A Neutrally Buoyant, Upper Ocean Sediment Trap

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ABSTRACT

The authors have designed and deployed a neutrally buoyant sediment trap (NBST) intended for use in the upper ocean. The aim was to minimize hydrodynamic flow interference by making a sediment trap that drifted freely with the ambient current. The principal design problem was to make the NBST descend to and stay near a prescribed depth. For a variety of reasons, the most success has been with NBSTs that were autoballasted by means of a microprocessor-controlled volume changer. Autoballasting NBSTs has demonstrated an ability to hold a prescribed depth to within 10 m.

There have been two successful, concurrent deployments of NBSTs and conventional surface-tethered sediment traps (STSTs) at the Bermuda Atlantic Times Series site. During both periods the observed flow past the STSTs was low, about 0.05 m s^{-1}, so that hydrodynamic effects on the STSTs would have been minimized. Comparisons of the trap results (described in a companion paper by Buesseler et al.) indicate that the total mass of collected material was generally similar in the two traps. Other variables, including the composition of the material and the fraction contributed by swimmers, were markedly different (swimmers are small animals that enter a trap intact and presumably alive). These are intriguing results but could not be conclusive since there is no absolute standard for such measurements. Future field work that includes comprehensive geochemical sampling will be required to learn which sediment trapping method yields the more useful observations.

1. Measuring the export flux in the upper ocean

The upper ocean budgets of most elements of biogeochemical significance include an export to the deep ocean associated with a slowly falling rain of biogenic particles. This material is highly heterogeneous, made up from fecal pellets, slime aggregations, etc., that fall at widely varying rates, from 1 to 1000 m day^{-1}. As this material falls through the water column it is also swept along with the ambient horizontal currents, which in the upper ocean are typically 0.2 m s^{-1}, or about 20 km day^{-1}. Thus the particle flux is directed almost horizontally. For many purposes the quantity of interest is the comparatively small *vertical* component of the flux, also called the export flux, since it will have a much larger divergence than does the horizontal component.

Much of what is known about the export flux has resulted from collecting samples in simple, open-top cylinders (Knauer et al. 1979; U.S. GOFS 1989), usually termed ''sediment traps,'' though only a small fraction of the upper ocean export flux survives to the seafloor. These sediment traps are the geochemist's equivalent of rain gauges and are attached either to moorings (deep ocean deployments; Deuser and Ross 1980; Deuser 1986; Honjo et al. 1995; Gardner et al. 1997) or are tethered from surface drifters (upper ocean deployments; Michaels et al. 1994). The ongoing Bermuda Atlantic Time-Series Study (BATS) utilizes surface-tethered sediment traps (STSTs) to sample the upper ocean particle flux, and similar investigations are a necessary component of any comprehensive upper ocean carbon budget (e.g., Murray et al. 1997; Rodier and Le Borgne 1997). BATS investigators have found that the carbon budget evaluated in part from STST data cannot be balanced to the lowest order (Michaels et al. 1994). The spring-to-fall change in total carbon stock in the upper 150 m has shown a decrease that is about three times the size of the STST-inferred export flux on sinking particles. Thus there appears to be a significant, missing sink for carbon during at least a portion of one year. The missing sink could arise from 1) an unknown and thus unaccounted process, 2) horizontal advection due to low-frequency currents (unlikely to be the sole cause, Carlson et al. 1994), or, more prosaically, 3) a substantial inaccuracy of the STST-measured export flux. A considerable body of indirect evidence points to the latter. Consistency checks made between measured thorium (Th) scavenging and STST thorium collection (Buesseler 1991; Buesseler et al. 1994), and between different kinds of sediment trap data (Quay 1998) often show unexplained differences of up to a factor of

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3 or more. In some seasons at some sites STSTs appear to overcollect material and on other occasions they appear to undercollect (based upon thorium budgets; Buesseler 1991).

Taken at face value, these results suggests that there is at least one important ''hidden'' (unmeasured) variable affecting STST sampling, and a likely candidate is a particle- and current speed–dependent collection efficiency [Gardner (1999)]. Ambient horizontal currents[1] tend to set up standing eddies that bring a very large volume of seawater into contact with the trap, and with it the potential for biased sampling of the export flux due to sorting on particle fall speed (Gardner 1985; Baker et al. 1988; Gardner and Zhang 1997). Small tilts of the sediment trap or motions caused by the mooring line may also be important (Gardner 1985; Gust et al. 1992; Gust et al. 1994). These phenomenon can be studied in some detail under controlled laboratory conditions (Butman 1986; Butman et al. 1986), but their effects cannot be removed from oceanographic observations because of the difficulty of simultaneously acquiring the relevant data, especially the distribution of particle sinking speeds.

The ambient flow past an upper ocean sediment trap would be greatly reduced if the trap were small and freely drifting, that is, not attached to a surface drifter. The present development effort has been guided by the neutrally buoyant sediment trap (NBST) hypothesis—a neutrally buoyant and freely drifting sediment trap will yield a more accurate estimate of the upper ocean export flux than does a conventional STST trap.[2] As we will discuss further in section 5, this hypothesis cannot be tested directly at this time, and hence it is worthwhile to consider the associated null hypothesis—concurrent STST and NBST deployments will collect equivalent samples. This is testable directly, though one might suspect not very interesting given the checkered history of upper ocean sediment trapping.

The desirability of an upper ocean NBST was recognized at least as long ago as U.S. JGOFS (1989), but the technical obstacles to making a usable NBST were sufficient to delay their full realization until fairly recently [Diercks and Asper (1994) describe one of the first development efforts]. We began the design of an NBST prototype (section 2) in 1995 using technology and methods that have been developed for neutrally buoyant float systems intended mainly for physical oceanography studies (Davis et al. 1992; Simonetti 1998; Duda et al. 1988). The resulting prototypes have been deployed on several occasions as part of the ongoing monthly cruises of the BATS program, and we have acquired some valuable experience in their use at sea (section 3), some of which has led to important design changes. Our scientific objective was to compare the sediment catch from NBSTs with that from the STSTs used routinely at BATS (section 4). We have found significant and somewhat surprising differences, though the end of the upper ocean sediment trapping problem is not yet in clear sight (section 5).

2. Design of a neutrally buoyant sediment trap

a. Mission requirements for an upper ocean NBST

For use at BATS or in other upper ocean sediment trapping programs, the nominal mission is a 2–5-day deployment at a depth of roughly 100–500 m. The operating depth should be accurate to within about 10 m and known after the fact from measured pressure. At the end of the mission, the NBST should return promptly to the surface for recovery. The trap contents will have to be protected from flushing while the NBST is ascending from depth and while on the surface pending recovery. The NBST should transmit some sort of signal while on the surface to expedite relocation. Finally, a fully developed NBST should be affordable in modest numbers, and it should be readily usable by investigators who are not familiar with the many subtleties of neutrally buoyant floats.

b. The NBST prototype

The prototype NBSTs were kept as simple as possible, consistent with the mission requirements, and were built from off-the-shelf components. The hull of the NBST is an aluminum cylinder 128 cm long by 11 cm in diameter that houses the batteries, controller, environmental sensors (pressure and temperature), and in one version, an autoballasting device that controls operating depth (Figs. 1 and 2). The hull also has to provide the buoyancy needed to support four sediment trap tubes, VERTEX-style acrylic cylinders (Knauer et al. 1979) that are 66 cm long by 7.5 cm in diameter [these are also called Particle Interceptor Traps (PITs)]. An NBST

[1] The ambient current past an STST trap will usually be reduced significantly compared to the horizontal current measured at a fixed point since the trap assembly (surface float, tether, and sediment trap array) will drift along at some vertical average of the horizontal current. The currents measured from (relative to) STST traps deployed at BATS are typically in the range 0.05 to 0.2 m s^{-1} (Johnson et al. 1991). In the equatorial Pacific where the upper ocean current is highly sheared vertically, the currents measured at the depth of a STST trap can be much larger, up to 0.5 m s^{-1} (Rodier and Le Borgne 1997).

[2] The horizontal flow past a neutrally buoyant instrument will be the order of the rms vertical shear over the length of the instrument, about 1.2 m in the present case. For nominal upper ocean stratification, $N = 5 \times 10^{-3}$ rad s^{-1}, the Garret–Munk spectrum indicates rms shear of $O(4 \times 10^{-3}\ s^{-1})$ due to internal wave motions so that the relative horizontal current should be $O(4 \times 10^{-3}\ m\ s^{-1})$ (Duda and Webb 1997, who show measurements on a 10-m-scale instrument). Shear due to low-frequency motions would be added (randomly) to this, but would generally be smaller, except in special circumstances as in the Equatorial Undercurrent. The Reynolds number based upon the tube diameter would then be $O(300)$, so that the flow past a small, freely drifting NBST should be laminar most of the time.

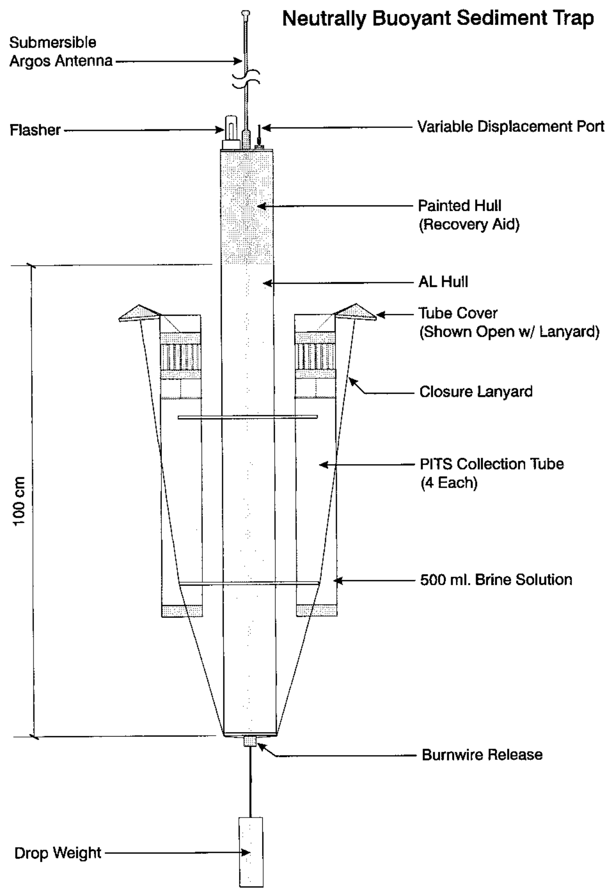

FIG. 1. Schematic of the prototype NBST showing the major external components. Only two sediment trap tubes are shown here; four are usually attached. The tube covers are shown in the open position, as they would be during a mission, held by a lanyard attached to the burnwire release. When the burnwire is activated, the drop weight (≈2 kg) and the cover lanyard are released and the covers are pulled into a closed position by an elastic cord attached inside the tube. These tubes are otherwise identical to the PIT tubes used in the conventional STST.

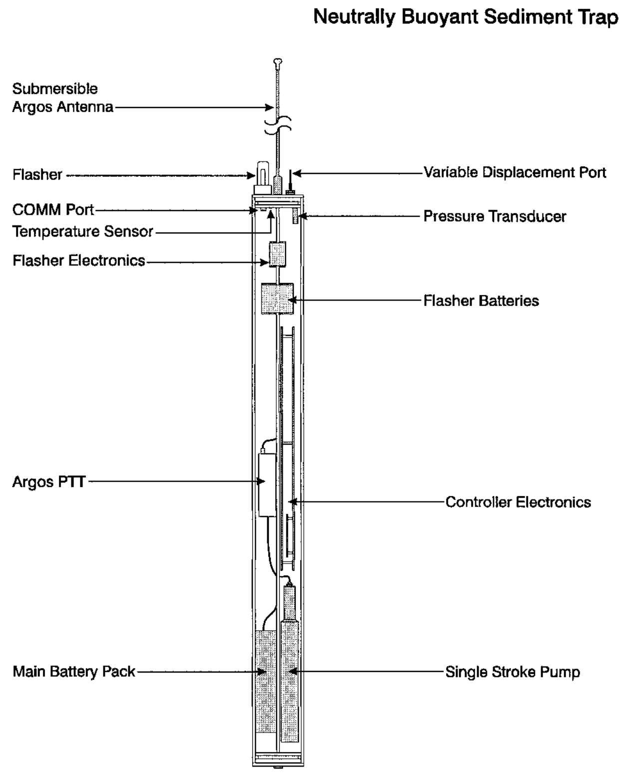

FIG. 2. Internal components of the NBST. The port for the variable displacement device is connected to the single-stroke pump and is freely flooded by seawater.

configured for deployment has a mass of 16.5 kg, and can be easily handled by two people.

The present aluminum hull limits the operating depth to about 500 m. The first prototype NBST was constructed with a glass hull, similar to that of an RAFOS float. Glass has several significant advantages as a hull material, including that glass hulls are capable of operation at depths of as much as 4000 m. However, in our experience, glass hulls are probably not sufficiently rugged for routine, repeated use at sea (section 3a).

The controller is an Onset Computer Corporation Model TT4 datalogger that was chosen on the basis of cost and low power consumption. Typical current drain is about 40 μA while the instrument is asleep (during shipment, say), and about 1 mA while on a mission. The present battery pack is sufficient for about five missions of up to 5 days each or a single mission of 30-day duration. The controller logs the in situ temperature and pressure along with various housekeeping parameters on an hourly basis. These may be downloaded immediately after recovery to determine the history of a mission. The controller also monitors the ''health'' of the NBST and can terminate the mission early if a serious problem is detected. For example, if the controller detects that the battery voltage is falling below acceptable limits or that the NBST has gone too deep, it will terminate the mission (an example is shown below).

The conclusion of a nominal mission is determined by elapsed time or date, at which point the NBST releases a drop weight, which causes it to come to the surface promptly. An Argos transmitter and a flasher facilitate relocation and recovery of the instrument once it is on the surface. The drop weight is released by burning through a wire that also restrains the trap covers. The tubes are thus closed before ascent, protecting the samples from flushing while the NBST is on the surface pending recovery.

Before deployment the tubes are filled to a depth of about 15 cm with a dense, highly saline (≈90 ppt) brine solution including 2% formalin, and then filled the rest of the way with seawater taken from the target operating depth. This provides a known aspect ratio of the brine-free tube (Gardner and Zhang 1997) and serves to preserve the collected material while also providing some protection from scavengers.

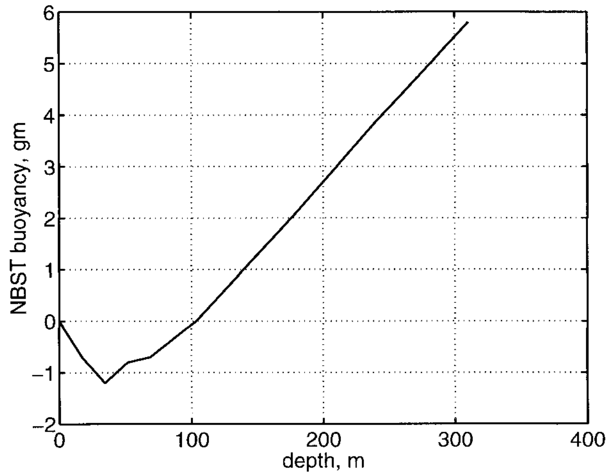

FIG. 3. Typical ballasting data for an NBST. Buoyancy is the measured weight of an NBST that is inside a pressure vessel filled with water. The pressure (here converted to depth) was increased while the weight of the NBST was measured and recorded. Note the marked change in the slope of the curve at around 50 m. This occurred when compressible material on the NBST (entrapped air, O-ring seals on the aluminum hull, elastic cords, etc.) had collapsed to a negligible volume. At still greater depths, the buoyancy changes of the NBST were as expected for an aluminum cylinder, that is, buoyancy increased with increasing depth. A purely passive float can operate stably only in a depth range where its compressibility is *less* than that of the ambient seawater, the region of positive slope on this curve, so that it gains buoyancy with increasing depth.

c. Ballasting

The greatest challenge was to make the NBST operate at a prescribed depth. Because the instrument is fairly small, it has an extraordinary sensitivity to weight (or volume) changes; a 1-g change in weight (or 1-cc change in volume) causes a roughly 40-m change in depth. For many applications a depth error of 40 m would be excessive. In any event, ballasting of a passive instrument to this precision is extremely difficult because the sediment traps and their associated closure mechanism are very likely to entrap air bubbles within crevices. The compressibility of an NBST is thus a rather awkward function of depth. An example is in Fig. 3, which shows the measured buoyancy of an NBST as a function of pressure (here converted to depth in meters for consistency with other figures). For increasing depth less than about 50 m, the NBST buoyancy decreases as air or other highly compressible material is compressed (i.e., the NBST is more compressible than seawater). By about 50 m all of the readily compressible material has been squeezed to negligible volume, and at still greater depths the NBST gains buoyancy since it is then less compressible than seawater. Because of this marked change in compressibility, an NBST could be neutrally buoyant at two different depths in the range from 0 to about 100 m. This makes neutrally buoyant operation in the upper ocean especially challenging. Still another complication arises from the hypersaline solution used to preserve samples. This solution has a weight of about 42 g in situ (four tubes) and is liable to be lost partially during the launch of instrument in high seas. (The weight of the accumulating sample is by comparison small and not a major factor for ballasting.) For these and other reasons it is very difficult to make a purely passive NBST operate at a prescribed depth, and indeed we have succeeded in doing so only once while failing on several other attempts.

The NBST ballasting problem has been solved, apparently, by adding a controllable buoyancy system consisting of a single-stroke piston pump that is driven by an electric motor, reminiscent of the volume changer (VOCHA) developed by Rossby et al. (1994) for use on RAFOS floats. Volume changes are commanded by the controller using measured pressure and an algorithm that was developed during extensive laboratory testing of the pump and controller. This autoballasting technique has proved to be reliable and highly effective, and is recommended for all future NBSTs. The volume changer used in the prototypes described here had a very limited dynamic range, only about 12 cc, so that very careful, predeployment ballasting at in situ pressures was required for the prototype NBSTs. We hope to eliminate the need for rigorous predeployment ballasting in the next generation of NBSTs by using a pump with a much larger dynamic range (section 5).

3. Field trials and lessons learned

a. Failures

We have deployed NBST prototypes at BATS seven times and have lost three instruments. One early glass-hulled NBST sank after a minor collision with the ship during deployment in rough seas. This caused a small but fatal leak, which convinced us to use aluminum hulls on all subsequent instruments. On the second trial we deployed and lost two NBSTs that had a new, high-voltage flasher that was intended to aid nighttime recovery. Prolonged bench-testing of this design revealed that electrical interference due to the flasher could lead to a rare, intermittent failure of the controller. The flasher was omitted from two instruments prepared for the third deployment, both of which functioned normally (though a passive NBST suffered from a ballasting error, as we will recount shortly). The flasher has since been added back to the design, but now segregated from the controller (Fig. 2).

Aside from these important design changes, the other lesson learned from these failures was to be reminded of the old oceanographer's adage ''never put anything over the side of a ship that you cannot afford to lose.'' This applies in full strength to NBSTs since they are freely drifting and autonomous during their missions. Internal failure of the electronics or batteries, etc., will thus result in the unexplained loss of the instrument and its samples. It is essential that NBSTs remain simple

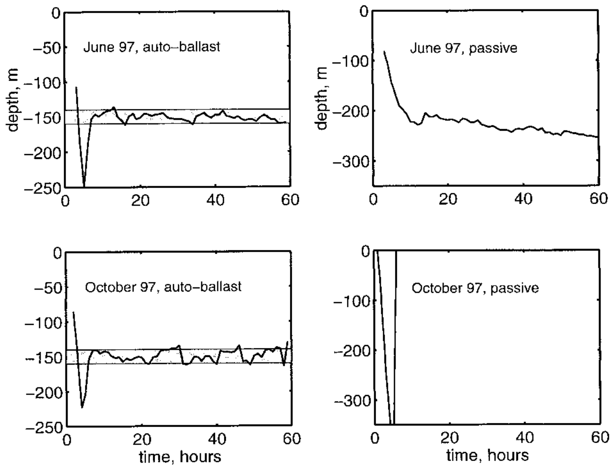

FIG. 4. NBST depth computed from internally recorded pressure during the June and October deployments. The autoballasting NBST (left panels) remained within its programmed depth range (140–160 m), while the passive NBSTs either drifted downward slowly (June 1997) or overshot the target depth due to a ballasting error of about 3 g (October 1997). In the latter case the NBST aborted its mission as it passed through 360 m and returned to the surface.

and affordable, so that the loss of one or several instruments will not cause the demise of a complete program.

b. Successes

The first completely successful NBST deployment occurred in June 1997 when two instruments were deployed, one targeted at 150 m and the other at 200 m. The first instrument included the only available autoballast mechanism, while the second instrument (200 m) was passive (no autoballast). The autoballasting NBST was given a predeployment ballasting for 200 m, so that it would descend well below the bistable range of Fig. 3, and thus it appeared to be somewhat heavy at launch (Fig. 4, upper left). The data from the internal logger shows that the instrument began to make ballasting adjustments as it passed through its target depth, 150 m, and that it quickly acquired depth control and remained near its nominal operating depth for the duration of the mission. The passive, 200-m NBST (Fig. 4, upper right) settled at about 200 m (rather surprisingly given the ballast sensitivity) and then slowly settled to 250 m over the term of the mission. This slow descent was probably due to trapped air dissolving into the water. Both of these instruments were readily relocated and recovered once they returned to the surface at the programmed end of their missions, and collection of the samples was routine.

Two NBSTs were again deployed in October 1997, one targeted at 150 m (autoballasting) and one at 300 m (passive). The 300-m NBST came to the surface within a few hours of deployment due to on an overpressure condition caused by a ballasting error of only a few grams. The controller functioned as we had intended, and terminated the mission early (Fig. 4, lower right). Once again, the 150-m autoballasting NBST successfully settled at the desired depth after acquiring depth control. The controller was programmed to take no action if the depth was within 10 m of the prescribed 150 m, and the instrument stayed within or very near this depth range throughout its mission (Fig. 4, lower left). These NBSTs were also relocated and recovered without difficulty.

Of the three successful NBST deployments made to date, two were made with the single instrument that was equipped with an autoballasting device. We have concluded that some form of autoballasting should be included on all future NBSTs. This adds to the cost and complexity of the instrument; however, the successful operation of a passive NBST appears to be highly problematic.

Compared with an STST assembly, the NBSTs require considerably greater preparation before deployment, and they also require greater attention and planning while at sea during a deployment. An important consideration is that their location will generally not be known during the time of a mission. Thus when the NBSTs come to the surface they will be an unknown distance from their launch point, requiring that some ship time be held in reserve. During these field trials we had the advantage of concurrent PITS deployments and found that the two kinds of traps drifted along roughly similar paths (positions differed by up to 20 km after several days). Hence we did not experience operational difficulties with these NBST deployments and recoveries, though we can imagine that this will not always be the case. Deep-drogued surface drifters provide an inexpensive and reliable means to ‘‘track’’ roughly the NBSTs, but other means, including the addition of a simple acoustic transponder or pinger, could also be used to track the NBSTs with much greater precision, if that were considered desirable.

4. A brief look at trapping results

The analysis and interpretation of the geochemical data acquired by the NBSTs are the subject of a companion paper by Buesseler et al. (1999). Here we provide only a very brief summary of the results from the October 1997 deployment. During that field trial we successfully deployed an NBST that operated at 150 m and that carried four sediment trap tubes. These provided two independent samples of composition and of ^{234}Th that may be compared to samples from an STST at the same depth. During this deployment the horizontal current measured at the depth of the STST trap was unusually low, approximately 0.05 m s^{-1} (R. Johnson 1997, personal communication), so that hydrodynamic interference on the STST should have been about as small as it is ever likely to be.

The (two) replicate samples from the NBST were quite similar, for example, the dry mass was 63 and 64 mg m^2 day^{-1}. Four comparable STST samples had a range of 83 to 92 mg m^2 day^{-1}. The average mass of the two datasets was not significantly (statistically) different because of the very small number of samples and the relatively large variance of the STST samples. The measured particulate organic carbon and nitrogen (POC and PON) were also fairly similar.

In other ways the two datasets were rather different. Compared to the STST samples, the NBST samples contained a smaller fraction of oval pellets (about a factor of 2 less, but the STST data were highly variable from tube to tube), and the NSBT samples had about one-third the ^{234}Th activity.[3] Thus, although the mass of collected material was about the same, the composition of the collected material was markedly different. This is of some importance since sediment traps collect particles, not mass or POC per se.

Another striking difference between the samples was that the NBST samples contained a much smaller fraction of swimmers (swimmers are zooplankton that enter the traps on passing currents or under their own power and are considered a contaminant; see Lee et al. 1988; Karl and Knauer 1989; Coale 1990; Rodier and le-Borgne 1997). In the STST samples the swimmer carbon content was comparable to the amount identified as sinking particles (swimmer POC/total sample POC $\approx$ 55%–250%), while in the NBST samples the swimmers were a small fraction, about 16%, of the total sample POC. A similar low incidence of swimmer collection by NBSTs was found in the June 1997 deployment. Thus the NBSTs appear to have suffered much less unwanted attention from swimmers. This is a significant and unexpected advantage for the NBSTs since the identification and removal of swimmers from sediment trap samples is tedious, subjective, and not readily quantified (Lee et al. 1988; Karl and Knauer 1989; Michaels et al. 1990).

5. Conclusions and future directions

The conclusions that we can reach from these field trials are necessarily limited. Given that the NBST and STST samples had differing composition, then we can at least reject the null hypothesis—that collection by concurrent NBST and STST would be the same. The positive NBST hypothesis—that NBSTs make a more accurate export flux measurement—is far more difficult to test since there is no standard against which to compare upper ocean sediment trap collection (Michaels et al. 1994; Gardner 1999). An argument could be made that the observed composition difference is due to velocity-dependent sorting acting on the STST collection since this has been inferred from other STST field trials (Gardner 1999). However, that argument used here would come perilously close to assuming the truth of the NBST hypothesis that we hope to test, eventually. In the absence of an external standard, it appears that testing of the NBST hypothesis can only be done as a consistency check against independent, comprehensive and temporally extensive geochemical datasets. Buesseler et al. (1994) and the equatorial Pacific studies in Murray et al. (1997) show how this might be accomplished.

To facilitate this and other future NBST field work we hope to build a second-generation instrument that will be easier to use and far more reliable than were the prototypes. As we indicated in sections 2 and 3, the prototype NBSTs are finicky and would not fare well in the hands of investigators unfamiliar with the intricacies of neutrally buoyant floats or who do not have the specialized facilities needed for ballasting at in situ pressures, for example. To make a user-friendly NBST will require some straightforward development beyond the prototype instruments described here. The main task will be to make the NBST nearly self-ballasting by providing an autoballasting device with much greater dynamic range than at present. Thus the predeployment ballasting of the instrument would have to be accurate to no better than about 10 g, which can be accomplished by ballasting in an open tank, rather than at in situ pressures as is now required. Other minor design changes would be made to reduce the magnitude of air entrapment and to facilitate sample collection from the tubes. It would be interesting to measure the ambient current and the motion of an NBST by means of a diagnostic measurement package.

A reliable upper ocean sediment trap that can make quantitative export flux measurements at prescribed depths is an essential tool for addressing some of the most important questions on biogeochemical cycling. 1) By acquiring sediment trap measurements at a range of depths from 100 to 1000 m one could observe the export flux divergence due to remineralization within the upper ocean. 2) By acquiring sediment trap measurements at enough sites and on enough occasions one could begin to compile the statistics of the export flux. 3) Finally, by acquiring sediment trap data over an annual cycle in conjunction with comprehensive geochemical sampling we might come much closer to knowing whether the imbalance in the BATS carbon budget (Michaels et al. 1994) is due to STST sampling error or is evidence of an unaccounted process of geochemical cycling.

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[3] Unfortunately there were no water column measurements of thorium made during these field trials. We note that the STST–NBST difference found here is consistent with the NBST hypothesis and the observed annual cycle of thorium water column and STST inventory differences which indicates overcollection of thorium-bearing particles by STST in the fall (Buesseler et al. 1999).

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