A new time series of particle export from neutrally buoyant sediments traps at the Bermuda Atlantic Time-series Study site

S.A. Owens[a,b,*], K.O. Buesseler[a], C.H. Lamborg[a], J. Valdes[c], M.W. Lomas[d,e],
R.J. Johnson[d], D.K. Steinberg[f], D.A Siegel[g]

[a] Department of Marine Chemistry and Geochemistry, MS#25, Woods Hole Oceanographic Institution, 266 Woods Hole Road, Woods Hole, MA 02543, USA
[b] MIT-WHOI Joint Program in Oceanography/Applied Ocean Science Engineering, 266 Woods Hole Road, Woods Hole, MA 02543, USA
[c] Department of Physical Oceanography, MS#25, Woods Hole Oceanographic Institution, 266 Woods Hole Road, Woods Hole, MA 02543, USA
[d] Bermuda Institute of Ocean Sciences, 17 Biological Lane, St George's GE 01, Bermuda
[e] Bigelow Laboratory for Ocean Sciences, 60 Bigelow Drive, P.O. Box 380, East Boothbay, ME 04544, USA
[f] Virginia Institute of Marine Science, The College of William and Mary, P.O. Box 1346, Gloucester Pt., VA 23062-1346, USA
[g] Earth Research Institute and Department of Geography, University of California, Santa Barbara, CA 93106, USA

ARTICLE INFO

ABSTRACT

Neutrally buoyant sediment traps (NBSTs) were deployed concurrently with particle interceptor traps (PITs) on monthly cruises of the Bermuda Atlantic Time-series Study (BATS) from June 2007 to July 2010. In most months, particulate organic carbon flux measured by the two sediment trap systems agreed within the range of variability for two separate NBSTs. In three periods of this study however, the PITs collected more than three times the amount of particulate organic carbon (POC) than the NBSTs. One of these periods coincided with two instances when the mixed layer was deeper than the trap deployment depth, which may lead to biased collection. One of the anomalous periods occurred during summer months, for which we were unable to find existing evidence of biogeochemical changes that would lead to such increases in POC flux. The third anomalous period occurred when the POC flux measured by the NBSTs was near zero. We hypothesize that the PITs may have a positive bias at low fluxes relative to the NBSTs. Zooplankton swimmers accounted for $49 \pm 20\%$ of the total measured carbon flux over the three year period and swimmer removal by screening of samples through a 350 μm mesh was established as an effective method for this site. Process blank corrections based on sample-identical blanks were important for determining mass and carbon flux from both the NBSTs and the PITs. This new record of particle export from NBSTs suggests that the observed carbon imbalance in this region of the ocean (Michaels et al., 1994) is not due to undersampling by the PITs and that export ratios may be even lower than previously thought.

© 2012 Elsevier Ltd. All rights reserved.

1. Introduction

Sediment traps are rain gauge-like instruments that are intended to capture sinking particles as they settle through the water column. They are the most direct means of determining the magnitude and composition of export production from the euphotic zone (Eppley, 1989). Though conceptually simple devices, there are several issues that arise when sediment traps are deployed in the complex and dynamic environment of the open ocean. Key problems associated with their use and potential solutions were most recently summarized by a Scientific Committee on Oceanic Research working group, tasked to evaluate methods used to determine upper ocean particle flux including upper ocean sediment traps (Buesseler et al., 2007). Sediment traps have several possible sampling biases. The first issue is referred to as the hydrodynamic issue, which is caused by horizontal flow over the mouth of the trap and trap motion that may lead to under or over sampling of sinking particulate material (Gardner, 1985; Gust et al., 1996). This issue most affects traps in the upper 1000 m of the water column, where current velocities are highest. The second issue is zooplankton "swimmers" that are inadvertently captured in sediment traps and should not be considered a part of the passively sinking flux (Michaels et al., 1990; Steinberg et al., 1998). The distinction between swimmers that entered the traps alive or passively sinking, deceased zooplankton can be difficult to make and the contribution of swimmers to the measured carbon flux can be large. Therefore, it is important that swimmers are removed from samples prior to analysis in an effective and reproducible manner (Buesseler et al., 2007). Finally, the third issue is solubilization, the problem of sample degradation

* Corresponding author at: Department of Marine Chemistry and Geochemistry, MS#25, Woods Hole Oceanographic Institution, 266 Woods Hole Road, Woods Hole, MA 02543, USA. Tel.: +1 508 289 3843; fax: +1 508 457 2193.
E-mail address: sowens@whoi.edu (S.A. Owens).

after collection and prior to sample processing (Lee et al., 1992; Antia, 2005; Lamborg et al., 2008). An overarching issue in the use of sediment traps is the lack of standardized methods across the field, ranging from the type of sediment trap used, to the details of sample processing and flux determination. In some cases, such as swimmer removal, different biological systems require different methods to remove swimmers, whereas some procedures, like the preparation of sediment trap process blanks, although unique to a particular processing method, could be standardized and adopted more widely.

Time-series studies have been a key tool in understanding the complexities of the biological carbon pump (Ducklow et al., 2009) and particle flux is one of the critical measurements at the US-supported ocean biogeochemistry time-series sites: the Bermuda Atlantic Time series Study (BATS), the Hawaii Ocean Time series (HOT), and the Carbon Retention in a Colored Ocean (CARIACO) time series. The goal of the present study was to carry out the first long-term comparison of traditional surface-tethered Particle Interceptor Traps (PITs) used at both BATS and HOT (Karl et al., 1996; Knap et al., 1997) and Neutrally Buoyant Sediment Traps (NBSTs) developed at Woods Hole Oceanographic Institution (Valdes and Price, 2000). In performing this work at BATS, we were able to deploy the two sediment trap systems side-by-side on a monthly basis for three years and take advantage of other measurements by the BATS group to aid in the interpretation of our results. Such a long-term study allowed us to compare the two sediment trap systems over a range of seasons and particle flux events. We were also able to carry out longer-term comparisons of sample processing methods such as swimmer removal techniques and sample blank determination. The BATS site was a particularly interesting place to perform this work because of the difficulties in creating a closed carbon budget for this region (Michaels et al., 1994). It has been estimated that the change in carbon stocks over an annual cycle is three times greater than the amount of carbon removed here. This imbalance was hypothesized to be due to either undersampling by the PITs sediment traps and/or unaccounted for horizontal processes. Using the NBSTs for the first time in a time-series capacity, we aimed to shed more light on the characteristics and composition of particle flux at the BATS site.

2. Methods

2.1. Study site and experimental design

Neutrally buoyant sediment traps (NBSTs) were deployed each month concurrently with a surface-tethered array of particle interceptor traps (PITs) during cruises of the Bermuda Atlantic Time-series Study (BATS) from June 2007 to July 2010. Two NBSTs were deployed at 150 m each month for replication and in case of failure of one of the traps. In some months only one NBST was deployed at 150 m, usually when the second trap required maintenance or when NBSTs were deployed at multiple depths (150, 300, and 500 m).NBSTs and PITs were deployed near the BATS site, near $31.6°N \times 64.15°W$ within 3 km of each other on average, for a period of approximately three days.

2.2. Particle interceptor traps (PITs)

Deployment and recovery of the PITs array and processing of the samples was carried out according to the BATS Method Manual (Knap et al., 1997), which is based on Knauer et al. (1979). PITs tubes are polycarbonate cylinders (collection area=0.0039 m^2) outfitted with plastic baffles at the top of the tube. Three tubes are mounted onto each stainless-steel frame at 150, 200, and 300 m that are

attached to a surface tethered mooring equipped with a bungee and surface/subsurface floats. A current meter is also attached to the array at 165 m. Each PIT tube is filled to the top with a density gradient solution or brine (1 L formalin and 2.5 kg NaCl in 50 L of filtered seawater) prior to deployment. Cleaned and pre-weighed polycarbonate filters are mounted in the base of each PIT tube. Upon recovery, entrained seawater at the top of each trap is siphoned off to just above the level of the visible density interface and the remaining brine solution is passed through the filter at the base of the tube. The filters are stored in a refrigerator until the samples are processed further on shore. Once on shore, recognizable zooplankton or swimmers are removed from the filters using forceps under a dissecting microscope. Swimmers are preserved in a formalin solution and archived. Next, material on the filter is scraped towards the center, into a bolus, with a scalpel. The sample is rinsed with a few milliliters of pH 9 Milli-Q water, to remove salts, and dried in an oven. Samples are transferred to a dessicator and weighed periodically until a constant weight is achieved. Mass flux was determined by the difference between post- and pre-deployment filter weights divided by the length of deployment and the area of a PITs tube. To determine particulate carbon and nitrogen flux, the bolus is scraped off the filter with a scalpel into a silver boat, which is weighed to determine the fraction of total weight transferred as the bolus. The silver boats with boluses are fumigated with HCl for 36 h to remove inorganic carbon, desiccated overnight, and then analyzed for organic carbon and nitrogen content with a Control Equipment Corporation 9cEC 240 XA elemental analyzer. Carbon and nitrogen flux are calculated by dividing the instrument-blank-corrected C or N values by the bolus weight and multiplying by the mass flux (% $C_{bolus} \times$ mass flux).

2.3. Neutrally buoyant sediment traps (NBSTs)

2.3.1. Preparation and deployment

The NBSTs and sample processing techniques employed in this study were similar to those described in Lamborg et al. (2008). NBST tubes are polycarbonate cylinders (12×70 cm, collection area=0.0113 m^2) with HDPE bases and lids, and plastic baffles 2.5 cm in height with 1 cm diameter holes. Five tubes are mounted onto the central float of the NBST. The lid of each tube is anchored to the tube itself with amber silicone shock cord and is held open by securing a loop of nylon lanyard onto a retracting pin mechanism in the upper part of the float's pressure casing. The traps descend open and prior to beginning their ascent to the surface, after 3 days deployment, the pin retracts and the lids snap shut. For a typical NBST deployment to 150 m, it takes up to 2 h for the NBST to reach its deepest depth, between 175 and 400 m, after which it rises to its pre-programmed depth of 150 m. The NBSTs are programmed to maintain their depth within a certain range of depths. No significant difference was found between traps deployed at the same time with $\pm$ 10, 15, or 25 m correction windows; a $\pm$ 10 m window was used for most of this study. The number of flux days is taken as the time between when an NBST reaches its deepest depth and when its lids shut. Occasionally, not all of the lids shut correctly; in instances when two or less lids shut, the number of flux days is taken as the time between when an NBST reaches its deepest depth and when it is recovered at the surface. Out of a total of 77 trap deployments, 83% of the time the traps returned with at least three lids shut. The time correction for two or less lids shutting ranged from 1 to 8 h.

In preparation for deployment, tubes were rinsed three times and then filled to the level of the baffle with filtered seawater that was collected from 150 m en route to the deployment site. A poisoned, borate-buffered brine solution (500 mL, salinity=70, 3 mM borate, 37 mM formalin), made by freeze-concentrating

1.0 µm filtered seawater from 400 m at the BATS site, was added to the base of each tube with acid-cleaned Teflon tubing (Lee et al., 1992; Lamborg et al., 2008). The trap lids were kept shut until immediately before deployment to prevent any sample contamination particularly from the ship's smoke stacks. Four additional tubes for use as blanks of sample processing techniques (hereafter "process blanks") were prepared in the same manner but remained onboard, in the lab, for the duration of the trap deployments.

2.3.2. Recovery, sample processing and sample analysis

Upon recovery of the NBSTs, the tubes were removed from the main body and any unclosed lids were closed and noted in the deployment logs. The tubes were allowed to sit for $1-2$ h to allow any material to finish settling into the brine at the base of the tube. The filtered seawater overlying the brine was siphoned off. Post-deployment measurements of the salinity of the brine layer suggested minimal mixing or dilution during deployments. Any material remaining on the sides of the tubes was rinsed to the bottom of the tube using filtered seawater. The remaining brine from four of the five tubes was drained through the base of the tubes, passed through an acid-washed 350 µm nylon screen to remove zooplankton swimmers, combined in a 4 L bottle, and stored in a refrigerator until further processing on shore. The screens were rinsed with filtered seawater to remove any particles adsorbed to zooplankton on the screen and these rinses were added to the screened brine. Swimmers from the screens were later rinsed onto silver filters using additional filtered seawater. An alternate swimmer removal technique was tested, in which swimmers were picked from the brine and placed on a silver filter (discussed further in the Section 3). Material from the fifth tube was drained directly into a separate bottle without removing swimmers and preserved with additional formalin for zooplankton and fecal pellet quantification and classification using microscopy.

From the beginning of the study in June 2007 through October 2008, the NBST sample processing described below was carried out in Bermuda at the Bermuda Institute of Ocean Sciences (BIOS). From November 2008 through February 2009, one sample was processed at BIOS while a second was preserved with an additional 1.2 mL of formalin and shipped to Woods Hole Oceanographic Institution (WHOI) for processing. Based on agreement over the three-month period between sample processing locations, from March 2009 through July 2010, all samples were subsequently split and filtered at WHOI. The only exceptions to the above are when sample processing occurred at sea as in June and July 2007, June and July 2008, and September 2009.

After swimmer removal, the material from the four combined tubes was split eight ways using the sample splitter set up described in Lamborg et al. (2008). These eight subsamples or "splits" were then filtered onto three Sterlitech silver membrane filters (1.2 µm nominal pore size), three Whatman Nuclepore polycarbonate membrane filters (1.0 µm nominal pore size), and two Whatman quartz microfibre filters. The four blank tubes were screened, combined, split, filtered, and analyzed in the same manner as the samples.

All sample analysis methods were adopted from Lamborg et al. (2008) and we note any deviations from these methods here. The three polycarbonate filters were first used to determine mass flux then two of the three filters were consumed for coulometric particulate inorganic carbon (PIC) analysis (Johnson et al., 1985; Honjo et al., 2000). The three silver filters were dried overnight in an oven at 60 °C then counted on anti-coincidence beta detectors (Risø National Laboratories) for ^{234}Th. One of the three silver filters was recounted after six half-lives ($t_{1/2} = 24.1$ days) to

determine the background associated with other isotopes in the sample. All three silver filters were subsampled and a half of each was used for analysis of total particulate carbon (C) and nitrogen (N), a quarter was used to determine biogenic silica (bSi) by inductively coupled plasma emission spectroscopy, and a quarter was kept as an archive. Thus for C, N, bSi, and ^{234}Th analyses, there were three replicates of each split. Particulate organic carbon flux for the three replicates was determined by subtracting the mean of the two PIC flux values from the total carbon value. The average contribution of PIC to the total carbon signal was 10%. The total carbon content of the swimmer fraction was determined also by CHN analysis. Early in the study, 50% subsamples of the swimmer filters were analyzed however, for the remainder of the study (May 2008, onward), whole filters were analyzed.

2.4. June/July 2008 trap inter-comparison experiment

In June and July 2008, along with the NBSTs and PITs array, an additional surface-tethered, drifting sediment trap array was deployed (McDonnell and Buesseler, 2012). Individual NBST tubes or "CLAP" tubes and PITs tubes were deployed on the sediment trap frame at 150 m. The array included two CLAP tubes with lids, two CLAP tubes without lids, and two PITs tubes. Also, 4 additional PITs tubes were placed on the PITs array to be processed by the WHOI group. The individual tubes were combined and split such that the resulting particle load on silver or polycarbonate filters was similar to that of NBST samples. For example, the two CLAP tubes with lids were combined, split four ways, and filtered onto two silver filters and two polycarbonate filters. Two PITs tubes were combined, split two ways, and filtered onto a silver filter and a polycarbonate filter. All samples were passed through 350 µm screens to remove swimmers. CLAP tubes were corrected using the NBST blank correction factor. PITs samples processed by our two groups were corrected using PITs blanks measured by the WHOI group ($n=2$) and the BATS group ($n=14$), respectively.

3. Results

3.1. NBST time-series flux results

Over the course of three years, NBSTs were successfully deployed 77 times at the BATS site. Only three months were unsampled by the NBSTs because of maintenance requirements or no cruise as in January 2009 and 2010. A consistent seasonal pattern was not apparent in the fluxes of the measured particulate components or their ratios (Figs. 1 and A1). Mass flux was more variable over the three-year period compared to POC flux, which varied little except for a large POC flux event in spring 2010. Split-to-split variability (Table 1) for POC and mass flux was consistent with previous results using the splitting technique (Lamborg et al., 2008).

The mean C:N of the material collected was 7.0 ± 2.7, not including values from November 2009 when the C:N ratios were abnormally high due to very low N fluxes (Figs. 1 and A1). There was good agreement between the three splits and two NBSTs for ^{234}Th fluxes, which were highly variable over the study period. Silica fluxes were very low for most of the study period except for a few peaks, most notably in May 2008 and December 2008. Replicate splits and separate NBSTs for biogenic silica also agreed well. PIC fluxes were similarly low except for a small increase in spring 2010. Reproducibility between the two splits and NBSTs was good except in December 2010, when the one NBST collected significantly more PIC. Over the entire study, NBST-to-NBST variability in the same deployment was on the order of 20% for

the flux components reported here, consistent with prior NBST deployments (Lamborg et al., 2008).

3.2. Sample processing methods

3.2.1. Swimmer removal techniques

During this study, the primary method of swimmer removal from NBST samples was screening of the sediment trap material through a 350 μm mesh. On average, swimmer carbon accounted for $49 \pm 20\%$ of the total carbon flux, ranging from $<1\%$ to 93% of the flux (Fig. 2). Early in the study, one of the three screened sample splits on silver filters was examined under a microscope ($n=17$). Any small swimmers that may have passed through the screen were picked onto a blank silver filter and both fractions were analyzed for their carbon content. The carbon content of

these small swimmers was equivalent to 0–2.45 mg C m^{-2} d^{-1} or 0–7% (mean 2.5%) of the total carbon flux in a given month. From this we concluded that small swimmers that passed through the

Table 1

Variability of sediment traps at BATS, June 2007–July 2010 based on the average relative standard deviation of replicate splits, NBSTs, or PIT tubes.

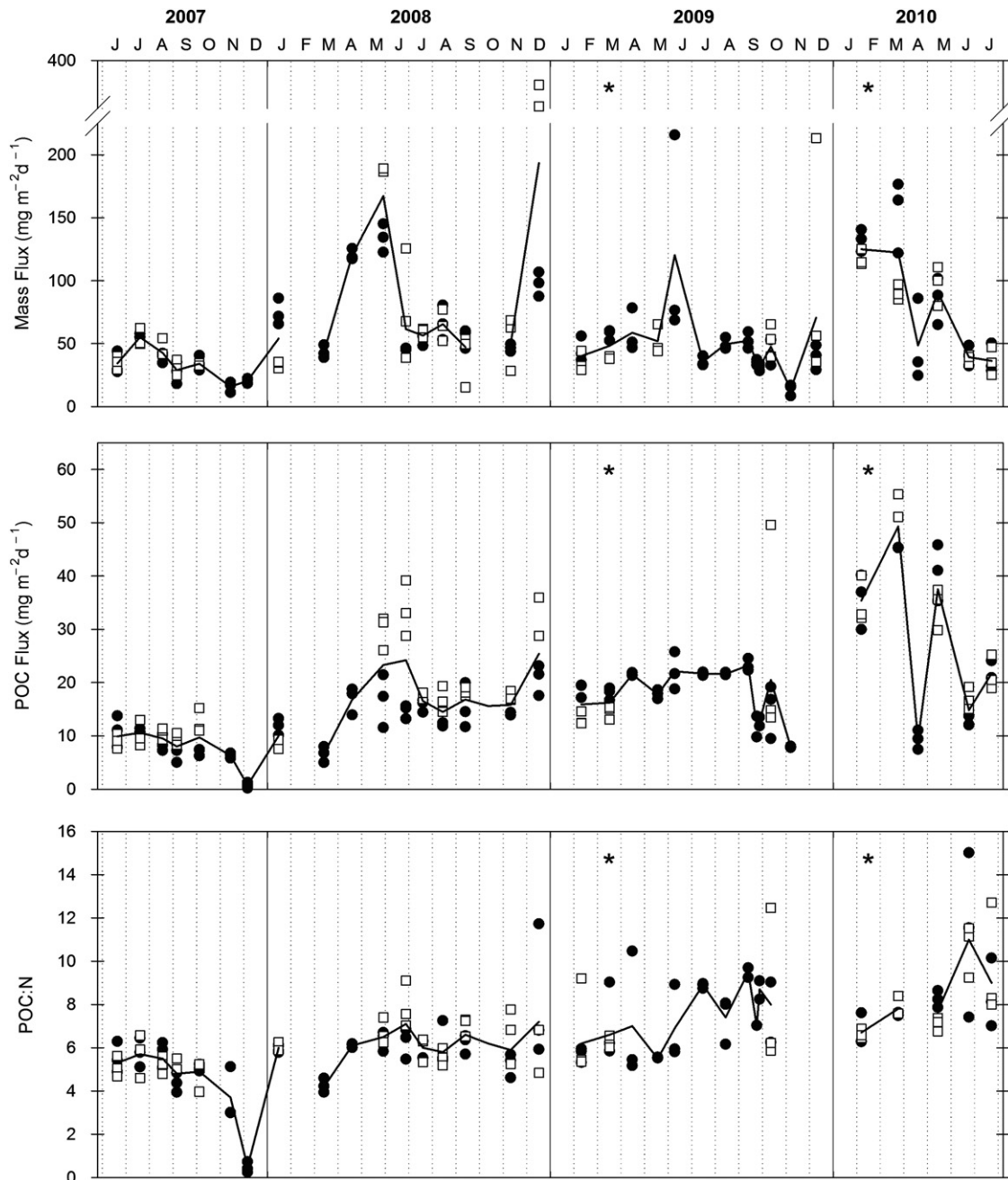|	POC (%)	Mass (%)
NBST		
Split to split	12 ± 11	19 ± 15
Device to device	19 ± 14	18 ± 19
PIT		
Tube to tube	24 ± 16	27 ± 17

Fig. 1. Mass flux, POC flux, and C:N ratios of sinking material captured by NBSTs at 150 m at the Bermuda Atlantic Time-series Study site. Two traps were deployed each month (circles and squares) and three replicates of each parameter were obtained (denoted by individual points). The solid black line in each figure is the average of the three replicates in the two traps. Stars above March 2009 and February 2010 denote months when the traps were in the mixed layer.
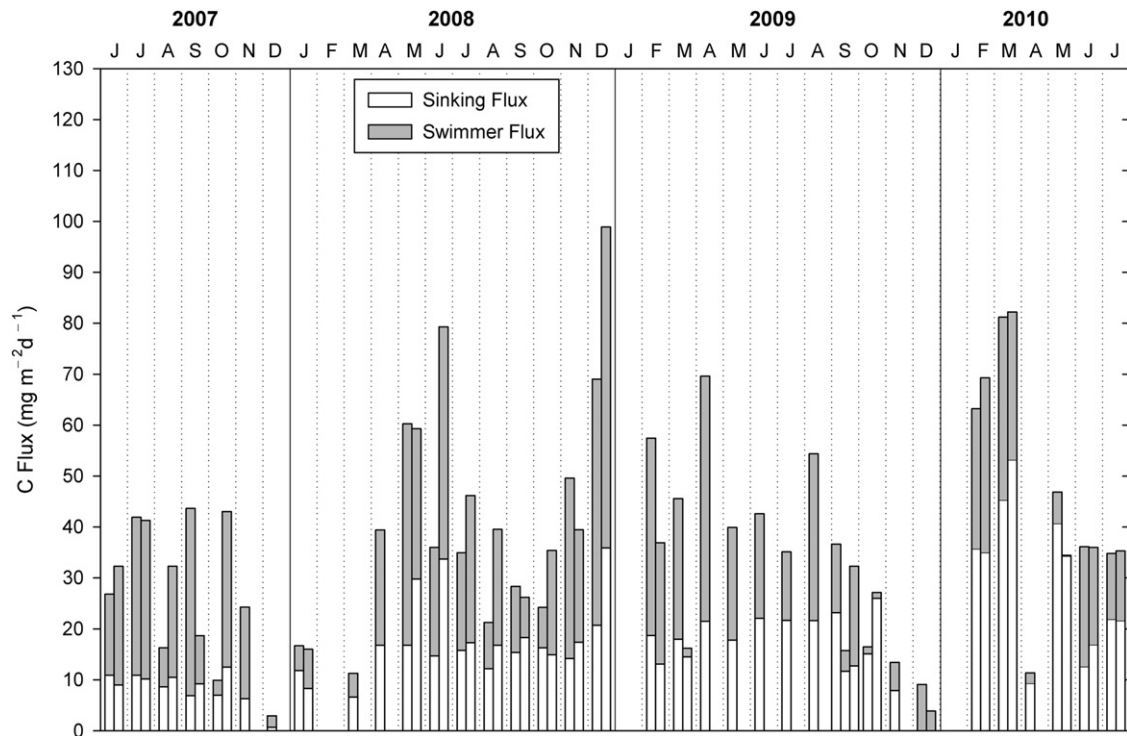
Fig. 2. Comparison of carbon flux associated with the sinking fraction ($< 350 \, \mu m$, in white) versus the swimmer fraction ($> 350 \, \mu m$, in gray) collected by NBSTs at 150 m. No sinking fraction carbon data was available for December 2009.

screen were a minor or insignificant contribution to the total flux in terms of carbon content.

An alternate method of swimmer removal, which we refer to here as "wet-picking," was also tested. For this method, at sea, the brine layer from four tubes was combined in a 4 L bottle without screening; on shore, the entire sample was examined in smaller-volume fractions under a microscope and swimmers were picked directly onto a silver filter. On five separate occasions, screening and wet-picking were carried out on separate NBST samples (Fig. 3). The POC flux of the sinking material, after swimmer removal, was comparable between the two methods (Student's t-test with equal variance, $P < 0.01$; Fig. 3, upper panel). The amount of swimmer carbon removed by each method was variable however, with more swimmer carbon from wet-picked samples in three instances and more swimmer carbon from screened samples in two instances (Fig. 3, lower panel). These differences in swimmer carbon content removed are likely attributable to variability between NBSTs, as it may take only one or two large zooplankton to impact the carbon data. In October 2008, for example (Fig. 2), when both NBST samples were screened to remove swimmers, the percent of total carbon from swimmers in the two traps was 34 and 58%, yet the percent difference between the POC fluxes was less than 10% or approximately 1 mg C m^{-2} d^{-1}. Looking at all instances when two NBSTs were deployed and both sets of samples were screened to remove swimmers ($n=18$), the absolute difference between percent carbon from swimmers for two NBSTs ranged from 0 to 50%. In the five cases in which screening and wet-picking were compared, the difference in swimmer carbon percentage between two NBSTs ranged from 21% to 37%, within the lower range for two NBST samples that were both screened.

3.2.2. NBST process blanks

NBST process blanks were prepared, processed, and analyzed in an identical manner to NBST samples. The blanks are viewed as

"process blanks" in that they account for any background signal inherent to the sampling and processing methodology. Table 2 shows blank "fluxes" for NBSTs from this study at BATS and from the Vertical Transport In the Global Ocean (VERTIGO) program in the subtropical (ALOHA) and subarctic (K2) North Pacific. Blank "fluxes" measured separately by the WHOI and BATS groups are also shown. NBST blank fluxes for most parameters were comparable to those measured in the VERTIGO study (Lamborg et al., 2008). The NBST process blank was most important for total carbon, mass, and biogenic silica (bSi) analyses, where the blank signal was 18, 13, and 40%, on average, of the total measured signal. In contrast, the contribution of the blank for ^{234}Th, total N, and PIC was less than 5% of the total measured amount or below detection. Blank corrections were applied to total C, mass, and bSi analyses before deriving fluxes. Blank corrections were not applied to ^{234}Th, N, and PIC samples because the blank values were low, they were minor contributions to the total measured values, and all had high uncertainties.

3.3. NBSTs versus PITs POC time series

The average POC flux collected by the NBSTs was 18.5 mg C m^{-2} d^{-1} (range 2.0–50.2 mg C m^{-2} d^{-1}) compared to an average PITs flux of 27.4 mg C m^{-2} d^{-1} (range 7.0–69.0 mg C m^{-2} d^{-1}). In most months of the time series, POC flux at 150 m measured by NBSTs and PITs agreed within a factor of two (Fig. 4). In three periods however, the PITs collected more than three times the amount of material than the NBSTs and the highest and lowest individual measurements for the two systems did not overlap (Fig. 5). This variability exceeds the largest variability seen between individual NBSTs, a factor of 2.2. The tube-to-tube variability of POC flux collected by the PITs was greater than the split-to-split variability of the NBSTs (Student's t-test with unequal variance, $P < 0.01$; Fig. 4; Table 1).This trend is not surprising, as the combining and splitting method used on the NBST samples homogenizes any tube-to-tube variability. In the
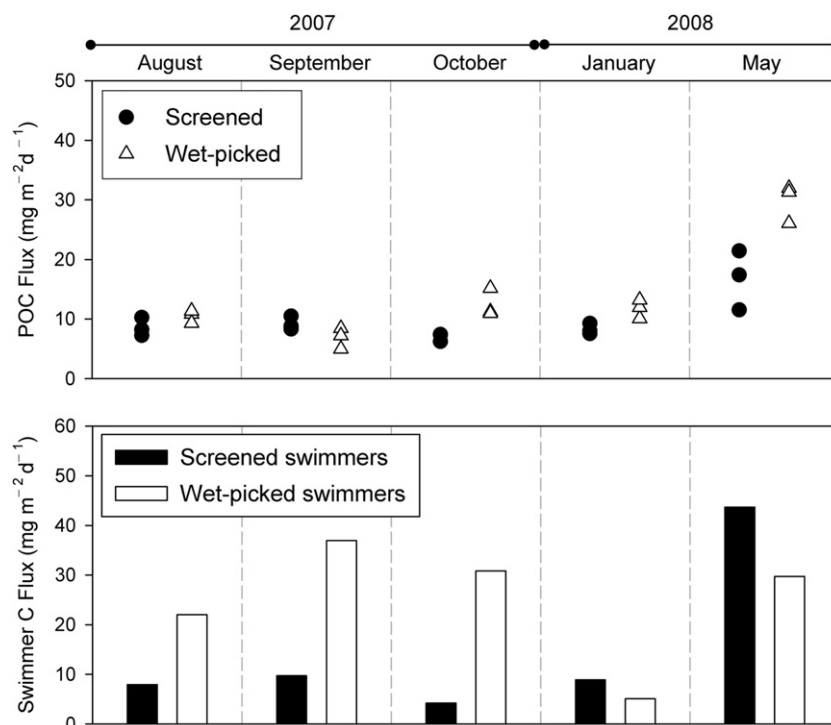
Fig. 3. Two methods for removing swimmers from the NBST samples were tested: screening using a 350 μm mesh (black circles and bars) and wet-picking directly from the sample volume (white triangles and bars). The top panel shows the POC flux measured in the sinking fraction, from which swimmers have been removed by either screening or wet-picking. The bottom panel shows the magnitude of the swimmer carbon removed from each sample by each method. While the magnitude of swimmers removed from by each method varied, the resultant flux of sinking material was comparable for the two methods.

Table 2
NBST Blank fluxes from this study compared to blank measurements during studies in the subtropical (ALOHA) and subarctic (K2) North Pacific. PITs blanks were measured separately by the WHOI and BATS groups.[a]

	Total C (mg m^{-2} d^{-1})	Mass (mg m^{-2} d^{-1})	bSi (mg m^{-2} d^{-1})	^{234}Th (dpm m^{-2} d^{-1})	N (mg m^{-2} d^{-1})	PIC (mg m^{-2} d^{-1})
NBST [b]						
ALOHA	1.3 ± 0.5	8 ± 2	0.11 ± 0.06	0 ± 43	0.07 ± 0.07	< 0.24
K2	4.1 ± 0.5	28 ± 14	0.11 ± 0.06	0 ± 17	0.35 ± 0.06	< 0.24
BATS (This study)	4.3 ± 1.0	8 ± 6	1.2 ± 0.6	9 ± 7	0.12 ± 0.35	0.01 ± 0.01
PITs						
WHOI [c]	10.5 ± 0.3	9	–	7 ± 3	0.77 ± 0.09	0.01 ± 0.02
BATS [d]	1.2 ± 0.7	19 ± 8	–	–	0.05 ± 0.04	–

[a] Blank "fluxes" were calculated based on the trap area (NBST—0.01143 m^2, PITs—0.0039 m^2) and a three day deployment period.

[b] Four-tube blanks were prepared and analyzed 17 times during this study. For C, mass, bSi, ^{234}Th, and N average blank fluxes, $n=51$ and for PIC, $n=34$. Average blank corrections were applied to C, mass, and bSi raw data.

[c] For C, ^{234}Th, N, and PIC, $n=2$; for mass, $n=1$.

[d] For BATS PITs blanks, $n=14$ and the C blank is for POC, not total C.

nine months that NBSTs were deployed at 150, 300, and 500 m, flux measured by the NBSTs and PITs agreed well (Fig. 6). The larger tube-to-tube variability of the PITs is also evident in the flux versus depth profiles. The average mesopelagic transfer efficiency (T_{eff}=300 m POC flux/150 m POC flux) from the NBSTs was $38 \pm 18\%$ versus $53 \pm 15\%$ for the PITs.

3.4. June/July 2008 trap comparison experiment

In June and July 2008, a more detailed experiment comparing NBST and PITs methodologies was carried out using both systems and an additional drifting array equipped with CLAP (NBST) tubes and PITs tubes (Fig. 7). In June, the flux measured by two NBSTs varied by about a factor of two, while in July, the measured fluxes were almost identical. We had aimed to capture the large discrepancy between the NBST and PITs observed in summer 2007 again (Fig. 5); however, the PITs and NBSTs agreed within the range of NBST-to-NBST variability in June and July 2008. The

CLAP tubes on the drifting array were deployed both with and without lids that closed prior to recovery. In both months, the flux was lower in the tubes without lids, which may suggest that during recovery, as traps are hauled to the surface, there is the potential for material to be washed out of tubes without lids. We are not able to estimate from this work however, the potential for this to occur in the PITs which also do not have lids. These data reinforce the importance of a process blank correction to the NBST/CLAP and PITs data.

4. Discussion

4.1. The swimmer issue

The significant and variable contribution of swimmer carbon to the total flux collected by the NBSTs in this study reinforces the importance of removing swimmers from sediment trap samples

to quantify passively sinking particle flux (Fig. 2). The effectiveness of the swimmer removal method used in this study was established in two ways: (1) examination of screened samples for small swimmers and (2) testing an alternate wet-picking method. The contribution to the total carbon flux by swimmers less than 350 μm was small, suggesting that for this study at the BATS site, screening was an effective method for removing swimmers from the bulk sample. The wet-picking method for removing swimmers produced sinking flux values that were comparable with

samples that were screened (Fig. 3). The screens were not examined to determine if they retained any non-swimmer material, however the similarity of POC fluxes determined by the two swimmer removal methods suggest that this was not a significant problem, consistent with previous applications of this method (Lamborg et al., 2008).

While both swimmer removal methods used in this study were effective, the wet-picking technique was time consuming and potentially susceptible to variable swimmer picking skills with changes in personnel. The screening technique was easy to perform at sea and more compatible with our sample-splitting technique. Although no trace metal data is reported in this work it may be easier to maintain trace metal cleanliness for analysis of particulate trace metals using the screening method. It is important to acknowledge that a method that is effective at removing swimmers at one study site may not always be a suitable method at other sites. For example, screening alone may not be as effective in coastal or other environments with high zooplankton biomass and large sinking fecal pellets, such as with krill in the Western Antarctic Peninsula region (Buesseler et al., 2010; Gleiber et al., in press).

In the only comparable study comparing the BATS picking method and screening (350 μm) at BATS, the POC flux determined from the picked samples was 40% lower than the POC flux from the screened samples (Buesseler et al., 2007). In addition, the C:N ratio of the picked samples was lower than the screened samples. These results were used to suggest that the screening method might have missed small swimmers and thus it has not been used at BATS. This is in contrast to our study, where the difference between POC flux from screened and wet-picked NBST samples was indistinguishable (Fig. 3) and the C: N ratio was the same (not shown; Student's t-test with equal variance, $P < 0.01$). PITs tubes picked for swimmers by the BATS group and PITs tubes screened through a 350 μm mesh by the WHOI group during the intercomparison study also produced comparable sinking POC fluxes, within the range of observed tube-to-tube variability (Fig. 7).

It has been hypothesized that surface-tethered traps such as PITs may be more likely to trap swimmers due to hydrodynamic effects around the mouth of the trap that allow the swimmers to
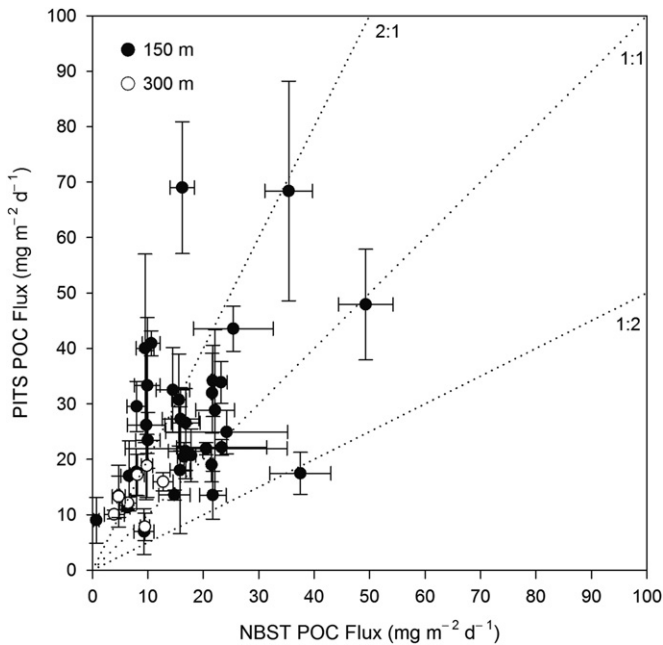
Fig. 4. Average POC flux determined using PITs versus average POC collected by NBSTs at 150 (black) and 300 (white) m. The error bars on the PITs data are the standard deviation of measurements from three PITs tubes while the error bars on the NBST data are the standard deviation of replicates from one or two NBSTs. A single NBST was deployed in November and December 2007, March and April 2008, April to September 2009, November 2009, and April 2010.
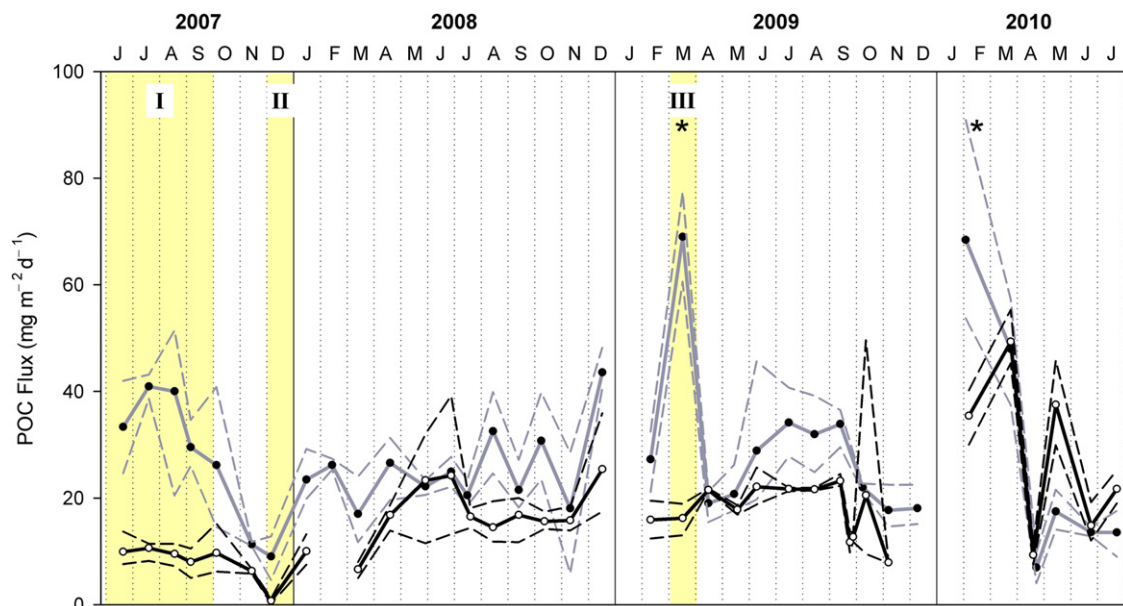
Fig. 5. The average POC flux measured by NBSTs (black solid line) and PITs (grey solid line) at 150 m. The dashed lines denote the highest and lowest fluxes determined for replicates of NBST samples or individual PITs tubes. The three periods of particular interest where the traps differed by more than a factor of three and none of the individual measurements overlapped are highlighted in yellow. Stars above March 2009 and February 2010 denote months when the traps were in the mixed layer.
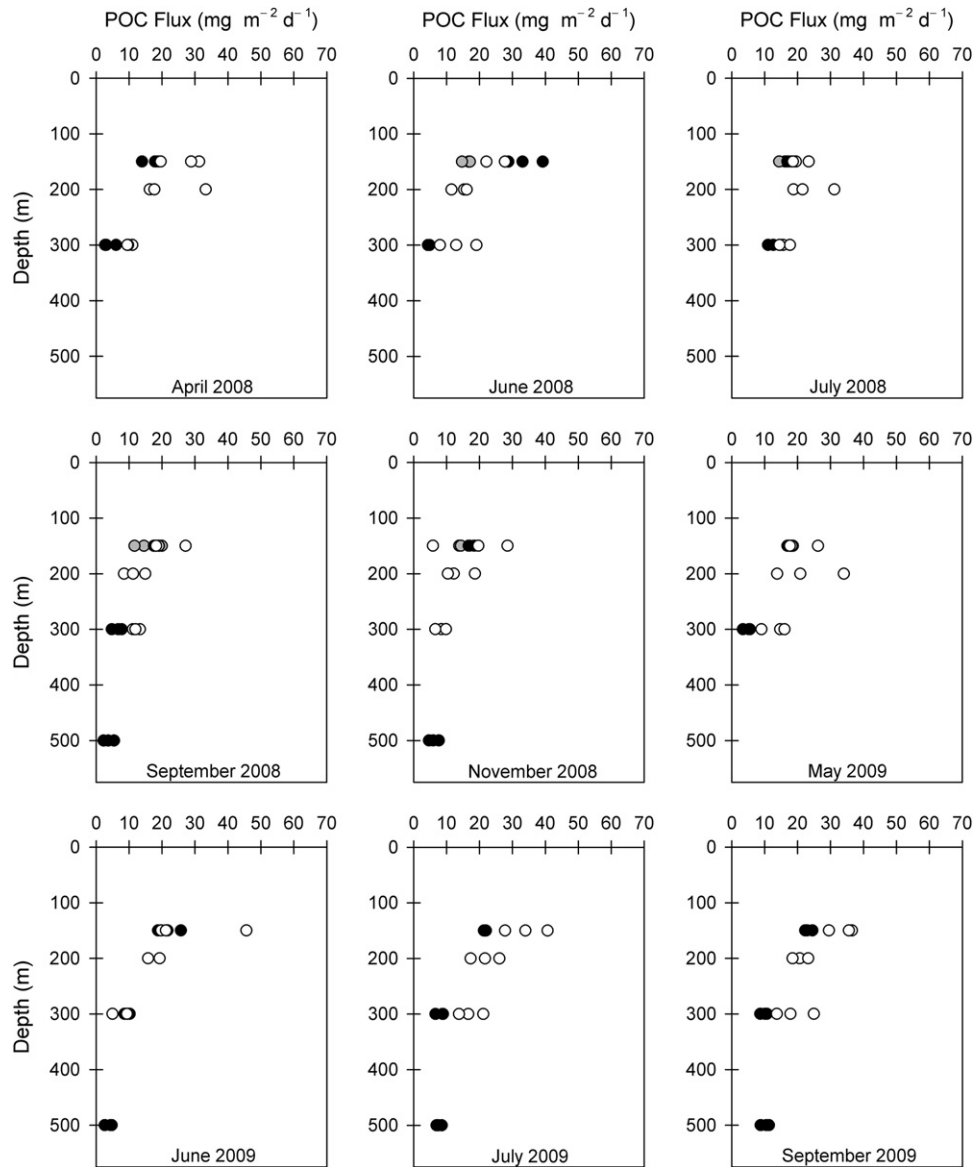
Fig. 6. POC flux versus depth as measured by NBSTs and PITs. Shown are individual NBST replicates (in black, grey for a second 150 m NBST) from traps at 150, 300, and 500 m and individual PITs tubes at 150, 200, and 300 m (in white).

"surf" into the device, in addition to swimmers that actively swim into the traps (Buesseler et al., 2007; Lampitt et al., 2008). Thus, traps that experience minimal or no hydrodynamic flow would ensnare fewer unwanted swimmers. Although fewer swimmers were captured in NBSTs than PITs in an early study (Buesseler et al., 2000), more recently, swimmers contributed significantly to the total carbon flux in NBSTs deployed in the Pacific (Lamborg et al., 2008). PELAGRA, another neutrally buoyant sediment trap design, captured very few swimmers in its early deployments (Lampitt et al., 2008), but during deployments in the Southern Ocean, swimmer contribution to the total mass flux ranged from < 1% to 40% (Salter et al., 2007). In the study here, swimmer carbon was a significant component of the total carbon flux captured by both the NBSTs and the PITs. In the two-month inter-comparison study, the swimmer carbon flux in the NBSTs ranged from 19 to 46 mg C m^{-2} d^{-1} while the range of swimmer carbon flux in the PITs was 27 to 72 mg C m^{-2} d^{-1}. If "surfing" swimmers are in fact fewer in neutrally buoyant trap designs, these results suggest that swimmers actively entering or zoo-plankton passively sinking into the traps are also important.

4.2. Sediment trap blanks

Process blank corrections are not common to all sediment trap programs. NBST blanks were implemented during the VERTIGO study primarily to quantify trace metal blanks but were also determined for major particulate components. In the present study, the NBST blank values for C, mass, and Si were significant relative to sample values, particularly as the particle flux at BATS is so low. BATS sediment trap flux measurements take into account analytical blanks but not process blanks (Knap et al., 1997). When measured by the BATS group, the PITs process blank was 28%, 9%, and 2%, on average, of the measured values for mass, POC, and N, respectively. To further demonstrate the importance of applying a process blank correction to the PITs data, Fig. 8 shows NBST and PITs POC fluxes as a function of primary production. Applying a correction for the process blank to the PITs data from the period of this study shifts the POC fluxes to lower values, implying lower export efficiency for the biological pump at BATS.

Some issues arose with these preliminary measurements of the PITs blank including how to blank correct for mass and

carbon/nitrogen on a single filter, the effect of blank corrections on C:N ratios, and what volume of brine to use for measurements for the blanks. For each PITs tube, mass flux is determined from the change in filter weight before and after filtration. After these weight measurements, the sample material is scraped off the filter and this subsample is reweighed to determine the fraction of material recovered off the filter. In some cases, the change in weight of blank and sample PITs filters was similar although the weight of the blank subsample was very small. This led to an overestimation of the blank mass flux and consequently an overestimation of the blank POC flux, which is determined by multiplying the percent carbon of the subsample and the mass flux. To avoid this problem, we applied the C blank value to the whole-sample C value rather than the subsample C value. This assumes that the C blank is independent of the calculation that scales from the subsample to the whole sample. The PITs blanks for mass and C were larger when measured on separate filters by the WHOI group in June and July 2008 (Fig. 7). We believe that these analyses by our two groups represent the upper and lower limits of the PITs blank contributions.

A second quandary arose when looking at the effect of C and N blank corrections on sample C:N ratios of the PITs data. Before blank correction the mean C:N of the PITs data was 6.6 ± 0.9 and after correcting for both C and N blanks, the mean C:N was 6.1 ± 0.9. Sinking particles tend to have higher C:N values than Redfield values (C:N=6.625) due to preferential remineralization of nitrogen (Martin et al., 1987; Lamborg et al., 2008). The blank-corrected PITs data are lower than Redfield values, which may suggest that the current C blank correction is too high or the N blank is too low; the standard deviations of these mean C:N values are too large however to establish this definitively.

A final consideration is how to account for the variable volume of PITs samples when determining process blanks. One third to one half of the brine solution that initially fills the PITs tubes is washed out during deployment. Before filtration, the entrained seawater is siphoned off and only the remaining brine is processed. As a result, individual tubes have different sample volumes. Blank corrections applied in Figs. 7 and 8 are whole-tube blanks and do not take this variability into account. Further work is necessary to determine if the volume of the PITs process blanks is important.

Sediment trap process blanks are an important methodological issue that should be considered in existing and future sediment trap studies. A less complex approach to determining PITs blanks would be to deploy additional tubes and measure fluxes and blanks of different components on separate tubes, although this complicates the calculation of elemental ratios due to tube-to-variability. Alternately, samples could combined, split, and filtered onto multiple filters for different analyses, like the NBSTs. To address the problem of variable sample volumes, the height of the brine in each sample tube could be measured then multiple blanks could be prepared based on these volumes. Alternately, if the brine solution was constrained to the bottom of the PITs
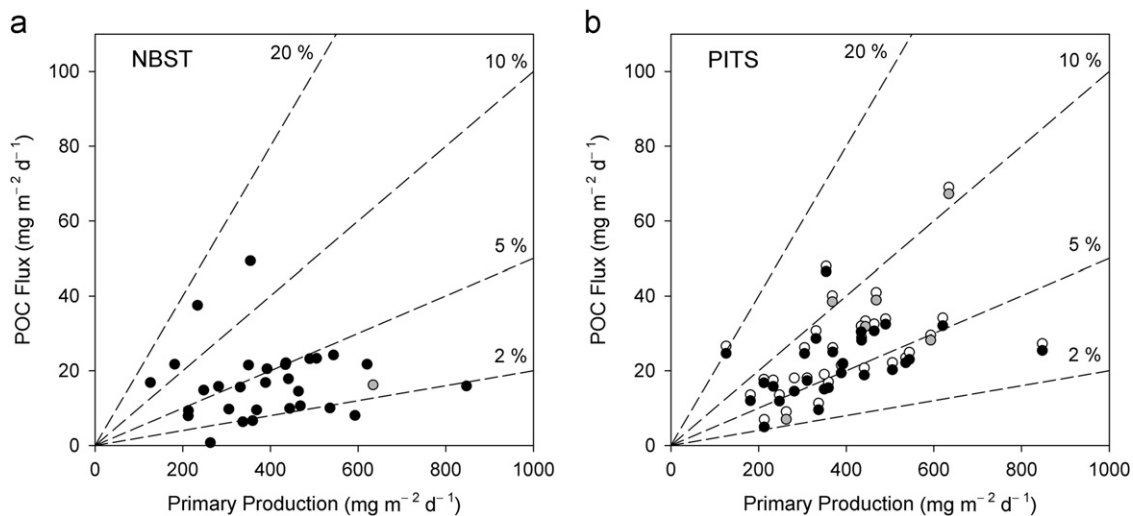

Fig. 7. Results of an experiment comparing sediment trap types in June and July 2008. Average POC flux for two NBSTs is shown (black bars, on left each month) and the error bars represent the standard deviation of three replicates. NBST (CLAP) tubes (with and without lids, dark and light grey) and PITs tubes (white) were deployed on a surface tethered drifting array (center). Additional PITs tubes on the PITs array were analyzed by the WHOI group (white bars). The standard PITs tubes analyzed by the BATS group each month are shown to the far right (hashed bars). The black dot above each bar denotes the POC flux before the method-specific process blank correction was applied.

Fig. 8. (a) NBST POC flux versus integrated primary production determined during the BATS cruises from June 2007 to July 2010 with lines of constant export ratios. The grey point corresponds with February 2010 when the NBSTs were within the mixed layer. No primary production data was available for March 2009. (b) For the same time period, PITs POC flux versus integrated primary production before blank corrections are shown in white. In black and grey are the blank-corrected data, using the PITs blank measured by BATS. The grey points are those from the months highlighted in Fig. 5.

tubes, a more reproducible sample volume might be obtained from each tube. One point however, is that a four-tube NBST blank was not four times as large as a single-tube NBST blank, so determining a process blank may not be as simple as scaling a blank tube measurement with volume. We recognize that there are arguably equal advantages and disadvantages to changing methods used in time-series studies; however this work also has implications for independent studies in which these process blank corrections may be more readily implemented.

4.3. Differences in NBST and PITs flux measurements

The purpose of this work was to compare the PITs and NBSTs over the annual productivity and export cycle at BATS. Our aim was not to inter-calibrate the two systems with water-column radio-nuclide measurements of export. Such an effort would have required multi-week and Lagrangian style sampling during each cruise (Buesseler et al., 1994, 2008b; Cochran et al., 2009), which was beyond the scope of our study. In previous comparisons of early-generation NBSTs to PITs at the BATS site, there were few replicates and while mass and POC fluxes agreed well, there were differences in fluxes of minor elements (Buesseler et al., 2000; Stanley et al., 2004). Over the course of the study presented here, flux measured by the two sediment trap systems agreed in most cases within the variability observed for two separate NBSTs, a factor of 2.2. However, we identified three periods, in which the flux collected by the PITs was more than three times higher than the NBST flux (Fig. 5): June to September 2007 (I); December 2007 (II); and March 2009 (III). Thus far, we have addressed methodological issues that should affect the entire time series. Below, we attempt to identify factors that may have caused the large discrepancies between the NBSTs and PITs in the three periods highlighted in Fig. 5.

4.3.1. Currents

The purpose of developing the NBSTs was to minimize hydro-dynamic biasing experienced by surface-tethered traps like the PITs. As a neutrally buoyant float by design, the NBSTs should have no mooring line, tilt, or other hydrodynamic effects; the current generation of NBSTs however does not have onboard sensors to measure these properties. Flow across the PITs is measured using a current meter located 15 m below the 150 m PITs array. In the 33 of 35 months that current meter was available for this study period (Fig. A2), the average current speed was 7 cm s^{-1} and ranged from 3 to 12 cm s^{-1}, similar to collection periods in prior NBST-PITs comparisons (Buesseler et al., 2000; Gardner, 2000; Stanley et al., 2004). Peak approach velocities measured during deployments here ranged from 10 to 23 cm s^{-1}. There was no direct relationship between mean ($r^2 = 0.03$, $P = 0.3$) or maximum ($r^2 = 0.05$, $P = 0.2$) current velocities and POC flux measured by the PITs, in agreement with previously published data (Gardner, 2000). Contrary to Gardner (2000) however, when periods of high and low net primary production (NPP) were considered separately, a trend of increasing PITs flux with velocity did not emerge. Also, there was no correspondence between periods of increased current speed and the three periods in which the PITs measured higher values of POC flux. Based on these current meter measurements, hydrodynamic biasing does not appear to be the cause of the discrepancies in these three periods.

4.3.2. Deep mixed-layer

Sediment traps used for measuring passively sinking particle flux are typically deployed below the surface mixed layer. Convective mixing in this layer increases the residence time of particles and aggregates (Gardner, 2000) and as a result, particles may have more than one opportunity to sink into a sediment trap, leading to biased sampling (Gardner and Richardson, 1992;

Buesseler et al., 2007). The intensity of stratification can also vary spatially during a sediment trap deployment. Data from sediment traps that are deployed within the mixed layer should therefore be viewed with caution. For example, in a summary of the first decade of BATS data (Steinberg et al., 2001), months in which the mixed layer depth exceeded the PITs depth showed dramatic increases in particle flux, even down to 200 and 300 m, and the data were considered suspect.

The NBSTs and PITs were within deep, winter mixed layers in March 2009 (188 m) and February 2010 (226 m), corresponding with one of the anomalous periods (III; Fig. 5) and the two months of highest POC flux measured by the PITs during this study. The mixed layer was defined using the variable sigma theta criteria and assuming a 0.3 °C diurnal temperature change (Sprintall and Tomczak, 1992). While the POC flux measured by the PITs in these two months represented significant deviations from the mean flux, a similar change was not observed in the NBST fluxes, particularly in March 2009. The properties used to indicate a deepened mixed layer may persist after the period of actual deep mixing, meaning that during the deployments, the sediment traps may not have been in the zone of active mixing. Nonetheless, until it can be shown that sediment traps of any design can quantitatively capture sinking particle flux in the mixed layer, these data should be regarded with caution. In this work, these data are not considered further and following the convention of Steinberg et al. (2001) are denoted with asterisks in Figs. 1, 5, and A1.

4.3.3. Spatial variability

Another factor to consider is differences in deployment locations of the two sediment trap systems resulting in variability in the sinking particle flux. For example, Fig. 9 shows the deployment and recovery positions of the NBSTs and the recovery positions of the PITs each month (#1–12) of 2008. On average, deployment locations of the PITs and NBSTs were within 3 km and in 27 of 35 months the recovery locations were within 15 km of each other. These distances were on the same scale as source funnels calculated for surface-
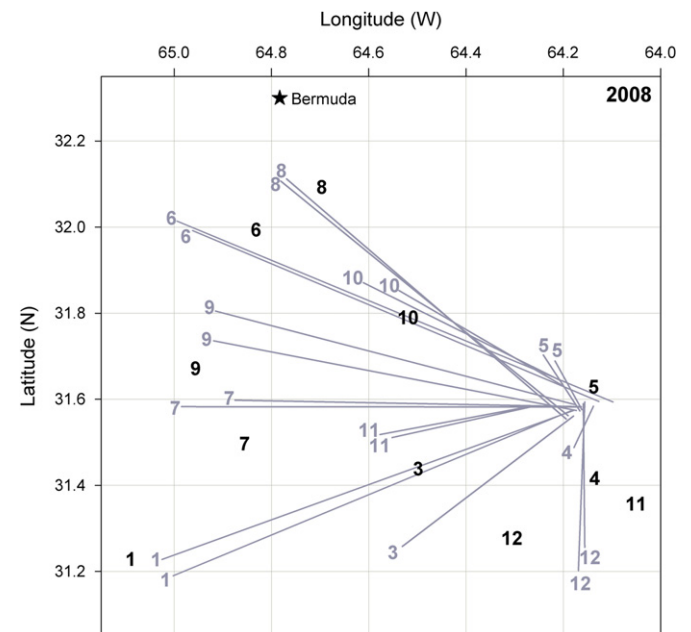

Fig. 9. Deployment and recovery positions for NBSTs in 2008 (in grey). Traps were deployed in the vicinity of 31.6°N × 64.15°W each month and the numbers correspond to the month of the year (e.g. January=1, February=2, etc.). The grey lines are not the exact tracks taken by the NBSTs but are the direct paths from the deployment to the recovery positions. PITs were close in time to the NBSTs, in the same general vicinity. Only the recovery positions of the PITs are shown (in black). The island of Bermuda is denoted with a star.

tethered and neutrally buoyant traps in the subtropical North Pacific (Siegel et al., 2008). In the North Pacific, although the spatial extent of the source funnels of the two trap types was similar, the source locations were spatially decoupled. Thus in our study, although the sampling locations of the NBSTs and PITs were similar, the source regions of the particles they collected may have been different. In January 2008, when a factor of 2.3 difference in POC fluxes was observed (Fig. 5), the final separation of the two trap systems was ~7.7 km, a relatively small distance after a 3.9 day deployment (Fig. 9). In contrast, in November 2008, the NBSTs were recovered west-by-south (~255°) of their deployment location while the PITs were recovered ~50 km away, south-southeast (154°) of their deployment location, yet the POC fluxes measured by the two systems were similar. No simple relationship between separation of recovery locations and difference in POC flux measured by the two systems was observed when all the data were considered.

Data were also examined to determine if mesoscale eddies, which have been shown to affect particle export, might have influenced measurements of export by the PITs and NBSTs during this study (Sweeney et al., 2003; Buesseler et al., 2008a; Goldthwait and Steinberg, 2008). The mean weekly sea surface height (SSH) (Fig. A3; from Maps of Absolute Dynamic Topography provided by the Archiving, Validation, and Interpretation of Satellite Data in Oceanography program) for the period of this study was 62 ± 11 cm. None of the anomalous periods corresponded with significant changes in SSH that would indicate the passage of eddies through the BATS region. Thus, we do not suspect that in-eddy versus out-of-eddy sampling was a cause for the differences between the NBSTs and PITs in any of these periods.

4.3.4. Particle composition

Elemental and mass ratios of the sample material from the NBSTs and PITs were compared to assess whether particles of the same composition were collected by each system. On average, the C:N ratio measured by the PITs was 6.6 ± 0.9 compared to an average C:N measured by the NBSTs of 7.0 ± 2.7 (excluding November 2009). The largest difference occurred in November 2009, when the particulate nitrogen flux measured by the NBSTs was very low, which resulted in elevated C:N ratios. The mean ratios are not significantly different (Student's t-test with equal variance, $P < 0.01$) and do not suggest any obvious particle sorting differences between the two trap types. The POC:mass ratios also agreed well between the PITs and NBSTs over the time-series (Student's t-test with equal variance, $P < 0.01$). Preserved and unfiltered PITs and NBST samples from the three periods in question were examined with microscopy but there were no obvious differences in bulk composition of the samples.

4.3.5. Summer flux peaks

Large differences in the PITs and NBSTs were observed from June to September 2007 (I), a period during the seasonal carbon cycle at BATS not typically thought to be associated with significant increases in particle flux. The highest values (40–105 mg C m^{-2} d^{-1}) of POC flux measured at BATS by the PITs are associated with a bloom that occurs in the February to April period, caused by entrainment of nutrient-rich water by a deep winter mixed layer and subsequent shoaling of the mixed layer in the spring. The average PITs POC flux at 150 m in June to September from 1989 to 2009 was 25.1 ± 5.6 mg C m^{-2} d^{-1} compared to 2007 when it was 35.9 ± 5.5 mg C m^{-2} d^{-1} in the PITs, the highest value ever recorded for this period at BATS. Though 2007 has the highest mean flux for this four-month period, higher POC fluxes were observed in July 1989 (42.7 mg C m^{-2} d^{-1}) and August 1998 (42.9 mg C m^{-2} d^{-1}) compared to July and August 2007 (40.9 mg C m^{-2} d^{-1} and 40.0 mg C m^{-2} d^{-1}, respectively). Nutrient concentrations are typically below detection limits of conventional methods in the summer at BATS (Steinberg et al.,

2001) and this holds true for 2007 to 2010. Diatom blooms have occurred in the late spring or summer at BATS (Steinberg et al., 2001), though not in the years with increased summer fluxes (1989, 1998, or 2007). These blooms were associated with increases in the diatom pigment, fucoxanthin, and enhanced biogenic silica fluxes but not with increases in POC flux (Brzezinski and Nelson, 1995; Nelson and Brzezinski, 1997). There were no significant changes in euphotic-zone integrated fucoxanthin stocks or biogenic silica flux in the NBSTs (Fig. A1) in the summer of 2007 to suggest the occurrence of a diatom bloom. Though the 2007 summer period is not unique in its elevated POC flux, there is no evidence of a bloom nor a clear physical or biogeochemical explanation for why the NBSTs would collect less POC flux than the PITs during this period.
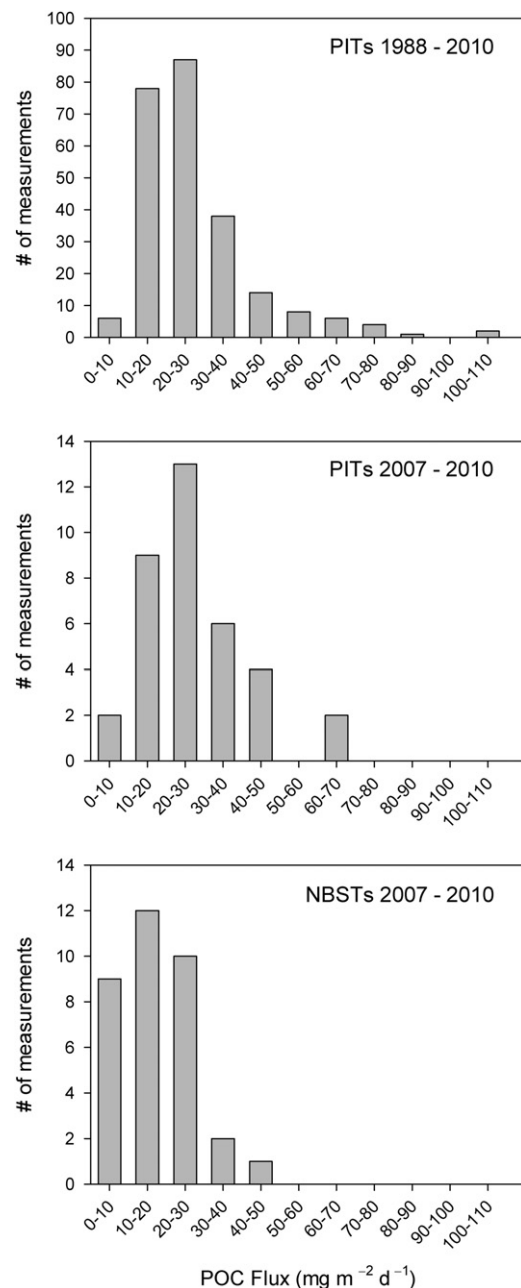

Fig. 10. The frequency of POC flux values measured by the PITs from 1988 to 2010 ($n=244$; top panel), during the period of this study ($n=36$; middle panel), and by the NBSTs during this study ($n=34$; bottom panel).

4.3.6. Near-zero fluxes

In period II, the POC flux collected by the NBSTs was very close to zero (0.7 ± 0.5 mg C m^{-2} d^{-1}) compared to the PITs, which measured a POC flux of 9.0 ± 4.1 mg C m^{-2} d^{-1}. Over the entire BATS PITs record, there are only six periods in which the mean POC flux at 150 m is less than 10 mg C m^{-2} d^{-1}, two instances of which were during our study in December 2007 (I) and April 2010. From 2007 to 2010 however, the NBSTs collected mean POC fluxes less than 10 mg C m^{-2} d^{-1} on nine occasions (Fig. 10). One of the conclusions of a calibration exercise of PITs at BATS was that PITs over-collected during low flux periods (Buesseler et al., 1994). That study calculated that over a 4-day deployment, the PITs were flushed with approximately 6000 L of seawater and particles. Only a minimal amount of sheer-induced aggregation of small particles into sinking particles would have to take place during the trap deployment to cause a positive bias in the flux measurements. Thus it may not be surprising that measured flux is rarely less than 10 mg C m^{-2} d^{-1}. As neutrally buoyant devices, the NBSTs should experience little shear over the mouth of the traps, in theory minimizing this hypothesized bias, and allowing for the measurement of near-zero fluxes.

4.4. Consequences for the BATS carbon cycle

A one-dimensional carbon budget for BATS, constructed using data from the first five years of the time-series, revealed that the decrease in carbon stocks from spring to autumn were three times greater than the fluxes out of the system (Michaels et al., 1994). This imbalance was attributed to two factors: failure to include horizontal advection of carbon and/or underestimation of the sinking particle flux. Additional measurements of carbon transport by migrating zooplankton reduced the imbalance to a factor of 2.4 (Steinberg et al., 2000). With respect to under sampling of the POC flux, hydrodynamic biases on the traps were suspected to be the most significant problem, rather than swimmers or sample preservation. The comparison of NBSTs and PITs presented in this work does not support the hypothesis in Michaels et al. (1994) of under-collection of sinking material by sediment traps at BATS. Adopting

the notation used by Michaels et al. (1994), of mol C m^{-2} period^{-1} (April to December), the NBST data reduces the sinking flux from 0.55 mol C m^{-2} period^{-1} to 0.40 mol C m^{-2} period^{-1}. The POC flux measured by the PITs during the period of this study was 0.56 mol POC m^{-2} period^{-1}. PIC data for the PITs was not available for this period, so using the NBST PIC value of 0.03 mol C m^{-2} period^{-1}, the PITs C flux value becomes 0.59 mol C m^{-2} period^{-1} or as low as 0.52 mol C m^{-2} period^{-1} if we apply a blank correction as in Fig. 8b. The NBST and PITs data together suggest that the observed carbon imbalance at BATS cannot be accounted for by undersampling of sinking carbon flux by these sediment traps.

The differences in the PITs and NBST data also have consequences for the export ratios (e-ratios) measured at BATS. For the NBST data set, e-ratios cluster between 2% and 5% (mean $4.9 \pm 3.8\%$) except for April 2008 and March, May, and July 2010 when the e-ratios are greater than 10% (Fig. 8a). To compare, the average e-ratio based on the PITS data (Fig. 8b, white and grey) was $7.7 \pm 3.5\%$ before blank correction and $6.2 \pm 3.4\%$ afterwards (Fig. 8b, black). The only remaining months in the PITs data with export ratios higher than 10% are April 2008 and March 2010, in agreement in with the NBST data. Three of the four highest export ratios were measured by the NBSTs in spring 2010, which was preceded by a winter of particularly deep mixing (Fig. 11). These increased e-ratios do not appear to be related to changes in particulate mineral composition (Fig. 11), consistent with Salter et al. (2010), and suggest that there is some unknown driver other than ballast for these highly efficient flux events.

5. Summary and conclusions

This study represents the first successful use of neutrally buoyant sediment trap technology in a time-series capacity, with 77 deployments of NBSTs at the BATS site between 2007 and 2010. NBST deployment and recovery operations were swift and less time was spent with wires under tension compared to surface-tethered trap operations. The sample processing regime of screening, combining tubes, and splitting the samples allowed for elucidation of multiple parameters with replication, thus providing details on the
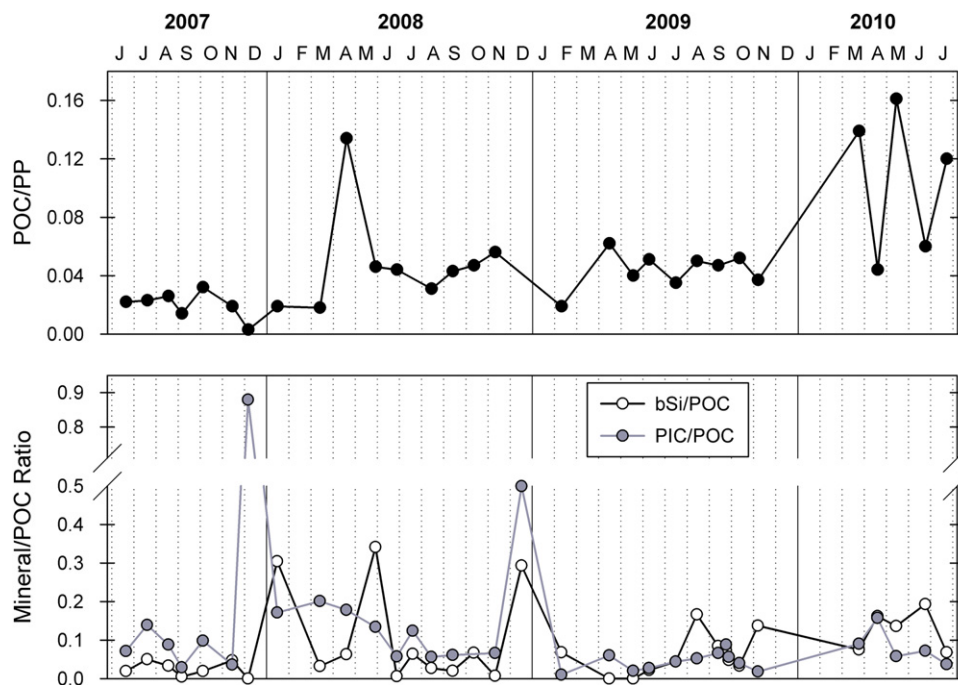

Fig. 11. Export ratio (POC flux at 150 m/integrated primary production, 0–140 m) versus time (top panel) and mineral (inorganic carbon or biogenic silica) to POC ratios versus time for NBSTs at BATS. Changes in export ratio were not associated with changes in mineral composition of the sinking particles.

composition of the sinking particle flux each month. Swimmer removal from trap samples was an important sample-processing step, as swimmers contributed significantly to the total collected flux. Screening and wet-picking methods were found to be comparable, however screening was adopted as the preferred method as it was less time consuming and conducive to the splitting approach. Blank corrections of mass, silica, and carbon measurements with a sample-identical set of blank tubes were important, particularly at this site where the ambient particle flux is very low.

In most months, the NBSTs were comparable to the surface-tethered PITs within the range of variability for two NBSTs (≤ 2.2). In three periods during the time-series however, the difference in POC flux collected by the two systems was greater than a factor of three. Based on available data, these large differences were not attributable to hydrodynamic biasing, differences in trap sampling locations, or particle composition. In two months of the study, one corresponding to higher fluxes in the PITs than NBSTs, the sediment traps were deployed within deep winter mixed layers. Collection by traps in these regimes may be biased, thus data from these periods should be viewed with caution, as their inclusion would bias analyses of POC export in the BATS record. A second period of higher fluxes in the PITs than the NBSTs spanned four summer months in 2007. Though similarly high fluxes were measured in July 1989 and August 1998, there was no evidence of a bloom, which occurs at BATS after periods of deep mixing that enhance nutrient concentrations in the surface, or a community shift that may have led to increased POC flux. Finally, one period of large discrepancy between the PITs and NBSTs occurred when the POC flux measured by the NBSTs was very close to zero, lower than any flux measurement by PITs in the entire BATS record. More frequent sampling of very low POC fluxes by the NBSTs in this study than by the PITs is consistent with earlier studies that suggested that the PITs might have a positive bias during low flux periods due to shear-induced aggregation in the mouth of the traps.

This new examination does not support the hypothesis that the carbon imbalance in the Sargasso Sea is due to undersampling by the PITs. The NBST data set confirms that carbon export is low over the annual cycle and there can be years with little flux seasonal variability, as was observed in 2008 and 2009. Export ratios for the NBSTs ($4.9 \pm 3.8\%$) were lower than for the PITs ($7.7 \pm 3.5\%$), implying even lower efficiency of the biological pump.

Sediment traps are critical tools for directly sampling sinking particle flux and trap design has been shown to be important. Previous studies have detailed the advances of neutrally buoyant traps and we encourage further development of these devices including the incorporation of physical and biochemical sensors. As shown in this work however, methods used to process sediment trap samples are as important as trap design and deserve equal attention.

Acknowledgments

Appendix. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.dsr.2012.10.011.

References

Antia, A.N., 2005. Particle-associated dissolved elemental fluxes, revising the stoichiometry of mixed layer export. Biogeosci. Discuss. 2, 275–302.

Brzezinski, M.A., Nelson, D.M., 1995. The annual silica cycle in the Sargasso Sea near Bermuda. Deep-Sea Res. I 42 (7), 1215–1237.

Buesseler, K.O., Antia, A.N., Chen, M., Fowler, S.W., Gardner, W.D., Gustafsson, O., Harada, K., Michaels, A.F., van der Loeff'o, M.R., Sarin, M., Steinberg, D.K., Trull, T., 2007. An assessment of the use of sediment traps for estimating upper ocean particle fluxes. J. Mar. Res. 65 (3), 345–416.

Buesseler, K.O., Lamborg, C., Cai, P., Escoube, R., Johnson, R., Pike, S., Masque, P., McGillicuddy, D., Verdeny, E., 2008a. Particle fluxes associated with mesoscale eddies in the Sargasso Sea. Deep-Sea Res. II 55 (10–13), 1426–1444.

Buesseler, K.O., McDonnell, A.M.P., Schofield, O.M.E., Steinberg, D.K., Ducklow, H.W., 2010. High particle export over the continental shelf of the west Antarctic Peninsula. Geophys. Res. Lett. 37 (L22606).

Buesseler, K.O., Michaels, A.F., Siegel, D.A., Knap, A.H., 1994. A three dimensional time-dependent approach to calibrating sediment trap fluxes. Global Biogeochem. Cycles 8 (2), 179–193.

Buesseler, K.O., Pike, S., Maiti, K., Lamborg, C.H., Siegel, D.A., Trull, T.W., 2008b. Thorium-234 as a tracer of spatial, temporal and vertical variability in particle flux in the North Pacific. Deep-Sea Res. I 56 (7), 1143–1167.

Buesseler, K.O., Steinberg, D.K., Michaels, A.F., Johnson, R.J., Andrews, J.E., Valdes, J.R., Price, J.F., 2000. A comparison of the quantity and composition of material caught in a neutrally buoyant versus surface-tethered sediment trap. Deep-Sea Res. I 47 (2), 277–294.

Cochran, J.K., Miquel, J.C., Armstrong, R., Fowler, S.W., Masqué, P., Gasser, B., Hirschberg, D., Szlosek, J., Rodriguez y Baena, A.M., Verdeny, E., Stewart, G., 2009. Time-series measurements of Th-234 in water column and sediment trap samples from the northwestern Mediterranean Sea. Deep-Sea Res. II 56 (18), 1487–1501.

Ducklow, H.W., Doney, S.C., Steinberg, D.K., 2009. Contributions of long-term research and time-series observations to marine ecology and biogeochemistry. Annu. Rev. Mar. Sci. 1, 279–302.

Eppley, R.W., 1989. New production: history, methods, and problems. In: Berger, W.H., Smetacek, V.S., Wefer, G. (Eds.), Productivity of the Ocean: Present and Past. Wiley & Sons, New York, pp. 85–97.

Gardner, W.D., 1985. The effect of tilt on sediment trap efficiency. Deep Sea Res. 32, 349–361.

Gardner, W.D., 2000. Sediment trap sampling in surface waters. In: Hanson, R.B., Ducklow, H.W., Field, J.G. (Eds.), The Changing Ocean Carbon Cycle: A midterm synthesis of the Joint Global Ocean Flux Study. Cambridge University Press, Cambridge, UK, pp. 240–281.

Gardner, W.D., Richardson, M.J., 1992. Particle export and resuspension fluxes in the western North Atlantic. In: Rowe, G.T., Pariente, V. (Eds.), Deep-Sea Food Chains and the Global Carbon Cycle. Kluwer Academic Publishers, Netherlands, pp. 339–364.

Gleiber, M.R., Steinberg, D.K., Ducklow, H.W. Time series of vertical flux of zooplankton fecal pellets on the continental shelf of the West Antarctic Peninsula. Mar. Ecol. Prog. Ser., http://dx.doi.org/10.3354/meps10021, in press.

Goldthwait, S.A., Steinberg, D.K., 2008. Elevated biomass of mesozooplankton and enhanced fecal pellet flux in cyclonic and mode-water eddies in the Sargasso Sea. Deep-Sea Res. II 55, 1360–1377.

Gust, G., Bowles, W., Giordano, S., Huettel, M., 1996. Particle accumulation in a cylindrical sediment trap under laminar and turbulent steady flow, An experimental approach. Aquat. Sci. 58, 297–326.

Honjo, S., Francois, R., Manganini, S., Dymond, J., Collier, R., 2000. Particle fluxes to the interior of the Southern Ocean in the Western Pacific sector along 170°W. Deep-Sea Res. II 47, 3521–3548.

Johnson, K.M., King, A.E., Sieburth, J.M., 1985. Coulometric TCO_2 analyses for marine studies—an introduction. Mar. Chem. 16, 61–82.

Karl, D.M., Christian, J.R., Dore, J.E., Hebel, D.V., Letelier, R.M., Tupas, L.M., Winn, C.D., 1996. Seasonal and interannual variability in primary production and particle flux at Station ALOHA. Deep-Sea Res. II 43 (2–3), 539–568.

Knap, A.H., Michaels, A.F., Steinberg, D.K., Bahr, F., Bates, N.R., Bell, S., Countway, P., Close, A., Doyle, A., Howse, F., Gundersen, K., Johnson, R.J., Little, R., Orcutt, K., Parsons, R., Rathbun, C., Sanderson, M., Stone, S., 1997. BATS Methods Manual. US JGOFS Planning Office, Woods Hole.

Knauer, G.A., Martin, J.H., Bruland, K.W., 1979. Fluxes of particulate carbon, nitrogen, and phosphorus in the upper water column of the northeast Pacific. Deep-Sea Res. 26 (1), 97–108.

Lamborg, C.H., Buesseler, K.O., Valdes, J., Bertrand, C.H., Bidigare, R., Manganini, S., Pike, S., Steinberg, D., Trull, T., Wilson, S., 2008. The flux of bio- and lithogenic material associated with sinking particles in the mesopelagic "twilight zone" of the northwest and North Central Pacific Ocean. Deep-Sea Res. II 55 (14–15), 1540–1563.

Lampitt, R.S., Boorman, B., Brown, L., Lucas, M., Salter, I., Sanders, R., Saw, K., Seeyave, S., Thomalla, S.J., Turnewitsch, R., 2008. Particle export from the euphotic zone: estimates using a novel drifting sediment trap, Th-234 and new production. Deep-Sea Res. I 55 (11), 1484–1502.

Lee, C., Hedges, J.I., Wakeham, S.G., Zhu, N., 1992. Effectiveness of various treatments in retarding microbial activity in sediment trap material and their effects on the collection of swimmers. Limnol. Oceanogr. 37 (1), 117–130.

Martin, J.H., Knauer, G.A., Karl, D.M., Broenkow, W.W., 1987. VERTEX: carbon cycling in the northeast Pacific. Deep-Sea Res. Pt. A 34 (2), 267–285.

McDonnell, A.M.P., Buesseler, K.O. 2012. A new method for the estimation of sinking particle fluxes from measurements of particle size distribution, sinking velocity, and carbon density. Limnol. Oceanogr. Methods, 10, 329–346.

Michaels, A.F., R., B.N., Buesseler, K.O., Carlson, C.A., Knap, A.H., 1994. Carbon-cycle imbalances in the Sargasso Sea. Nature 372, 537–540.

Michaels, A.F., Silver, M.W., Gowing, M.M., Knauer, G.A., 1990. Cryptic zooplankton "swimmers" in upper ocean sediment traps. Deep-Sea Res. I 37 (8A), 1285–1296.

Nelson, D.M., Brzezinski, M.A., 1997. Diatom growth and productivity in an oligotrophic midocean gyre: a 3-yr record from the Sargasso Sea near Bermuda. Limnol. Oceanogr. 42 (3), 473–486.

Salter, I., Kemp, A.E.S., Lampitt, R.S., Gledhill, M., 2010. The association between biogenic and inorganic materials and the amino acid composition of settling particles. Limnol. Oceanogr. 55 (5), 2207–2218.

Salter, I., Lampitt, R.S., Sanders, R., Poulton, A., Kemp, A.E.S., Boorman, B., Saw, K., Pearce, R., 2007. Estimating carbon, silica and diatom export from a naturally fertilised phytoplankton bloom in the Southern Ocean using PELAGRA: a novel drifting sediment trap. Deep-Sea Res. II 54 (18–20), 2233–2259.

Siegel, D.A., Fields, E., Buesseler, K.O., 2008. A bottom-up view of the biological pump: modeling source funnels above ocean sediment traps. Deep-Sea Res. I 55, 108–127.

Sprintall, J., Tomczak, M., 1992. Evidence of the barrier layer in the surface layer of the tropics. J. Geophys. Res. 97, 7305–7316.

Stanley, R.H.R., Buesseler, K.O., Manganini, S.J., Steinberg, D.K., Valdes, J.R., 2004. A comparison of major and minor elemental fluxes collected in neutrally buoyant and surface-tethered sediment traps. Deep-Sea Res. I 51 (10), 1387–1395.

Steinberg, D.K., Carlson, C., Bates, N.R., Goldthwait, S.A., Madin, L.P., Michaels, A.F., 2000. Zooplankton vertical migration and the active transport of dissolved organic and inorganic carbon in the Sargasso Sea. Deep-Sea Res. I 47, 137–158.

Steinberg, D.K., Carlson, C.A., Bates, N.R., Johnson, R.J., Michaels, A.F., Knap, A.H., 2001. Overview of the US JGOFS Bermuda Atlantic Time-series Study (BATS): a decade-scale look at ocean biology and biogeochemistry. Deep-Sea Res. II 48, 1405–1447.

Steinberg, D.K., Pilskaln, C.H., Silver, M.W., 1998. Contribution of zooplankton associated with detritus to sediment trap "swimmer" carbon in Monterey Bay, CA. Mar. Ecol. Prog. Ser. 164, 157–166.

Sweeney, E.N., McGillicuddy Jr., D.J., Buesseler, K.O., 2003. Biogeochemical impacts due to mesoscale eddy activity in the Sargasso Sea as measured at the Bermuda Atlantic Time-series Study (BATS). Deep-Sea Res. II 50, 3017–3039.

Valdes, J.R., Price, J.F., 2000. A neutrally buoyant, upper ocean sediment trap. J. Atmos. Ocean Technol. 17 (1), 62–68.
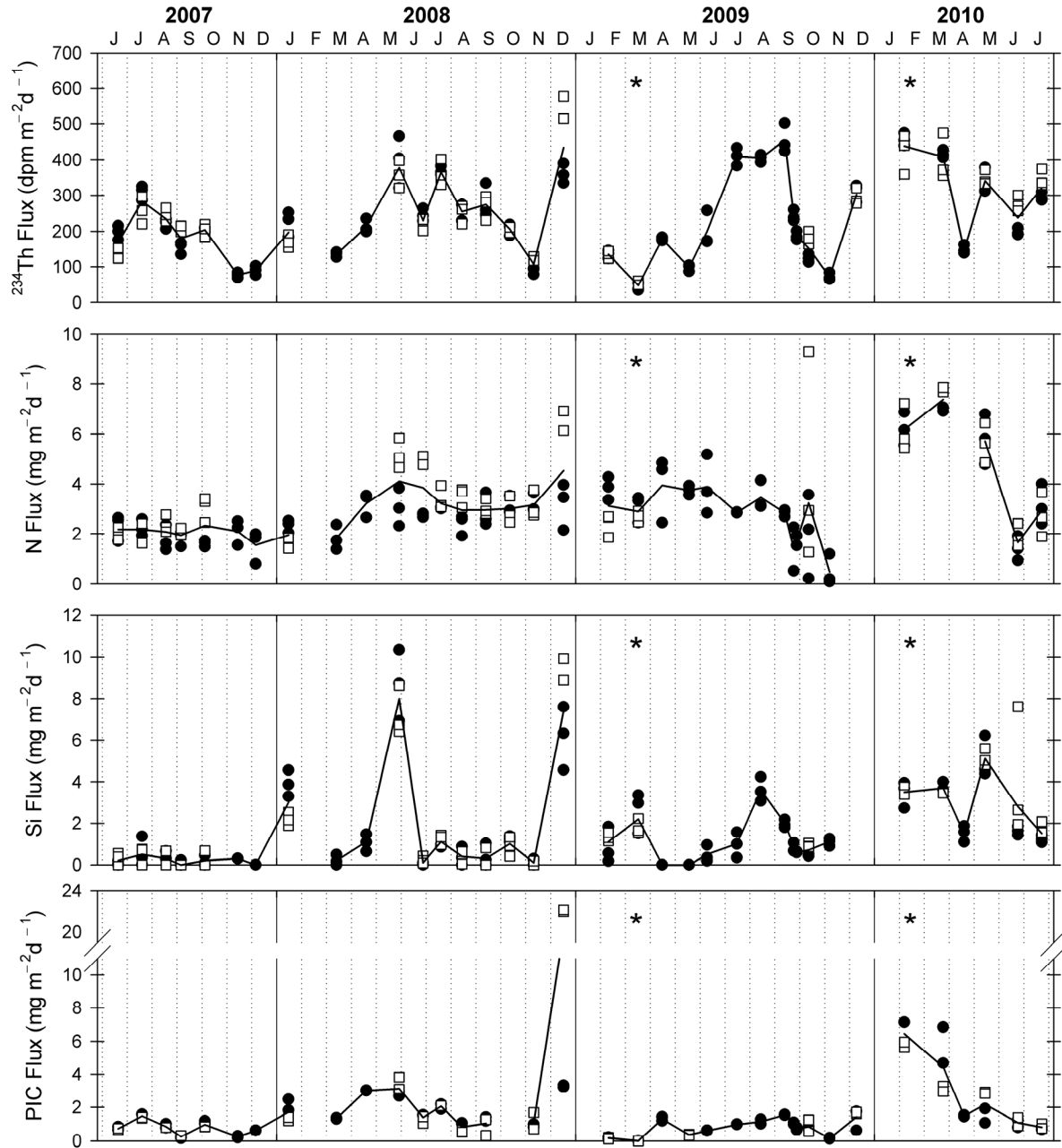
Supplemental Material

Figure A.1 – Th-234 flux, N flux, biogenic Si flux, and PIC flux captured by NBSTs at 150 m at the Bermuda Atlantic Time-series Study site. Two traps were deployed each month (circles and squares) and three replicates of each parameter were obtained (denoted by individual points). The solid black line in each figure is the average of the three replicates in the two traps. Stars above March 2009 and February 2010 denote months when the traps were in the mixed layer.
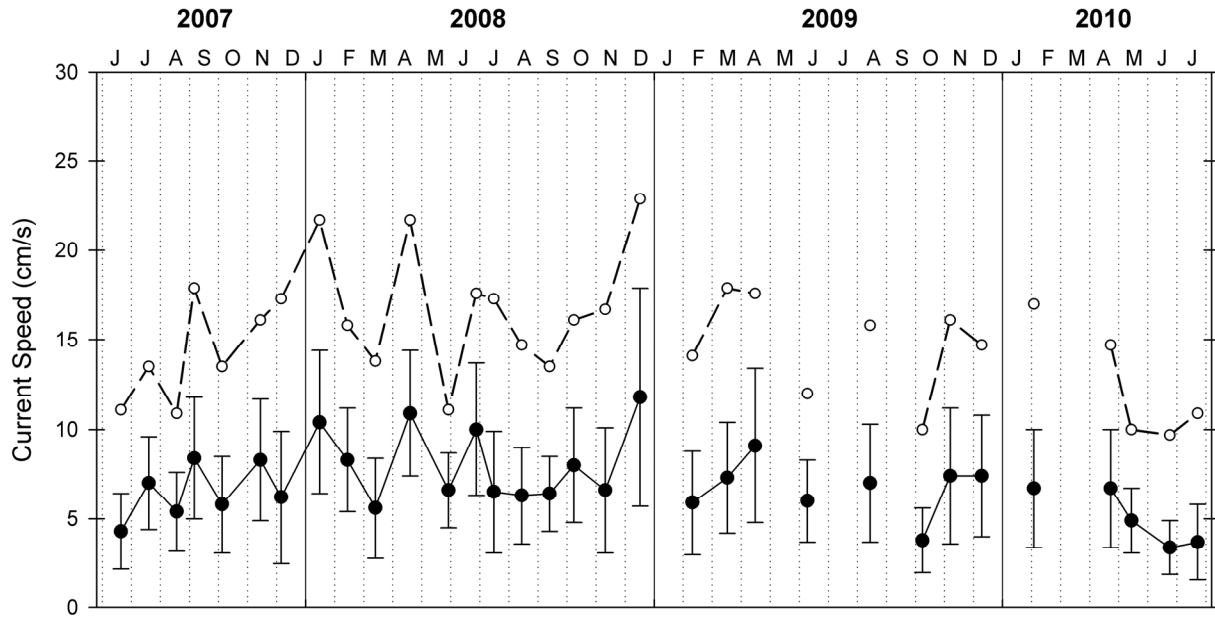
Figure A.2 – Average current speed from a current meter 15 m below the 150 m tubes on the PITs array (in black). The maximum current speed measured during deployment is also shown (in white).
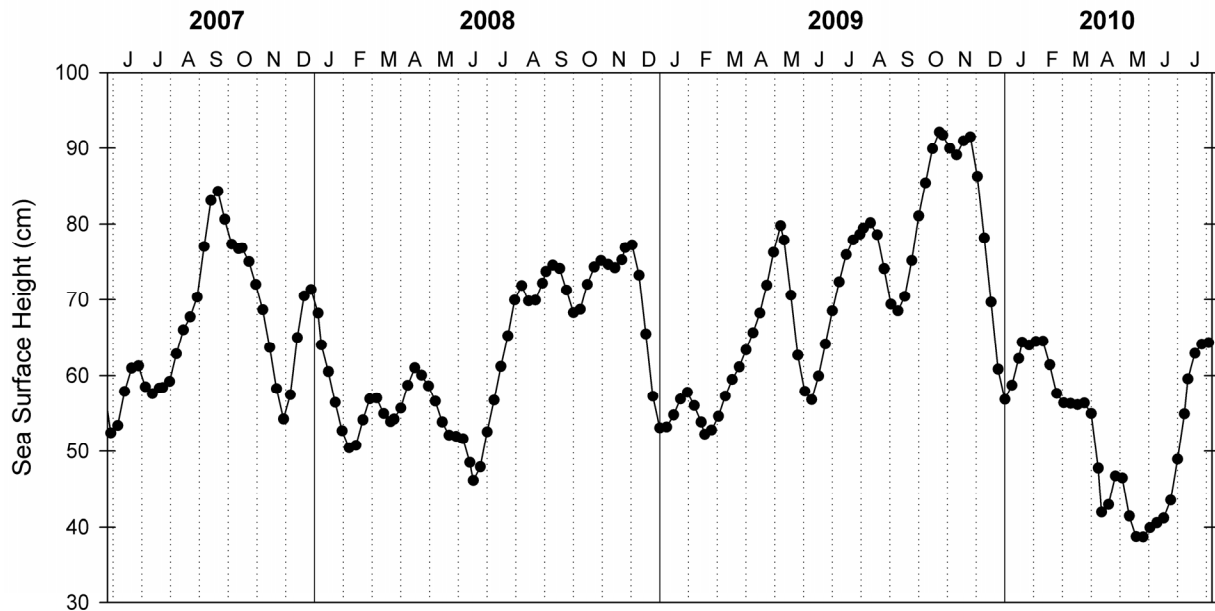

Figure A.3 – Weekly sea surface height at the BATS site during the course of this study.