is described in Knap et al. (1997). A Control Equipment Corporation (CEC) 240-XA Elemental Analyzer (Leeman Labs, Inc.) was used for POC and PON analysis.

3.2. Swimmers

Swimmers were removed from filters using a Wild dissecting microscope under bright field illumination at 100–250 × magnification. Swimmers picked include all recognizable zooplankton, including gelatinous zooplankton. Other material, such as egg clusters which probably became dislodged from crustacean swimmers, and whole or pieces of pteropod and heteropod shells were also removed. After removal, swimmers were identified by major taxon, counted, and analyzed for CHN. Swimmer data are presented as numbers per trap, as traps are not meant to measure active animal-mediated fluxes (Silver and Gowing, 1991). However, for comparison with detrital POC fluxes, we also express swimmer carbon content in flux units of mgC m^{-2} d^{-1} (i.e. measured carbon in swimmers divided by trap collection area and deployment time). Flux of swimmers cannot be considered quantitatively accurate, because of differential behavior of organisms in response to traps that results in biased species collection (Harbison and Gilmer, 1986; Michaels et al., 1990; Steinberg et al., 1998). However, it is appropriate to use these units for carbon because the incomplete removal of swimmers leads directly to biases in the estimate of carbon fluxes. Aggregates >0.5 mm and all fecal pellets were counted on filters using an Olympus SZH10 research stereo dissecting microscope with bright field illumination. Fecal pellets were sized, and most were small ovoid copepod pellets 20–30 μm wide × 60–100 μm long. Aggregate comparisons should be considered qualitative, as some disaggregation and reaggregation may have occurred during the trap deployment or during filtration.

3.3. Thorium-234

Thorium-234 trap and swimmer samples were combined from material collected in 2–4 trap tubes that were mailed to WHOI for purification and analyses (analytical details can be found in Buesseler et al., 1994). Briefly, the sample was combusted and a ^{230}Th yield monitor was added along with concentrated nitric acid to digest the sample. Two sets of ion-exchange columns were used to purify ^{234}Th from other interfering beta emitters, and the final purified aliquot was electroplated on a stainless-steel planchette, covered in mylar and foil, and beta counted on low background gas flow proportional counters. Samples were counted 5–6 times over the course of 30–50 d, to follow the decay of the original ^{234}Th signal ($t_{1/2} = 24.1$ d). A solution blank was also run, but these levels were not above the detector background (0.3 counts min^{-1}). All data are decay corrected to the mid-point of the trap deployment, corrected for the deployment duration and surface area per collection tube, and reported here on a disintegration per minute per square meter per day flux basis (dpm m^{-2} d^{-1}). Note that thorium water column profiles were not measured in these experiments. Thus, the thorium data allow for a comparison between traps but do not allow for an estimate of the absolute accuracy by comparison with the water column deficit.

4. Results

Results will be presented for the October Experiment first, since these data include more replicates and an explicit comparison of different brine treatments.

4.1. October experiment

Fluxes are provided for each individual trap tube (Table 1) for each of the four possible sampling configurations and as averages (Fig. 1) for the net mass, POC, PON, ^{234}Th fluxes and the number of oval pellets and aggregates enumerated in each sample type. Similar data for the swimmer fractions are shown in Fig. 2. The mass, POC and PON fluxes were consistently lower in the NBST than in the other three PIT samples. On average, the ratio of the NBST/PIT fluxes was 72, 82 and 73%, for mass, POC and PON, respectively. The average flux differences were relatively small, however, and individual trap tubes from the floating arrays overlap at least partially with the NBST mass, POC and PON fluxes. A single-factor analysis of variance suggested that there was no significant difference among the mass, POC and PON fluxes (ANOVA test, $P > 0.05$). These data also indicate that, in this experiment, there was no discernible difference as a result of the choice of brine solution.

Larger flux differences are seen in the ^{234}Th and fecal pellet flux data. Though no replicates between tethered arrays are available, the flux of the particle-reactive nuclide ^{234}Th was roughly three times higher in the floating-trap sample PIT 1A than in NBST 3. Two sets of tubes were analyzed for ^{234}Th from the floating array, one undergoing standard BATS swimmer removal protocols and another analyzed unpicked. Though the picked sample was 10% lower in ^{234}Th, the difference was smaller than the analytical uncertainty. This low apparent swimmer contribution for ^{234}Th is consistent with the low ^{234}Th activity measured in two swimmer samples collected from PIT 1A and the NBST. These swimmer samples had an activity at our detection limit, or equivalent to <10 dpm m^{-2} d^{-1}. Prior studies have also suggested that the swimmer contribution for ^{234}Th is quite low (Buesseler et al., 1994).

The oval pellet data also show higher collection efficiencies in the floating PIT versus the NBST. The average pellet flux in the floating PIT was twice more than that in the NBST, or 1.7 times higher, if only the data from PIT 1A and PIT 1B are compared (pellet counts are significantly different, ANOVA test, $P < 0.05$). There was no significant difference between the number of aggregates in the different trap designs, but these data should be considered less quantitative than the pellet data.

In addition to reporting net flux results, we measured the quantities and types of swimmer material removed from the trap collection tubes. Data for five swimmer types are shown for each of the four trap configurations, and these swimmer data were also converted to an equivalent POC "flux" for comparison to the net POC fluxes. In general, the NBST swimmer counts were lower than found in any of the free-floating PITs. This difference holds ($P < 0.05$) according to a single-factor analysis of variance for the number of copepods, ostracods, and other crustaceans, though not at this level of significance for the other swimmer fractions (Fig. 2).

Though the swimmer data are somewhat variable and the inclusion of single large swimmers can certainly bias any flux estimates, it is clear that the total swimmer material removed from the NBST was only a small percentage of the total flux. For the NBST sample, the total quantity of POC removed as swimmers represented only 16% of the net POC flux (i.e. swimmer POC/net POC). For the surface-tethered samples, the swimmer/net POC flux ratios were 55, 140, and 250%, for samples PIT

Table 1
October trap fluxes at 150 m

	Mass dry weight (mg m^{-2} d^{-1})	POC (mg C m^{-2} d^{-1})	PON (mg N m^{-2} d^{-1})	^{234}Th (dpm m^{-2} d^{-1})	No. of oval pellets[c]	No. of aggregates[c]	Swimmwer equivalent[d] (mg C m^{-2} d^{-1})
PIT 1A	92	26	4.0	440[a]	42	10	16
	75	18	2.4	490[b]	86	12	7
					42	17	
					53	9	
PIT 1B	90	25	4.6		42	22	29
	64	19	3.3		63	18	8
	123	29	5.0				65
PIT 2	94	23	3.6		86	9	79
	80	19	2.8		116	10	26
NBST 3	63	19	3.0	150	41	6	3
	64	18	2.2		33	12	3
					24	15	
					27	16	

Data are from individual trap collection tubes except for ^{234}Th whereby 2–4 tubes were combined.
PIT 1A = floating trap array 1 with NBST brine treatment.
PIT 1B = floating trap array 1 with standard BATS brine treatment.
PIT 2 = floating trap array 2 with NBST brine.
NBST 3 = neutrally buoyant sediment trap.
[a] = ^{234}Th tubes picked for swimmers.
[b] = ^{234}Th tubes not picked for swimmers.
[c] = Number of pellets and aggregates normalized to 3 d deployment time.
[d] = Equivalent "swimmer flux" in carbon units as described in text.

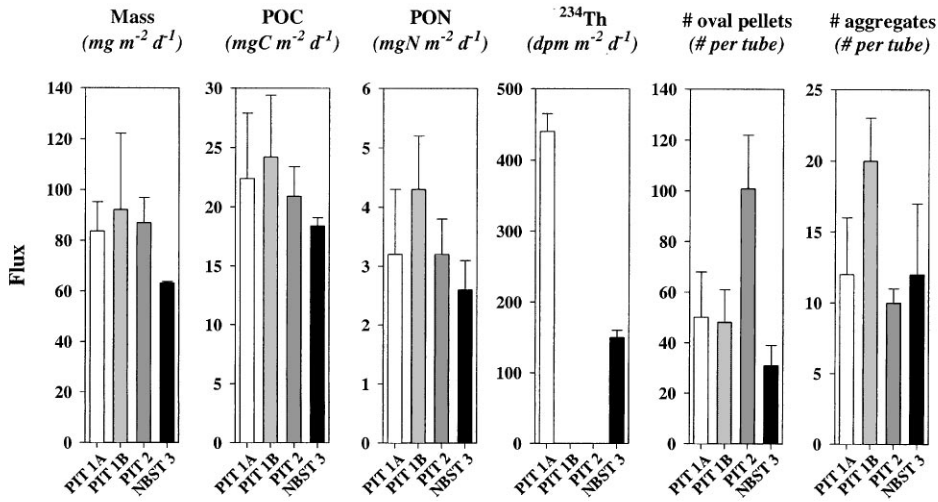

Fig. 1. Net flux data – October experiment. In each panel, the average fluxes of different components at 150 m for each trap design are compared (data in Table 1). Error bars are the standard deviation or range of these fluxes between replicate trap tubes of a single type. PIT 1A and PIT 1B were deployed on the standard BATS floating array, but with differing brine treatments, while PIT 2 was deployed on a separate array. NBST 3 is the neutrally buoyant trap. These fluxes are corrected for swimmer contributions, hence they are defined as net flux data (units provided along y-axis).

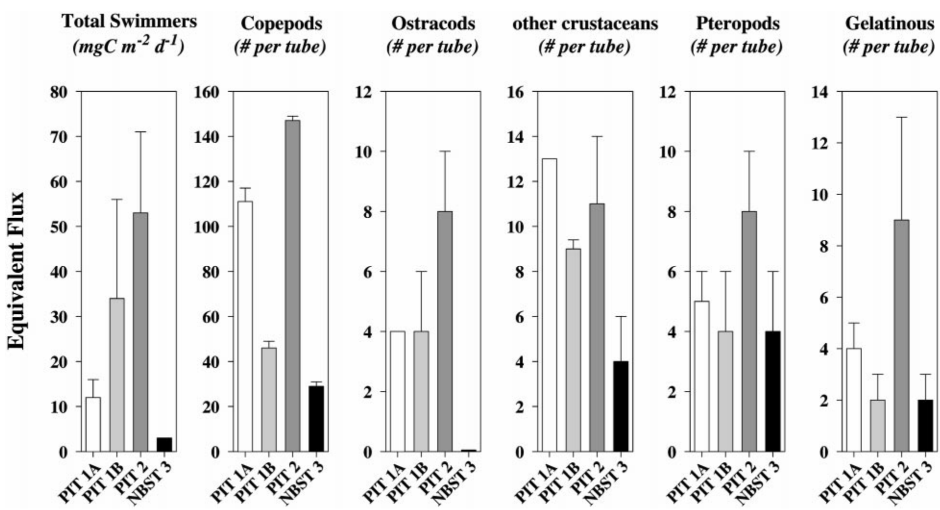

Fig. 2. Swimmer data – October experiment. Equivalent flux data and swimmer count data are shown arranged to compare the different trap designs as in Fig. 1.

1A, PIT 1B and PIT 2, respectively. The fact that the net POC (and mass and PON) fluxes were so similar between these three PIT samples, despite this factor of 5 difference in total swimmer C removed, attests favorably to at least the reproducibility of the BATS picking procedures. It is common at the BATS site and other locations that more POC is removed as swimmer material than is left behind as a net POC flux. The magnitude of swimmer C versus sinking C points to a potential source of bias that is difficult to control in shallow trap deployments, especially since picking procedures differ amongst researchers and the implications of these methodological differences are difficult to quantify (Gardner, 1999). An important and unforeseen advantage of the NBST may be the very large reduction of swimmers in the trap sample, thus alleviating many concerns regarding over- or underremoval of swimmer material.

4.2. June experiment

In the June experiment, there were no specific brine tests or ^{234}Th analyses conducted. We did however have NBSTs at 150 m and approximately 225 m. The main result was that the mass, POC and PON flux gradient between 150, 200 and 300 m in the standard PIT was much sharper than observed between the 150 and 225 m NBSTs (Fig. 3). While POC and PON fluxes in the NBST overlapped somewhat with the range of the fluxes in the PIT array, the mass fluxes in the NBST were up to two times lower overall and the NBST depth gradient was less steep. Therefore, the NBST data taken alone would lead to a significant difference in apparent remineralization rates for bulk mass fluxes derived from these profiles. Also, there were differences in POC to mass ratios in the NBST versus PIT (POC/mass = 15 and 14% in 150 and 200 m PITs, respectively, and 29 and 26% in 150 and 225 m NBSTs, respectively), again suggesting some selective sorting of material between trap designs. Microscopic examination of a single NBST and PIT

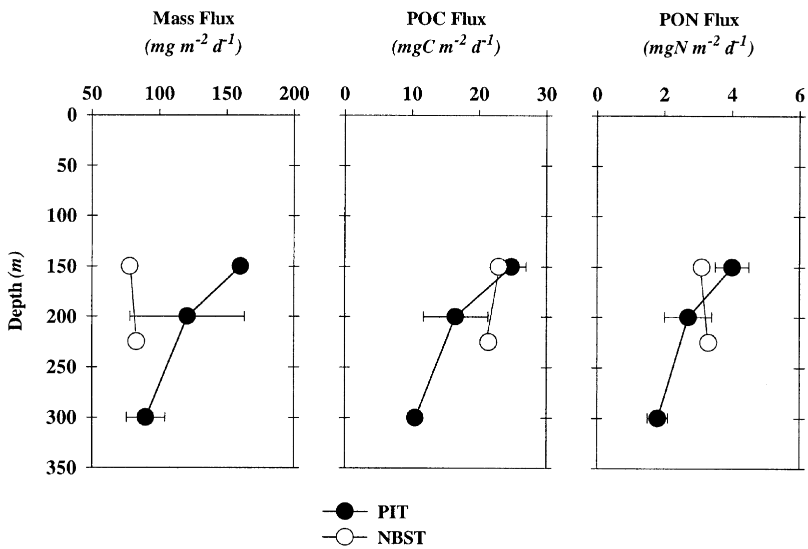

Fig. 3. Trap flux data – June experiment. Net flux profiles of mass, POC and PON are shown for both the standard BATS array (PIT; filled circles at 150, 200 and 300 m) and the NBST (open circles at 150 and 225 m).

tube showed that the NBST collected lower quantities of all identifiable swimmer types (e.g. for copepods, $n = 74$ in NBST versus 130 in PIT).

5. Discussion

The data presented here are one step in the evaluation of current trapping techniques and will need to be replicated and enhanced by further controlled studies. However, from these limited data we can draw four preliminary conclusions regarding: (1) bulk fluxes, (2) ^{234}Th and minor component fluxes, (3) brine effects and (4) improved swimmer avoidance designs.

First, the bulk mass, POC and PON fluxes are similar between the PIT and NBST during these low flux and, perhaps more importantly, low horizontal flow conditions. More specifically, the October NBST mass, POC and PON fluxes were 70–80% of those measured in the standard PIT at 150 m. In our first deployment in June, we found similar results for POC and PON at 150 and 200 m, though the mass fluxes were lower by up to a factor of two in the NBST, and the flux versus depth profiles were significantly less steep for mass, POC and PON in the NBST compared to the standard PIT array used at BATS. How these two trap designs would compare under higher relative velocities or under differing particle flux regimes is an open and extremely important question. In essence, these data appear to confirm lab studies that have suggested that under conditions of low horizontal flow, mass accumulation in traps with these identical aspect ratios should be minimally affected by flow-related effects (Gardner, 1980; Butman et al., 1986).

The second conclusion is that in contrast to mass, POC and PON, different components of the sinking flux can, even under these low flow conditions, be collected with significantly different efficiencies using two different trap designs. Thus the ^{234}Th flux was a factor of three lower, and the fecal pellet flux a factor of two lower, in the NBST than in the PIT in October. Prior studies have suggested that ^{234}Th tends to be enriched in pellet material, compared with bulk POC or swimmers (Coale, 1990), and fractionation of both of these components may be related to a bias for a similar carrier phase. Laboratory-based studies under differing horizontal flows indicate different collection efficiency responses for different particle sinking speeds and thus particle types (Gust et al., 1996). These data thus caution against the use of traps for determining the absolute composition of sinking particles in shallow traps until it can be resolved how ambient conditions and variations in the carrier phases might affect the relative collection efficiencies of different particle types.

Our third conclusion from the NBST and PIT comparison was not specifically designed into the experiment. Due to ballasting issues, we were forced to change the brine treatment on the NBSTs compared to the standard PITs at BATS. In October, we tested both the standard brine treatment on the same PIT array, where the tubes are deployed filled with brine, and a second partially filled brine procedure as was required on the NBST. This NBST brine treatment has been suggested as being optimal for cylindrical traps (Gardner, 1997). We see no difference in the PIT fluxes of any components between the two brine treatments. This does not mean that brine treatments cannot affect trapping efficiency, but this was not a measurable effect under this specific set of field conditions. This is in contrast to the data from studies in a laboratory flume that consistently show strong evidence of a brine effect on collection efficiency, particularly during the early parts of a deployment (Gardner and Zhang, 1997).

Our fourth conclusion is that the observed NBST swimmer "flux" is much smaller than in the standard PIT. In the NBST, the equivalent of only 16% of the net POC flux is identifiable swimmer material. In the standard PIT, more swimmer POC is generally removed from the trap than is left behind as "detritus". In this experiment, the swimmer flux ranged from 50 to 250% of the net POC flux in the three standard PIT samples. The median swimmer POC/net POC ratio from 10 BATS cruises (July 1991–June 1992) is 278%, with a wide range of 115 to $>4000\%$ (Steinberg and Michaels, unpublished BATS data). Logistically, this implies that uncertainties traditionally associated with swimmer picking become less critical if these low swimmer abundances in NBSTs prove to be universally true. In a past PIT experiment, when internal flows were measured, $6\,m^3$ of seawater was calculated to have flushed through a single PIT tube during an average BATS trap deployment (Buesseler et al., 1994). Our speculation, which is supported by these new data, was that swimmer fluxes were enhanced by horizontal flow. We suggested that once zooplankton were carried into the trap tube via horizontal flow, natural escape responses and disturbance due to turbulence within the trap would cause behaviors that accelerate the collection of these swimmers in standard PITs (we used the term "surfers"). A combination of passive (Coale, 1990) or active (Peterson et al., 1993) swimmer avoidance technologies could be added to the NBST design, but the POC flux attributable to swimmers is already quite small in the current NBST design.

5.1. Significance of results for ^{234}Th studies

The ramification of these results for ^{234}Th studies deserves further elaboration given the wide use of this radionuclide as a particle flux tracer. Thorium-234 is now widely used as both a trap calibration tool (Buesseler, 1991; Bacon, 1996; Murray et al., 1996) and to derive upper ocean POC fluxes (summarized in Buesseler, 1998). The application of ^{234}Th as a trap calibrator has been detailed elsewhere (Buesseler, 1991). Measured activities of total ^{234}Th in the water column and a simple 1-D production and decay model are used to predict the ^{234}Th fluxes that should be collected by an ideal sediment trap. These ^{234}Th-predicted fluxes are compared to the measured trap ^{234}Th flux to derive the trap calibration efficiency.

In our own applications of ^{234}Th as a trap calibrator, we have been careful to state that the "calibration of particle flux using ^{234}Th may not hold for organic carbon or other elements if the particle classes that carry these elements differ" (Buesseler, 1991). The main issue of concern is that different components of the sinking flux will likely have different collection efficiencies, depending upon relative vertical sinking speeds and the local horizontal velocities. Our data from this single experiment suggest that the relative collection efficiency of ^{234}Th and POC can differ in two trap designs. Thus, simply multiplying the measured trap POC flux by a single ^{234}Th-derived trap

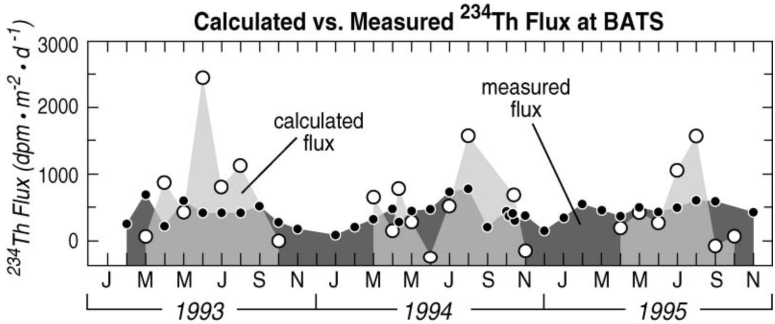

Fig. 4. Calculated versus measured ^{234}Th flux at BATS for 1993–1995. The measured trap flux at 150 m (solid circles) is compared to the flux calculated from water column ^{234}Th data using a simple 1-D steady-state model (open circles). Note that the difference in using this steady-state model and a non-steady-state version such as outlined in Buesseler et al. (1992) is insignificant. Model assumptions and uncertainties have been published elsewhere (Buesseler, 1998).

collection efficiency may not yield more accurate POC flux results. This makes trap calibration with a single tracer difficult and suggests that it would be more fruitful to encourage trap designs that minimize horizontal flow rather than try to correct flux data collected with biased traps.

The measured ^{234}Th trap flux in the NBST and PIT can be compared to more extensive ^{234}Th water column and PIT sediment trap data collected at BATS during the period 1993–1995. The first year's results were presented in Michaels et al. (1994), and the full 3 year record of predicted flux versus measured flux for ^{234}Th is shown in Fig. 4. We note periods of both under- and overcollection for ^{234}Th in the BATS PIT data and conclude that there may be a seasonal pattern of undercollection during the summer months and overcollection during the spring and fall (note that this ^{234}Th calibration cannot be made during winter months at BATS, when the mixed layer depths are deeper than the 150 m trap).

In the present study, water column ^{234}The measurements were not made; however, the new trap data can be compared to this three year record. The PIT ^{234}Th flux measured in October 1997 of 440 dpm m^{-2} d^{-1} is similar to the measured PIT fluxes seen in 1993–1995, and these PIT ^{234}Th fluxes do not exhibit great seasonal variability. The October NBST ^{234}Th flux of 150 dpm^{-2} d^{-1} is significantly lower and consistent with the three year pattern of lower predicted ^{234}Th export during the fall months. Obviously, water column ^{234}Th data collected at the same time would be needed to confirm that the predicted and measured NBST ^{234}Th fluxes are in agreement, but we note that the magnitude of the measured October 1997 NBST ^{234}Th flux agrees with the expected flux based upon data collected in other years at BATS.

A related application of ^{234}Th is to use the ^{234}Th water column activities to calculate ^{234}Th export (similar to the trap calibration studies), and then to use this flux multiplied by the observed POC/^{234}Th ratio on particles collected using in situ or bottle filtration to calculate POC export (as summarized in Buesseler, 1998). The major assumption made is that the POC/^{234}Th ratio of the filtered particles is the same as the mean ratio of the sinking particles. These studies often use filters and screens of different effective pore sizes to examine the size- and depth-related variations in POC/^{234}Th on filterable particles. In general, POC/^{234}Th appear to be the highest in sites dominated by large-celled diatoms suggesting that the POC/^{234}Th ratio may be determined by volume/surface area issues (higher volume/surface ratios in large diatoms, hence more POC relative to surface-bound ^{234}Th; Buesseler, 1998). POC/^{234}Th ratios have also been observed to decrease with increasing depth suggesting the preferential remineralization of POC versus ^{234}Th with depth on sinking particles (Buesseler et al., 1992; Bacon et al., 1996; Rutgers van der Loeff et al., 1997).

In some studies, PITs are also used to determine the POC/^{234}Th ratio on particles (Buesseler et al., 1992; Murray et al., 1996). Obviously, if the PITs are collecting the dominant ^{234}Th and POC bearing particles with differing efficiencies, then the PIT material may not be an accurate representation of the POC/^{234}Th ratio on sinking particles. Additionally, the incomplete removal of swimmers will elevate the POC/^{234}Th ratio in trap material because of the very low ^{234}Th content of swimmers. In October, the POC/^{234}Th ratio in the PIT was 4.2 μmol dpm^{-1} versus 10.2 in the NBST. Therefore, using the ^{234}Th method, the NBST-derived POC export flux would be 2.5 times greater than the PIT-derived flux. Using time-series ^{234}Th water column data, a 1-D ^{234}Th export model and PITs for POC/Th ratios, the average annual POC flux at 150 m at BATS has been estimated to be 1.0 molC m^2 yr^{-1} (Buesseler, 1998). Increasing this flux by a factor of 2.5 (assuming this single NBST POC/^{234}Th ratio is relevant for the entire year) results in a predicted carbon flux of 2.5 molC m^2 yr^{-1}. Using a Redfield C/N ratio of 6.6 would result in an annual export flux in nitrogen of 0.4 mol N m^2 yr^{-1}. This higher export flux is similar to the estimates of new production at BATS of Jenkins (1982, 1988) and would help balance the overall C budget at BATS (Michaels et al., 1994).

We are not suggesting that this single NBST POC/^{234}Th ratio can resolve the many difficulties associated with estimating carbon budgets in the upper ocean. It does, however, point to the importance of improving our understanding of the behavior of traps for collecting all of the sediment flux components. While the PITs may not provide ideal samples for determining the POC/^{234}Th ratio on sinking particles, we cannot conclude from this experiment that filter-derived POC/^{234}Th ratios are more accurate. In any case, the absolute accuracy of the ^{234}Th approach would be improved if we had more reliable techniques for sampling sinking particles. At present, using the ^{234}Th approach, the seasonal and spatial patterns of export and the POC fluxes derived from ^{234}Th and POC on filtered particles appear to be reasonable within a factor of 2–3, or within the errors now associated with most upper ocean biogeochemical flux estimates (Ducklow, 1995; Michaels et al., 1994; Emerson et al., 1997). Enhanced export associated with the sinking of large diatoms is evident in the existing ^{234}Th studies, and these events appear to cause considerable variation in the ratio of primary production to POC export (Buesseler, 1998). Logistically, it would be difficult to sample using NBSTs with the temporal and spatial resolution possible when ^{234}Th distribution data are used as a proxy for upper ocean export. Thus, considerable improvement in understanding upper ocean flux variations in general could be gained if frequent measurement of ^{234}Th activities in space and time were combined with more accurate, but perhaps less frequent, sampling of sinking particles using an NBST. A mechanistic understanding of the dynamics of particle capture by traps and of the distribution of ^{234}Th on particles of different types and sinking speeds would also allow for a more robust extrapolation of these few measurements to the regional and global scales.

6. Conclusion

The goal of sediment trapping experiments is to accurately quantify the vertical flux and composition of sinking material in the oceans. As with any "rain gauge", the critical issue is how well one can calibrate or test the accuracy of these collectors under differing physical environments and flux conditions. The data collected here do not resolve the question of whether the current trap fluxes are correct. Rather, they present results from a pair of engineering tests where we can compare the standard upper ocean trap presently used in ocean sciences with a new trap design, both of which use identical collection tubes. The NBST is designed to minimize a potential collection bias due to horizontal flow across the trap mouth. The "good news" is that under these conditions (low-flow and relatively low-flux environment), the differences in bulk fluxes measured as total mass, POC and PON were small between the NBSTs and currently used PITs in October at BATS, and certainly less than a factor of two. This needs to be tested under differing conditions of flow, particle composition, depth and flux. The "bad news" is that even under the benign conditions of low horizontal flow, there is evidence of significant compositional differences in the material caught in the NBST and PIT designs. Here we find that the measured ^{234}Th, pellet, and June mass fluxes can vary by up to a factor of 2–3 between two traps with collection tubes of identical aspect ratio. An important additional finding is that the NBST design also significantly reduces the flux of non-passively sinking material caught in traps, i.e. swimmers.

Given the importance of quantifying vertical export on sinking particles in the oceans, we feel that rigorous tests of trapping efficiency, both through intercomparison studies, as done here, and through intercalibration of trap fluxes against other radionuclide or major elemental budgets, are of the highest importance. Future experiments should measure trap collection efficiency over a larger range of environmental conditions. These tests should include a broad suite of compositional measurements and sufficient replication for complete statistical treatment of the results.

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