Estimating upper ocean particle fluxes using sediment traps: Current Status

The continual "rain" of marine particles has long been considered to be one of the critical processes linking the surface and deep ocean. There is considerable interest in this particle flux and its role in the vertical exchange of particulate organic carbon (POC) which is formed in the surface ocean via photosynthetic processes. As these particles sink, they remove POC and associated elements to depth where they serve as a food source for sustaining life in deeper layers, and are re-mineralized and returned to the surface waters via slower mixing process, or become sequestered in the bottom sediments. These and related processes involving physical exchange of dissolved organic carbon (DOC) and active C transport by zooplankton grazers are all viewed as parts of a marine "biological pump" (Figure 1). The workings of this pump has an impact on the net exchange of CO_2 between the atmosphere and ocean and the gradient with depth in POC flux, and thus the sequestration of C on longer time scales in the deep sea and underlying sediments. Determining the gradient in POC flux in the upper ocean is therefore particularly important, yet particularly difficult.

The instrument of choice to directly measure particle flux has been the sediment trap, basically a cylindrical or conical rain gauge-type device, which is moored or floated at depth to collect sinking particles. Considerable advances in understanding the ocean's biological pump are attributed to the use of sediment traps; nevertheless, it is well known that there are many processes that can readily confound trap accuracy and lead to incorrect or, at best, ambiguous results [Gardner et al. 2000]. To assess trap accuracy, independent flux gauges have been sought. Use of radiometric techniques to calibrate the collection efficiency of sediment traps over proper temporal and spatial scales has proven helpful in constraining flux variability measured with traps. However, methodologies such as $^{234}Th/^{238}U$ and $^{210}Po/^{210}Pb$ disequilibria measurements in the water column are very time consuming and have their own drawbacks, and thus may be difficult to use as a standard means of trap calibration.

With the above considerations in mind, the Scientific Committee on Ocean Research (SCOR) established in 2001 Working Group 116 **"Sediment Trap and ^{234}Th Methods for Particulate Organic Carbon Export in the Upper Ocean: Current Status".** One of this group's tasks was to assess the problems, advantages, and associated measurement uncertainties and their magnitudes of using sediment traps, as well as recommending the most suitable trap designs, necessary protocols, and trap calibration methodologies that might be used to obtain the most reliable particle flux data. The working group, composed of approximately a dozen members, met over the last six years in Amsterdam, Netherlands (2001); Catalina Island, CA (2003); Woods Hole, MA (2004) in conjunction with an aquatic ^{234}Th applications workshop; Xiamen, China (2005); and in Honolulu, HI in conjunction with the AGU Ocean Sciences Meeting (2006). The group used as a starting point previous reports from the Joint Global Ocean Flux Study (JGOFS) [Gardner 1996, 2000], which summarized information on sediment trap technology and sampling in surface waters up until the mid-1990s, and then undertook a thorough search for relevant new data collected over the last decade. While the group's deliberations, conclusions and recommendations have been reported on a regular basis to SCOR, it was hoped that their critical review and synthesis would reach a larger audience through publication in the open literature. This has now been accomplished and the group's assessment, conclusions and recommendations for best sediment trap practices will appear in a paper to be published in the *Journal of Marine Research* [Buesseler et al., in press, May 2007, Vol. 65, No. 3].

The assessment primarily focuses on four principal issues related to traps that have been under intense discussion within the marine scientific community for some time: hydrodynamic biases,

inclusion of zooplankton "swimmers" in traps, solubilization of trapped particulates, and independent methods for calibrating trap collection efficiency (Table 1). The emphasis was on traps in the upper 1000m as these issues are generally more significant in shallow waters. With respect to hydrodynamics, because sediment traps (which are usually moored or drifting) rarely move with the flow of the surrounding water, fluid flow over and within the trap can affect how sinking particles move in and out of the funnel- or cylindrical-type trap used (Figure 2). Obviously the net effect of these biases can compromise accurately quantifying the vertical particle flux.

In the case of drifting traps, the report notes that employing "best practices" is imperative, but that they can be difficult and expensive to achieve involving additions of current and tilt meters, drogues to slow down local slip velocity, minimum drag designs for the surface-tethered array, and the avoidance of using more than one trap depth, which essentially guarantees differential flow for traps at different depths. In order to avoid (rather than back-correct) many of the hydrodynamic problems associated with the most commonly used trap arrays, the report recommends using neutrally-buoyant sediment traps (NBSTs), a free vehicle that moves with the flow at depth and thus in theory more accurately collects sinking particles (Figure 2). NBSTs have been developed and tested by two groups over the last few years with much success. It is pointed out that contrary to common belief, the NBSTs are no more expensive than a fully-instrumented, drifting trap array. However, costs are difficult to ascertain, as unlike deep moored traps where a few designs have become commercialized, neither shallow drifting traps or NBSTs are commercially available and are generally supported within larger ocean research programs.. In any case, whatever type of trap and array is used, it is important to fully document the conditions of deployment in order to discern their probable influences on the qualitative and quantitative collection of sinking particles.

While zooplankton fecal pellets are a major source of the sinking particles caught at depth in traps, their preponderance in the upper water column also results in many motile forms actually swimming into the traps and being deposited in the collectors along with the sinking particles that form the passive particulate flux. These "swimmers", which are often invisible to the naked eye, can contain more carbon and other elements than the passively sinking particles and, if not taken into account, can greatly bias the fluxes. The report stresses that best practice is to try to avoid the swimmers altogether, and to this end, "indented rotating sphere" (IRS) traps have been designed to separate the sample reservoir from active contact with the overlying water via a rotating ball mechanism at the base of the sample tube. Indeed, this design and the few other swimmer avoidance traps presently used have shown some success in excluding certain kinds of zooplankton from entering the sample reservoir. It is suggested that future designs of swimmer avoidance traps should try to exploit zooplankton swimming behaviors to minimize the problem. Whether using the avoidance trap designs or not, swimmers should be removed as thoroughly as possible from all trap samples (screening is quick but can be less precise than hand-picking using microscopy), and the methods documented for future reference. Finally, it is recommended that the removed swimmers should be saved and quantified (numbers and/or mass) for estimating their contribution to each trap sample.

Particles produced in the upper waters are slowly degraded and solubilize as they sink to depth. Likewise such particles that collect in the traps continue to solubilize after collection, and measures need to be taken to reduce these effects. First, emphasis should be placed on short-term deployments along with rapid post-deployment sample treatment. In conjunction with this approach (and especially where long deployments are necessary), trap solutions should be effectively poisoned and buffered and contained in sealed sample reservoirs (called "cups" on deep time-series traps that collect multiple samples), and any swimmer-avoidance mechanisms

optimized. Swimmers should be picked from the trap samples and the remaining particles carefully filtered under low pressure. Analyses of the removed swimmers for carbon, nitrogen and other elements will allow estimating their maximal contribution of those elements to the trap supernatant. Comparison of the element concentrations in trap cup supernatant can then be compared with concentrations in the solution used to fill the collection cups (blanks) as well as corresponding concentrations in the trapped particles. Ensuring all such data are available will greatly aid in determining the actual fraction of elements solubilized from the sinking particles themselves. Basically, our understanding of how and to what extent elements are solubilized from particles in traps is very limited. To fill this gap, the report recommends carrying out more experimental studies to examine trapped particle degradation rates over time at *in situ* temperatures and under differing poisoned and un-poisoned conditions.

To assess trap accuracy, independent methods are sought, and each is subject to its own uncertainty. Time-series analyses of 3-D chemical balances of C are difficult at best, as POC fluxes on sinking particles are small relative to the stocks, and thus difficult to constrain via mass balance approaches. More promising are measurements of naturally occurring radionuclides, whose export from the surface ocean are strongly impacted by loss on sinking particles. In this regard ^{234}Th/^{238}U disequilibria are used to predict ^{234}Th export on sinking particles which is then compared to particulate ^{234}Th flux caught in traps. Where such coupled water column-trap measurements have been made over appropriate time and space scales (^{234}Th half-life = 24.1 d), this method has proved useful in assessing the collection efficiency of the traps. Furthermore, the report presents an analysis of four long-term ^{234}Th trap records and concludes that there was a consistent flux weighted average of under-trapping by approximately a factor of two. The report notes that future long-term trap studies would benefit from determining collection efficiencies with the ^{234}Th proxy and, in terms of time and space scales, recommends that trap deployment periods should be better designed to match the ^{234}Th residence time in the surrounding waters. In addition, both measured (trap) and expected (from water column^{234}Th/^{238}U disequilibria) radionuclide fluxes should be reported along with the calculated collection efficiencies. Many of these recommendations could be facilitated by establishing more continuous (ideally year-round) trapping and calibration programs. The report also warns that ^{234}Th-based estimates of trap particle collection efficiency should be applied with care to other components of the settling flux, since the calibration for particles based on ^{234}Th concentration may not hold for other elements (e.g. carbon) if the particle classes carrying those elements differ from those transporting ^{234}Th.

The SCOR working group's review underscores that variability in sediment trap practices is common, and that some standardization of trap designs and processing protocols needs to be undertaken to facilitate relative comparisons of different flux studies. Since reliable estimates of sinking particle flux are an important parameter needed to answer many of ocean sciences' most pressing questions, it is imperative that improvements in the use of these devices and other proxies for estimating sinking flux continue to be made. In summary, sediment traps serve as a valuable tool in ocean sciences but, as with every tool, there are design, environmental and practical limitations. With careful study the scientific community is making progress in both understanding their limits and in improving designs. Therefore the group hopes its report will be both timely and instructive in serving as roadmap for all those undertaking sediment trap studies in the future.

References

Buesseler, K. O., A. N. Antia, M. Chen, S. W. Fowler, W. D. Gardner, O. Gustafsson, K. Harada, A. F. Michaels, M. Rutgers van der Loeff, M. Sarin, D. K. Steinberg, and T. Trull (in press). Estimating upper ocean particle fluxes using sediment traps. In press, *J. Mar. Res*. Volume 65, Number 3.

Buesseler, K.O., C.H. Lamborg, P.W. Boyd, P.J. Lam, T.W. Trull, R.R. Bidigare, J.K.B. Bishop, K.L. Casciotti, F. Dehairs, M. Elskens, M. Honda, D.M. Karl, D. Siegel, M.W. Silver, D.K. Steinberg, J. Valdes, B. Van Mooy and S. Wilson (2007). Revisiting carbon flux through the ocean's twilight zone. In press, *Science*

Gardner, W.D. (1996). Sediment trap technology and sampling in surface waters. JGOFS Report on Sediment Trap Technology, Texas A&M Univ., 24p.
http://www-ocean.tamu.edu/Research/JGOFS/contents.html

Gardner, W.D. (2000). Sediment trap technology and surface sampling in surface waters, in *The Changing Ocean Carbon Cycle: A Midterm Synthesis of the Joint Global Ocean Flux Study*, edited by R.B. Hanson, H.W. Ducklow, and J.G. Field, pp. 240-281.

Author Information

KEN O. BUESSELER, Woods Hole Oceanographic Institution, Woods Hole; SCOTT W. FOWLER, IAEA Marine Environment Laboratories, Monaco and Marine Sciences Research Center, State University of New York, Stony Brook; AVAN N. ANTIA, Leibniz-Institute for Marine Sciences, Kiel, Germany; MIN CHEN, State Key Laboratory of Marine Environmental Science, Xiamen University, Xiamen, China; WILFORD D. GARDNER, Department of Oceanography, Texas A&M University, College Station; ORJAN GUSTAFSSON, Department of Applied Environmental Science, Stockholm University, Stockholm, Sweden; KOH HARADA, Marine Environment Division, National Institute for Resources and Environment, Ibaraki, Japan; ANTHONY F. MICHAELS, Wrigley Institute for Environmental Studies, University of Southern California, Los Angeles; MICHIEL RUTGERS VAN DER LOEFF, Alfred-Wegener Institute for Polar and Marine Research, Bremerhaven, Germany; MANMOHAN SARIN, Physical Research Laboratory Ahmedabad, India; DEBORAH K. STEINBERG, Virginia Institute of Marine Science, Gloucester Point; and THOMAS TRULL, ACE CRC, University of Tasmania, and CSIRO Marine Research, Hobart, Australia

Figure 1. The biological pump and processes regulating the flux of particles. CO_2 fixed during photosynthesis by phytoplankton in the upper ocean is transferred below the surface mixed layer via three major processes: passive sinking of particles, physical mixing of particulate and dissolved organic matter (DOM), and active transport by zooplankton vertical migration. The sinking flux includes senescent phytoplankton, zooplankton fecal pellets, molts, mucous feeding-webs, and aggregates of these materials. The sinking particle flux decreases with depth as aggregates are fragmented into smaller, non-sinking particles, decomposed by bacteria, and consumed and respired by zooplankton. This remineralization returns carbon and nutrients to dissolved forms. The structure of the plankton community governs particle size, form, density, content of biogenic minerals, and also affects particle sinking and remineralization rates. [From Bu esseler et al., in press, JMR].
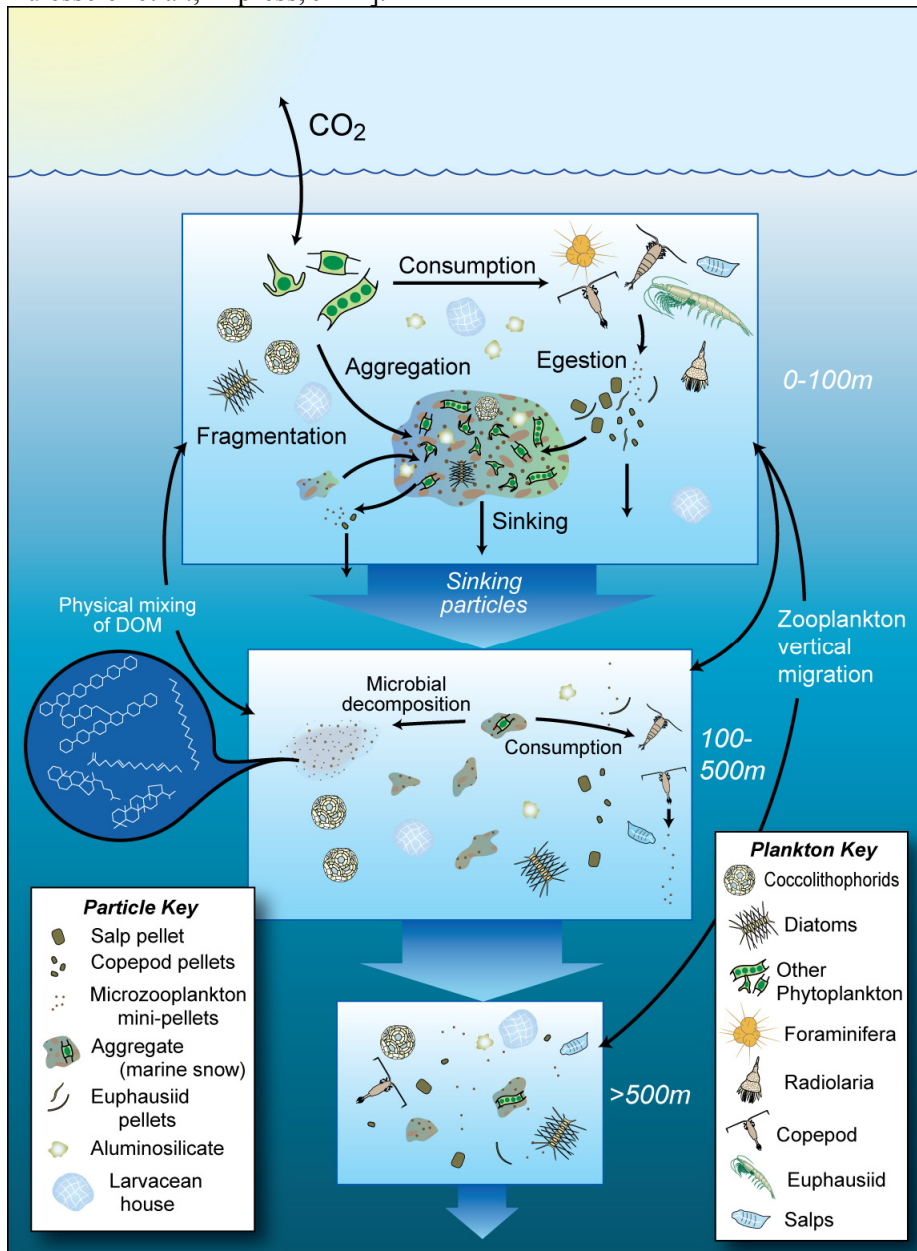
Figure 2. Schematic diagram showing relative difference between NBST and standard surface tethered traps for the direct collection of sinking particles in the ocean. Particles derived from surface ocean biological processes are sinking at velocities of 10 to >200 m/d within a flow field of ocean currents on the order of km/d. The NBST moves at the same relative speed as the water flow (v ~ 0) so there is near zero flow across the trap mouth and within the trap (v= approach velocity). For standard traps, the surface tether and float result in flow across the trap mouth (v = 1 to >15 cm/s are common), flow within the trap, possible tilting and vertical motion, and particles entering the trap at non-vertical angles. Any of these hydrodynamic effects can alter the collection characteristics of the trap (e.g. Gardner, 2000). From Buesseler et al. in press, Science, supplimental materials.
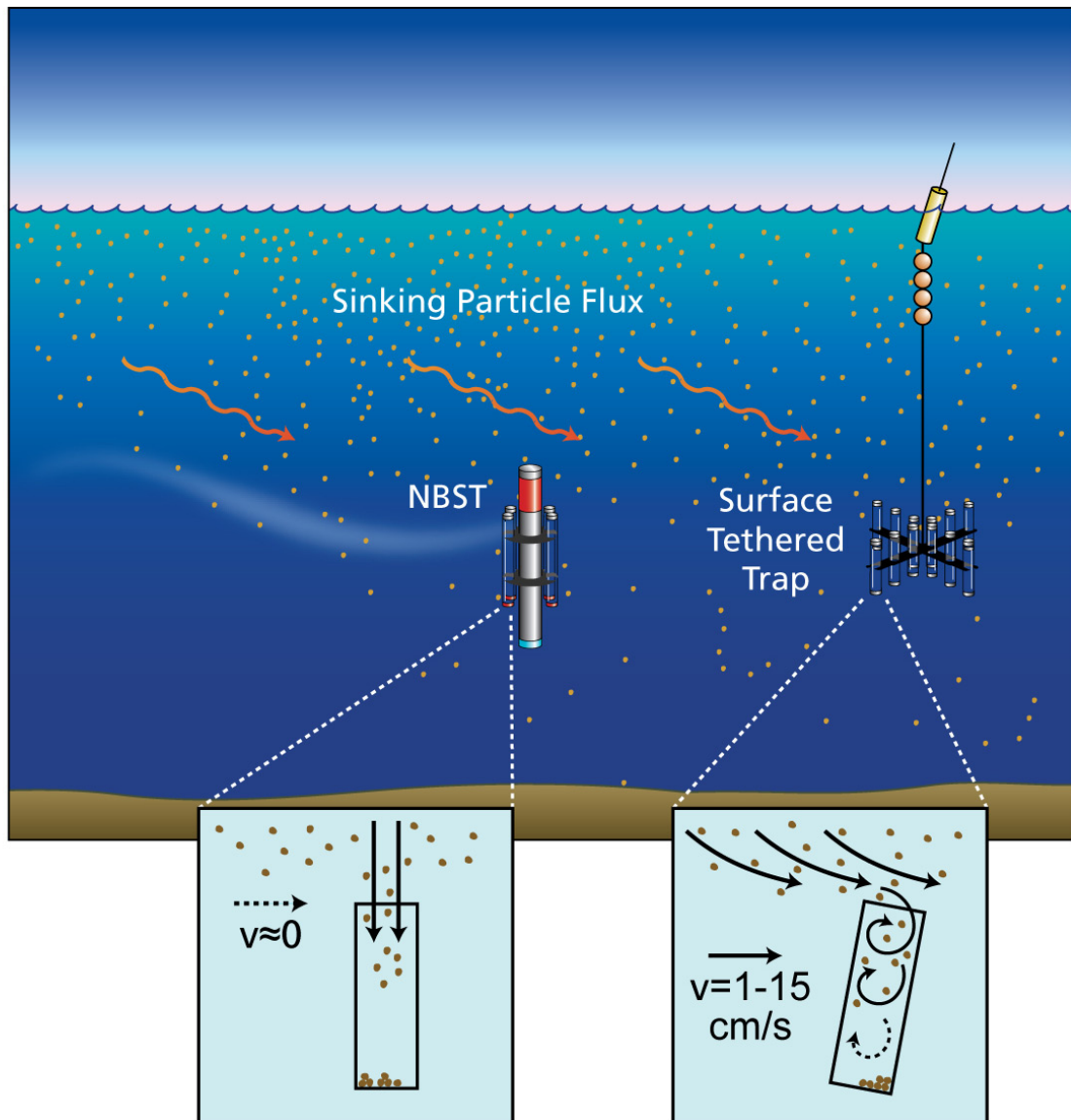
Table 1. Summary of best practices and recommended protocols for improving the usefulness of sediment traps in particle flux studies. [From Buesseler et al., in press, JMR].

	Best practices	Compensation/Considerations	Documentation
Hydrodynamics	Neutrally buoyant sediment traps	Drifting trap, minimum drag, trap at one depth, measurements of current and tilt Cylinder *faster velocities, slower sinking particles* Cylinder or Cone *lower velocities, faster sinking particles*	Full array design Estimates of currents and tilt
Swimmers	Swimmer avoidance trap Inspect for swimmers	Removal of swimmers by picking and/or screening	Quantify swimmer numbers and mass Estimate of contribution to flux Photograph (representative) Identify swimmers Retain swimmer sample
Solubilization *short term (days)*	Process quickly & poison Use sealed cups if possible	Check for dissolved and/or test possibility of dissolution via incubation experiments Measure dissolved components	Document time from collection to processing
long term	Use poison and buffers and sealed cups		
Radionuclide Calibration *Shallow (upper 100-200m)*	^{234}Th in water column and in trap	First order correction using calibration data Comparison between multiple radionuclides and/or elemental budgets	Correction factors and whether applied to all elemental fluxes or not Radionuclide methods Flux model assumptions
Mesopelagic and below	^{230}Th and preferably also ^{231}Pa in annual deployments		