Development and Testing of a Neutrally Buoyant Sediment Trap for Studies of Biogeochemical Cycling in the Upper Ocean

by

James R. Valdes and James F. Price
Physical Oceanography Department, Woods Hole Oceanographic Institution
Woods Hole, MA, 02543
jvaldes@whoi.edu and jprice@whoi.edu

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Summary: We have designed and field tested a neutrally buoyant sediment trap (NBST) intended for use in upper ocean sediment flux studies. The aim was to make a sediment trap that drifted freely with the ambient current so that hydrodynamic flow interference would be minimized. The principal design problem was to make the NBST descend to and stay near a prescribed depth. For a variety of reasons we have had the most success with NBSTs that were auto-ballasted by means of a simple volume changer that was controlled by a microprocessor. Auto-ballasting NBSTs have demonstrated an ability to hold a prescribed depth to within ten meters.

There have been two successful, concurrent deployments of NBSTs and conventional shallow surface-tethered traps (SS-T traps) at the Bermuda Atlantic Times Series site. During both periods the ambient flow past the SS-T traps was low, about 0.05 m s^{-1}, so that hydrodynamic effects on the SS-T traps would have been minimized. Comparisons of the trap results (described in detail in a companion paper by Buesseler et al., 1998) indicate that the total mass of collected material was generally similar in the two traps. Other variables, including the composition of the sediment, and the fraction of the total sediment sample that was contributed by swimmers, were markedly different. These are intriguing results, but are not conclusive since there is no absolute standard for comparison. Future field work that includes comprehensive geochemical sampling will be required to learn which sediment trapping method yields the more useful observations.

1 Sediment Trapping in the Upper Ocean.

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

Nearly all that is known about the sediment flux has resulted from direct measurements made by collecting samples in simple, open-top cylinders (e.g., Knauer et al., 1979, and US GOFS, 1989). These 'sediment traps' are attached to moorings (in the deep sea, Honjo et al., 1995) or are tethered beneath surface drifters (in the upper ocean, Rodier and Le Borgne, 1997; Buesseler et al., 1994; these shallow surface-tethered sediment traps are termed SS-T traps). The Bermuda Atlantic Time Series Program (BATS) utilizes data from SS-T traps to estimate the carbon flux carried downward from the upper ocean by falling sediment. Evidence to date is that the one-dimensional (local in space) carbon budget evaluated in part from these data is significantly out of balance (Michaels et al., 1994, and see Quay, 1997, for a general discussion of error estimates on fluxes). This might indicate that an important process has been left out of the carbon budget, e.g., horizontal advection or an unknown biological process. More prosaically, it might also indicate that the measurements of the vertical sediment flux as presently made by SS-T traps are seriously biased (see Gardner, 1996 for review of sediment trap biases). Comparisons of predicted and sediment trap-measured fluxes of ^{234}Th (a radionuclide produced by decay of dissolved ^{238}U and scavenged by particles) point toward this latter possibility (Michaels et al., 1994; Buesseler, 1992).

A sampling bias due to hydrodynamic effects is possible or even highly likely given the nearly horizontal direction of the sediment flux[1] (Baker et al., 1988; Gust et al., 1992; Gust et al., 1994; Gardner, 1996). The ambient flow past an open cylinder will set up standing eddies that effectively cycle a very large volume of water through the trap, leading to a possible sorting of the sediment due to the wide range of falling rates (Michaels et al., 1994). Sampling biases might also arise from small tilts of a sediment trap away from the vertical, or from mooring-induced vertical motions of the trap (Gust et al., 1994). These hydrodynamic effects can be studied and quantified under laboratory conditions (Butman, 1986; Butman et al., 1986), however, they can not be readily removed from field data because of the widely varying fall rates of the sediment.

1.1 Hypothesis and Goal of This Program.

The hypothesis of this development program is that a neutrally buoyant and freely drifting sediment trap (NBST) will yield a more accurate estimate of the vertical flux of sediment in the upper ocean than does a conventional SS-T trap because an NBST will not be subject to ambient horizontal currents and the attendant hydrodynamic sampling biases. The desirability of a freely drifting sediment trap was recognized long ago (U.S. JGOFS #10, 1989) but the technical obstacles to making a usable neutrally buoyant trap were sufficient to delay their full realization until fairly recently (Diercks and Asper, 1994, describe an earlier development effort). We have applied technology and techniques that have been developed for a variety of neutrally buoyant float systems used for physical oceanography studies (for example, Davis et al., 1992; Simonettie, 1998; Duda et al., 1988) and have developed a neutrally buoyant sediment trap that we hope can be used routinely for upper ocean sediment-trapping.

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[1] The ambient current past a SS-T 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) a SS-T traps 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 estimated at the depth of a SS-T trap can be much larger, up to 0.5 m s^{-1} (Rodier and Le Borgne, 1997).

1.2 Outline of This Paper.

The design of the NBST is described briefly in Sections 2.1 and 2.2. We have deployed several prototype NBSTs as part of the ongoing monthly cruises of the BATS program and have acquired some valuable experience in their use at sea (Section 3), some of which have led to important design changes. Our scientific objective was to compare the sediment catch from NBSTs with that from the conventional SS-T traps used at BATS (Section 4). We have found some significant differences, perhaps consistent with hydrodynamic effects on the latter, however, only future work (Section 5) will allow sharp conclusions regarding the best methods.

2 Design of a Neutrally Buoyant Sediment Trap.

2.1 Mission Requirements for an Upper Ocean NBST.

For use at BATS or in other, upper ocean sediment trapping programs, the nominal mission is a two to five day deployment at a depth of from 150 m to roughly 300 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 on the surface and 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.

2.2 NBST Prototype Design.

The prototype NBSTs were kept as simple as possible, consistent with the mission requirements, and made use of off-the-shelf components. The hull of the NBST is an aluminum cylinder 128 cm long x 11 cm in diameter that houses the batteries, controller, environmental sensors (pressure and temperature), and in one version, an auto-ballasting device that controls operating depth (Figures 1 and 2). The aluminum hull also has to provide the buoyancy needed to support four sediment traps which are VERTEX-style acrylic cylinders (Knauer et al., 1979) that are 66 cm long by 7.5 cm in diameter. Either piece alone can be handled easily by one person; the complete NBST configured for deployment weighs 16.5 kg in air, and can be 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 a 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 3.1).

The controller is an Onset Computer Corp. model TT4 data logger that was chosen on the basis of cost and low power consumption. Typical current drain for the complete system is about 40 uA, and about 1 mA while on a mission. The present battery pack is sufficient for about five missions of up to 5 days each, and a single mission of 30 days duration is possible. 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 instrument's history during the mission. The controller continuously 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 NBST has gone too deep or that the battery voltage is falling below acceptable limits it will terminate the mission (an example is shown below).

At the conclusion of a nominal mission (determined by elapsed time or date) 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. Thus the traps are closed before ascent, preserving the samples against flushing while the NBST is on the surface awaiting recovery.

Before deployment the sediment trap tubes are filled to a depth of about 15 cm with a dense, highly saline (approx 90 ppt) solution of 2% formalin, and then filled the rest of the way with sea water taken *in situ* from the target operating depth. This follows in part

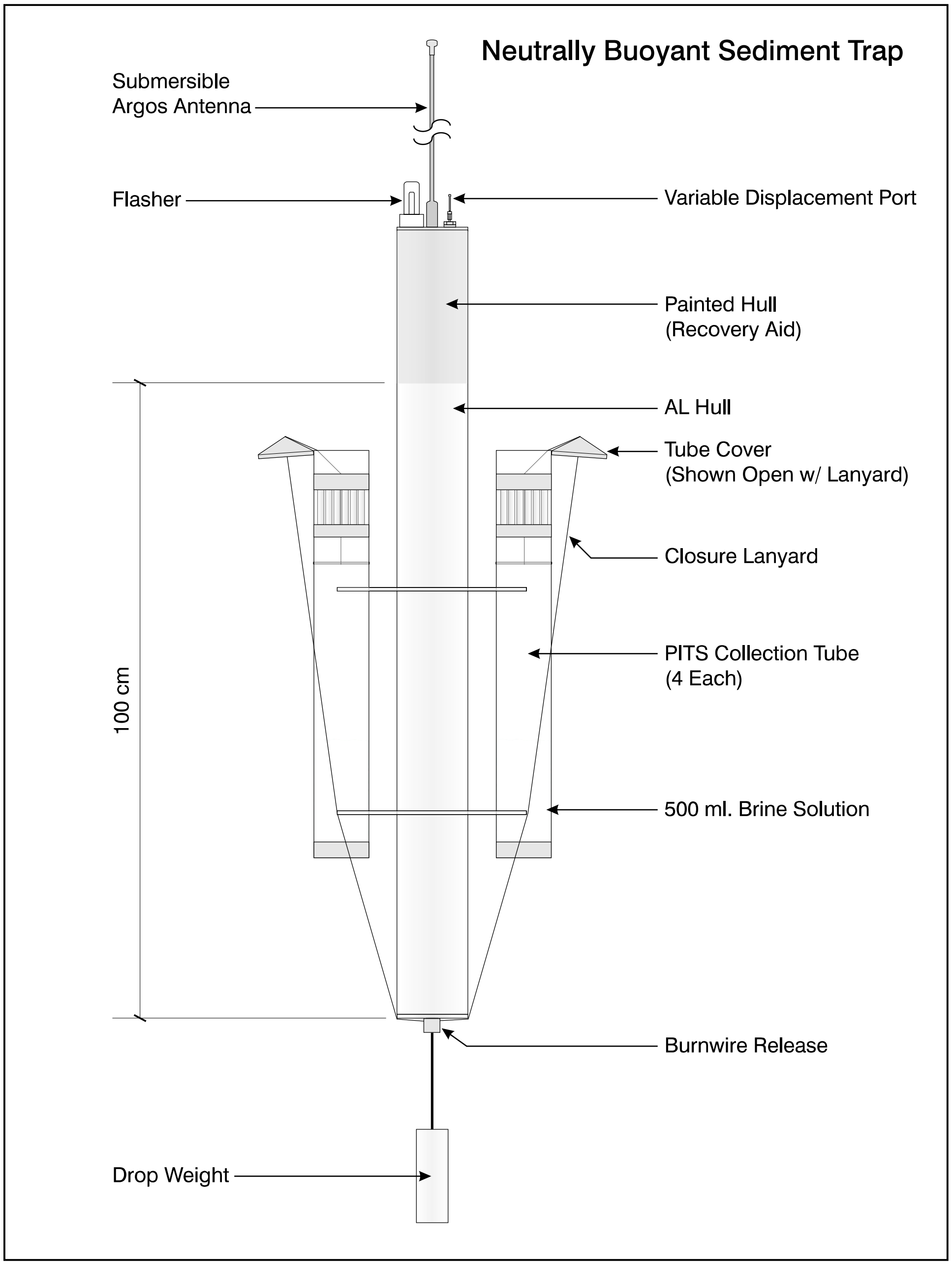

Figure 1: Schematic of the prototype NBST showing the major external components. Only two sediment trap tubes are shown here; four are usually attached. The tube covers are here shown in the open position held by a lanyard attached to the burnwire release. When the burnwire is activated, the drop weight (approx. 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. The trap tubes are otherwise identical to those used in the conventional SS-T traps.

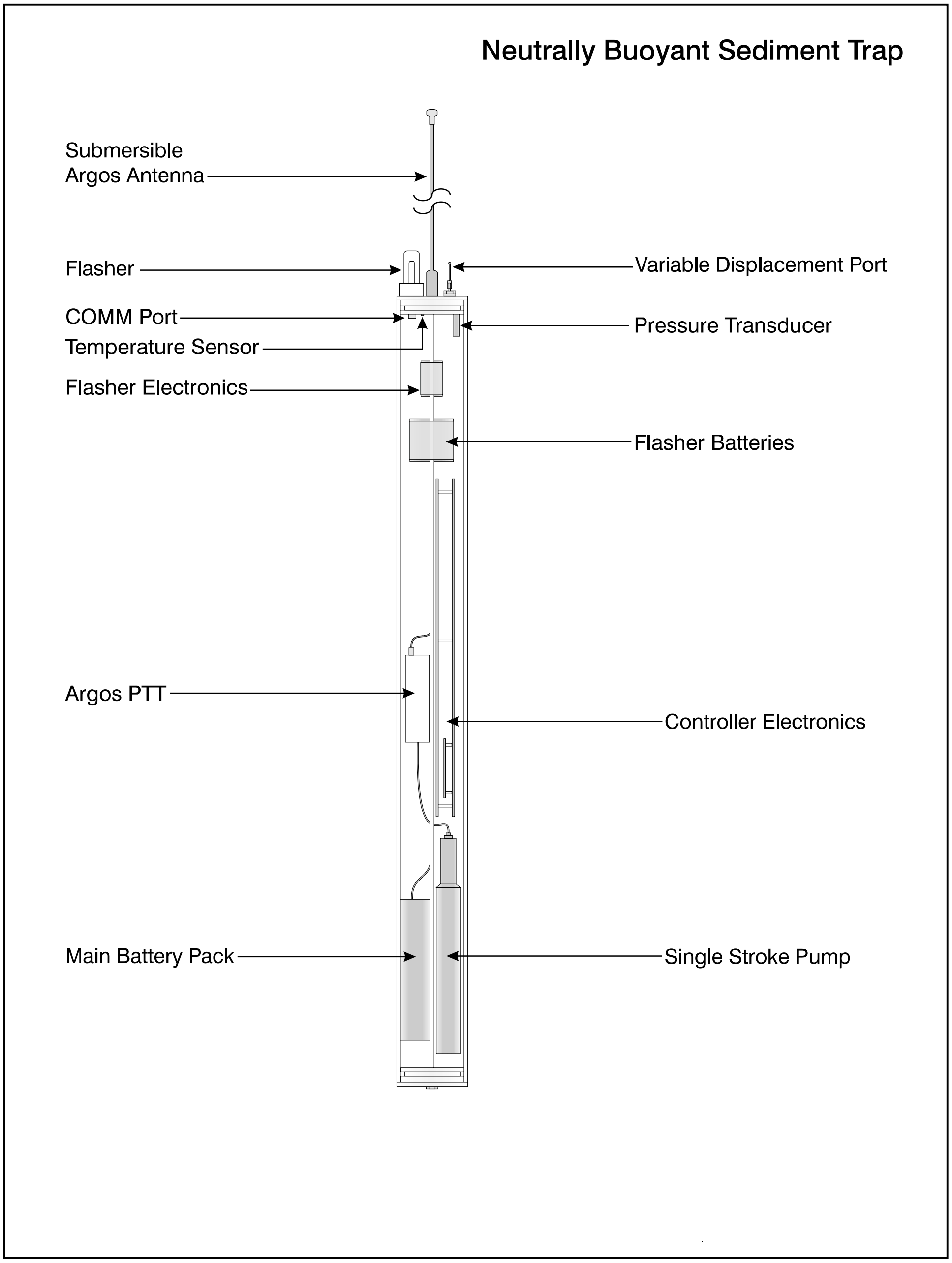

Figure 2: Internal components of the NBST. The port for the auto ballasting device (single stroke pump) is at top and is freely flooded by sea water.

the usual protocol for PITS traps, and serves to preserve the sediment while also providing some protection from scavengers (swimmers).

2.3 Ballasting.

The most difficult task for an NBST is to operate at a prescribed depth in a reliable and consistent manner. Because the instrument is fairly small, it has an extraordinary sensitivity to weight (or volume) changes; a 1 gm change in weight (or 1 cc change in volume) causes a roughly 40 m change in depth, for nominal stratification. 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. Thus the compressibility of an NBST is typically a rather complex function of depth compared with most other neutrally buoyant instruments. An example is in Figure 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 100 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 hyper-saline solution used in the traps to preserve samples. This solution weighs about 42 grams *in situ* and is liable to be partially lost during the launch of instrument in high seas. For either reason it is very difficult to make a passive NBST operate at a prescribed depth, and indeed we have succeeded in doing so only once while failing several other times.

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

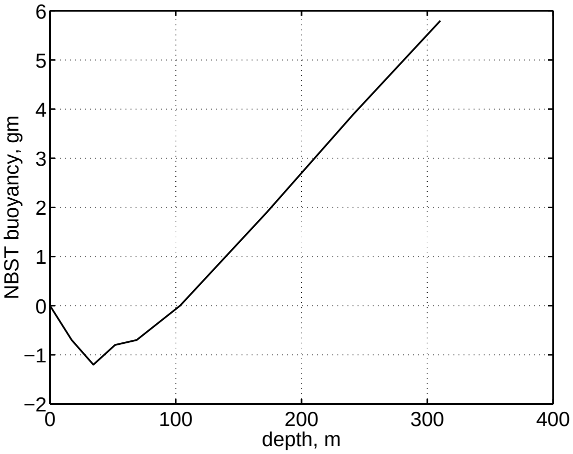

Figure 3: Typical ballasting data for an NSBT. Buoyancy is the measured weight of an NBST that is inside a pressure vessel filled with water. The pressure (here converted to depth) was increased while the weight of the NBST was recorded. Note the marked change in the slope of the curve at around 50 m. 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, i.e., buoyancy increased relative to water. 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).

pressure and an algorithm that was developed during extensive laboratory testing of the pump and controller. Deep ocean pressures were simulated by a high pressure circuit that had the compressibility of sea water *in situ*. This auto-ballasting 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, high-pressure ballasting of the prototype NBST was required. We hope to eliminate this requirement in the next generation of instruments by including a pump with a much larger dynamic range (Section 5).

3 Field Tests and Lessons Learned.

3.1 Failures.

We have deployed NBST prototypes on seven occasions and have lost the instrument on three of those occasions. One early glass-hulled NBST was lost 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 test cruise we deployed and lost two NBSTs that both 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 occasional failure of the controller. The flasher was omitted from two instruments prepared for the third test cruise, 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 (Figure 2). Aside from these important design changes, the lesson learned from these losses was confirmation of the adage 'never put anything over the side of a ship that you can not afford to lose'. This applies in full strength to NBSTs, since they are freely drifting during their missions. Internal failure of the electronics or batteries, etc., will usually result in the unexplained loss of the instrument and its samples. It is thus essential that the NBST design be kept simple and affordable, so that the inevitable loss of one or several instruments will not lead to the demise of a complete program.

3.2 Successes.

The first completely successful NBST deployment occurred in June, 1997. Two instruments were deployed, one targeted at 150 m and the other at 200 m. The first instrument included the only available auto-ballast mechanism while the second instrument (200 m) was passive (no auto-ballast). Pressure data logged by these instruments is in Figure 4a and 4c (converted to depth). The auto-ballasted NBST appeared somewhat heavy at launch, as it was ballasted for 200 m and set to auto-ballast to 150 m. The data from the internal logger shows that the instrument began to make ballasting adjustments as it passed through 150 m and settled at the nominal operating depth for the duration of the mission. The passive 200 m NBST started 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 (auto-ballasting) and one at 300 m (passive). The 300 m NBST came to the surface within a few hours of deployment due to on an over-pressure condition caused by a ballasting error of only a few grams. The controller functioned as we had intended, and terminated the mission early (Figure 4d). Once again, the 150 m auto-ballasting 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 (Figure 3b). These NBSTs were also relocated and recovered with no difficulty.

Of the three successful NBST deployments made to date, two were made with the single instrument that was equipped with an auto-ballasting device. This device functioned well on both occasions, and we intend to include some kind of auto-ballast device on all future NBSTs. While this adds somewhat to the cost and complexity of the instrument, the successful operation of a purely passive NBST appears to be highly problematic.

Compared with a surface-tethered PITS trap, the NBSTs require considerably greater preparation before deployment, and they also require greater attention and planning while

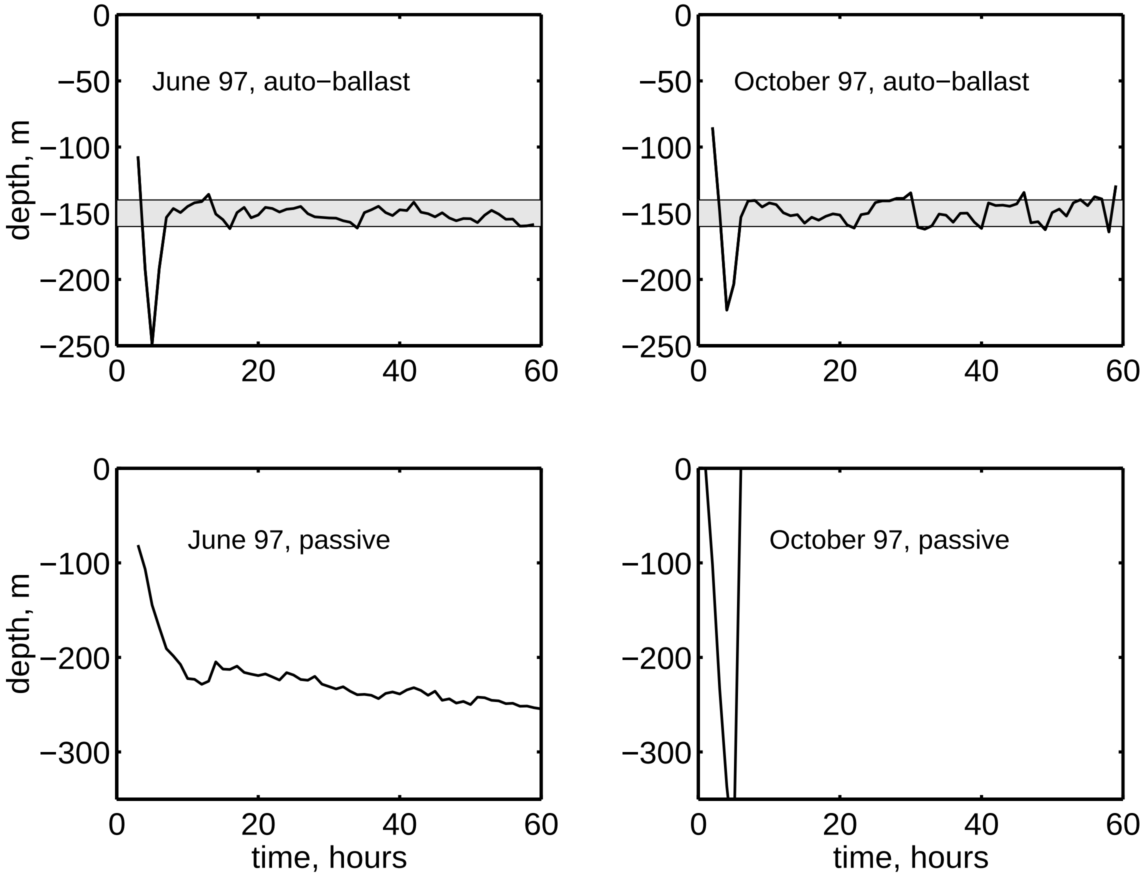

Figure 4: NBST depth computed from internally recorded pressure during the June and October deployments. The auto-ballasting NBST (top two panels) remained within its pre-programmed depth range (140 - 160 m), while the passive NBSTs either drifted downward slowly (June 97) or overshot the target depth due to a ballasting error of about three grams (October 97). In the latter case the NBST aborted its mission as it passed through 360 m and returned to the surface.

at sea during a deployment. One 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 Summary of Trapping Results.

The analysis and interpretation of the geochemical data acquired by the NBSTs is the subject of a companion paper by Buesseler et el., 1998. Here we provide only a very brief summary of results from the October 1997 deployment taken from that paper. During the October test we successfully deployed a single NBST that operated at 150 m and that carried four sediment trap tubes. These provided replication (two independent samples) of some variables. These NBST data may be compared to samples from a conventional SS-T trap at the same depth. During this deployment the horizontal current measured at the depth of the SS-T trap was quite low, approx. 0.05 m s^{-1} (R. Johnson, personal communication, 1997), so that hydrodynamic interference on the SS-T traps should have been about as small as it is ever likely to be.

The (two) replicate sediment samples from the NBST were quite similar, e.g., the dry mass was 63 and 64 mg m^2 day^{-1} compared with a range of 83 to 92 mg m^2 day^{-1} over four comparable SS-T trap samples. Thus the average mass of the two data sets was not significantly (statistically) different. The measured POC and PON were also fairly similar.

In some other ways the two data sets were rather different. The PITS data contained a larger number of oval pellets (mostly copepod fecal pellets) (about a factor of two larger but highly variable from tube to tube), and about three times the total ^{234}Th. Recall that the total mass of sediment was about the same. These rather large differences in sediment composition suggest that even the weak currents encountered by the PITS during these tests may have caused some selective sorting of the material collected as falling sediment.

Perhaps the most striking difference between the samples was that the SS-T trap samples contained a much larger fraction of swimmers (small scavengers, shrimp, etc., that probably entered the trap under their own power, see Karl and Knauer, 1989; Coale, 1990). In the NBST sample the swimmers were a negligible fraction of the total mass, while in the SS-T trap samples the swimmer total carbon, for example, was comparable to the amount retained as (falling) sediment. Thus the NBSTs seemed to have suffered much less attention from swimmers. As Buesseler et al. (1998) point out, this could be a significant and unexpected advantage of the NBSTs, if it turned out to be a general property, since the identification and removal of swimmers from sediment trap samples is tedious, subjective, and not readily quantified.

It is important to note that there is no absolute standard against which to compare an upper ocean sediment trap sample (Gardner, 1996). About all that we can do here is point to the differences between the new NBST data and the conventional SS-T trap data. These differences could be attributed *a priori* to unwanted hydrodynamic effects acting upon the SS-T traps. However, the only reliable way to know whether either trapping method yields the more accurate flux measurement is to make consistency checks over an extended period of time against independent, comprehensive geochemical data sets (Buesseler et al., 1994 and the equatorial Pacific studies in Murray et al., 1997 show how this might be accomplished).

5 Future Directions.

As we indicated in Sections 2 and 3 the prototype NBSTs are somewhat finicky, and probably 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 high pressure ballasting, for example. We hope that the next generation of NBSTs will be entirely user-friendly. This 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 a volume changer (pump) with much greater dynamic range than at present. Thus the initial ballast would have to be accurate to no better than about 10 grams, which can be accomplished by ballasting at sea level pressures, rather than at *in situ* pressures. Other design changes would be made to reduce the magnitude of air entrapment, and to facilitate sample collection from the tubes.

A reliable and relatively inexpensive NBST could be a key technology needed to address 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 sediment 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 sediment flux. 3) Lastly, and most fundamentally, by acquiring sediment trap data over an annual cycle in conjunction with comprehensive geochemical sampling we might learn whether the present imbalance in, e.g., the BATS carbon budget (Michaels et al., 1994), is due to SS-T sediment trap sampling error or is evidence of an unaccounted process in geochemical cycling. Our goal is that the NBST, or perhaps some as yet unforeseen progeny, will soon be able to make these and other measurements needed to observe the biogeochemical cycling of the ocean.

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