The Flux of Particulate Organic Carbon Into the Ocean Interior: A Comparison of Four U.S. JGOFS Regional Studies

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Introduction

The delivery of nutrients to the sunlit surface ocean spurs phytoplankton growth and the production of particulate organic carbon (POC). As organisms die or are consumed and excreted, some of these particles settle and are exported deep into the ocean interior before remineralization occurs; this process is a component of what is commonly called the "biological pump" (see Ducklow et al., this issue). Equations that generalize the relationship between the amount of carbon produced and the amount exported from the surface ocean, as well as the relationship between the export flux and ocean depth, are key components of models that seek to predict the distribution of CO_2 in the ocean in time and space.

This paper represents a summary of carbon budgets, an assimilation of U.S. JGOFS data related to the production and export of POC from the surface ocean to the deep sea floor. Two major concerns arise in the assembly of such budgets. One is whether or not particles settle vertically from the spot where formation occurs to a spot on the sea floor. We know that this does not happen to all particles, yet there is evidence in budget calculations and in the sedimentary record suggesting that there must be some major component of the particulate "rain" that falls essentially vertically (Berelson et al., 1997; Lee et al., 1998; Nelson et al., 2001).

Another major concern in constructing the vertical flux budgets is that various types of measurements made by various individuals and groups, at different times and different locations, are assembled and presented as a uniform picture when, in fact, they are a melange of many techniques, sites and timescales. One of the accomplishments of the U.S. JGOFS field program was that many POC flux measurements were made using consistent protocols, by many of the same investigators, at the same locations and during the same times.

In this paper we present 17 POC budgets for U.S. JGOFS sites in the North Atlantic, equatorial Pacific, Arabian Sea and the Southern Ocean. One budget is from the North Atlantic Bloom Experiment (NABE) site at 48°N, 21°W; seven are from the Equatorial Pacific Process Study (EqPac) between 9°N and 12°S at approximately 140°W; five are from the Arabian Sea (AS) from 10°N to 19°N and 57°E to 65°E, and four are from the Pacific sector of the Southern Ocean (SO) from 55°S to 68°S at approximately 170°W.

We are primarily considering four types of flux determinations: the production of POC during primary productivity (PP) in the surface ocean as determined through the carbon-14 (^{14}C) method; the export of POC from the upper few hundred meters of the water column as determined by thorium isotope budgets (Figure 1a); measurement of the rain of POC at a variety of depths with sediment traps (Figure 1b) and the sum of sea-floor remineralization rates determined using benthic landers (Figure 1c) and pore water measurements plus POC burial rates. Although the budgets presented in this paper integrate measurements made, with a few exceptions, during the same time intervals (Table 1), it is noteworthy that each measurement records fluxes on a different timescale. Productivity measurements, for example, can be considered a snapshot of carbon production over a few hours, whereas burial-rate measurements integrate hundreds to thousands of years.

The primary goal of this paper is to assemble POC budgets for various oceanic regions and to compare the relationships between primary productivity and export and export versus depth between regions. We have a choice in constructing these budgets as to what space and time frames to include. By including the longest time interval over which measurements were made, we are more likely to smooth and average out spurious data in favor of a more generalized picture. Sites were identified by the presence of a sediment-trap mooring. For the EqPac region, we show how grouping stations may influence budget interpretations. Measurement methodologies used for various studies are described in the papers referenced in Table 1.

Results

The logarithmic scale used in Figures 2 and 3 tends to emphasize the two orders of magnitude difference between PP and particulate rain below 2000 m and to minimize the changes in POC flux below this depth. The between-site range in PP and rain below 2000 m

varies by an order of magnitude. However, there are differences of approximately 2 orders of magnitude in estimates of POC export at 100 m, reflecting variability both in this parameter and in our ability to quantify export. As a general rule, roughly 1% of the POC produced in the surface ocean is exported to depths below 2000 m, although there are systematic differences between regions. Another general observation is that POC rain between 2000 m and 5000 m shows little change.

We compare three models relating POC export to PP with observed data (Figure 4). These models vary in the way they formulate the relationship between PP and POC flux, but they are all based on data. It is apparent that the models overestimate POC export. We examine this relationship further in the summary presented in Figure 5, where export flux at 1000 m and 3000 m at all sites is compared to the flux predicted in the models. In constructing these plots, we used a linear interpolation of export flux at the target depth for sites where flux data existed within 500 m of this horizon. At three depth horizons, there were not enough data to make the interpolation.

We also compare POC flux profiles to a function describing flux vs. depth as a power law. This function, known as the Martin equation (Martin et al., 1987), has the following form:

$$\text{POC flux at depth } z = \text{POC flux at 100 m} * (z/100)^{-b} \quad (1)$$

In this equation, z represents depth in meters and b is a unitless fitting parameter. Solution of this equation requires knowledge of the POC flux at 100 m. The data presented in this paper were fitted with this equation after we determined an average flux value for export at 100 m. We used values supplied by Lee et al. (1998) for the Arabian Sea and values from Nelson et al. (2001) for the Southern Ocean sites.

For EqPac and NABE, POC flux at 100 m was determined as the simple average of all estimates of export; these included estimates of export at depths between 75 m and 150 m that were grouped into a single export value. For EqPac, we only used flux estimates that incorporated results from both study seasons.

It may be argued that an average value for POC export at 100 m should not be derived by combining estimates based on different measurement techniques (floating traps vs. thorium, for example). With few exceptions, the various methods, when applied at the same location and during the same time period, yield flux estimates that agree within a factor of three or better. The plots in Figure 2 show the fit of Equation 1 to the observed data and the calculated value of b.

Discussion

The assemblage of primary productivity and POC export data from the U.S. JGOFS process studies in the North Atlantic, equatorial Pacific, Arabian Sea and Southern Ocean permits comparison among the regions (Figures 2-5). Several regional trends are apparent. At sites in the Arabian Sea and the equatorial Pacific where PP values are comparable, the export of POC from 100 m is greater in the Arabian Sea. Southern Ocean POC export rates are comparable to export fluxes at other

Table 1
Identification of Data References

Depth	North Atlantic	Equatorial Pacific	Arabian Sea	Southern Ocean
Euphotic (PP)	Martin et al. (1993) DSR, 40	Barber et al. (1996) DSR II, 43	Lee et al. (1998) DSR II, 45	Nelson et al. (2001) DSR II (in press)
75–850 m (Export)	Buesseler et al. (1992) DSR, 39 Martin et al. (1993) DSR, 40	Buesseler et al. (1995) DSR II, 42 Luo et. al. (1995) DSR II, 42 Murray et al. (1996) DSR II, 43 Bacon et al. (1996) DSR II, 43 Wakeham et al. (1997) DSR II, 44	Lee et al. (1998) DSR II, 45	Nelson et al. (2001) DSR II (in press)
Deep Traps	Honjo & Manganini (1993) DSR, 40 Martin et al. (1993) DSR, 40	Honjo et al. (1995) DSR II, 42 Wakeham et al. (1997) DSR II, 44	Lee et al. (1998) DSR II, 45	Honjo et al. (2000) DSR II, 47
Benthic Recycling	Pfannkuche (1993) DSR, 40	Hammond et al. (1996) DSR II, 43 Berelson et al. (1997) DSR II, 44		Nelson et al. (2001) DSR, in press

North Atlantic (NABE): Late April-early June 1989.
Equatorial Pacific (EqPac): Spring and fall 1992. One field season took place during El Niño conditions, and the other during non-El Niño conditions.
Arabian Sea (AS): November 1994-December 1995, covering both monsoon and inter-monsoon seasons.
Southern Ocean (SO): October 1997-March 1998. Sediment trap measurements were not made beyond January 1998. Thus trap fluxes for December 1996 to March 1997 and October 1997 to February 1998 were combined to compute POC rain rates representative of the time when water column measurements were made.

Figure 1. a) *Large-volume* in situ *pump used for collecting thorium-234 samples, photo courtesy of Ken Buesseler.* ***b)*** *Recovery of benthic lander, photo courtesy of William Berelson.* ***c)*** *Recovery of deep sediment trap in Southern Ocean, photo courtesy of Susumu Honjo.*

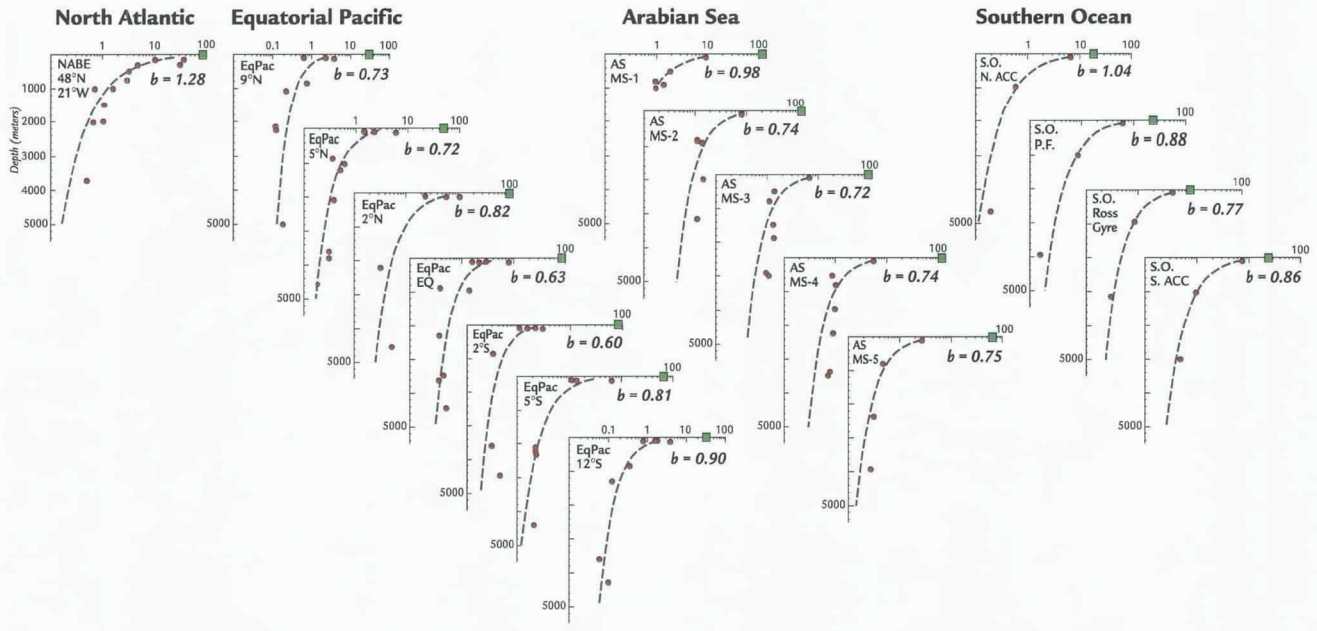

Figure 2. *Plots of POC flux vs. depth for all 17 stations in the U.S. JGOFS regional studies conducted in the North Atlantic, equatorial Pacific, Arabian Sea and Southern Ocean. Squares identify estimates of primary productivity, and solid circles are estimated flux values at various depths. The deepest points for EqPac, SO and NABE are defined by benthic recycling and sediment burial fluxes. Note the log scale for the flux (mmol C m^{-2} d^{-1}) and some variability in this scale. Depth scale is in meters. An average value of POC flux at 100 m was determined, and that value was used as an anchor point in defining the best fit given by the Martin equation (Equation 1). We show equation fits to all the observed data for each of the study sites and the calculated fitting parameter b, described in the text.*

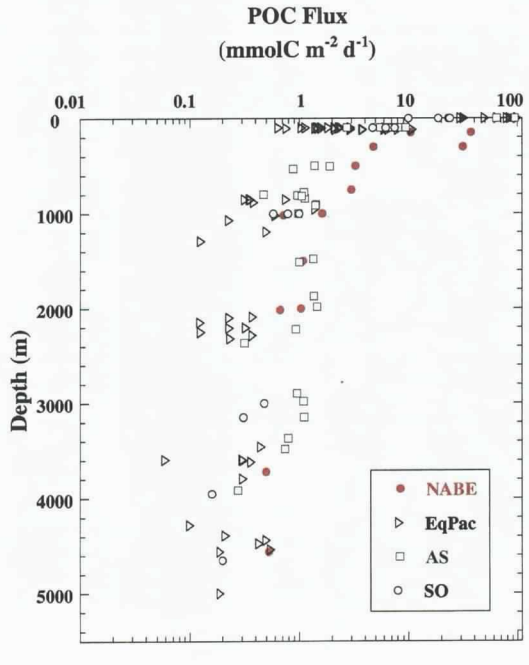

Figure 3. *Summary plot of POC flux vs. depth. Points plotted on the depth = 0 axis represent estimates of primary productivity.*

sites even though PP in the Southern Ocean is significantly lower. In the Arabian Sea, 1% of primary production reaches a depth of 2000 m; in the equatorial Pacific, this value is closer to 0.6%, and in the Southern Ocean, 1–2%. Finally, the Martin function tends toward a systematic underprediction of POC fluxes at depths greater than 3000 m.

We find that previously published models overestimate the amount of POC reaching 1000 m by a factor of 2 to 5 when primary productivity values are greater than 40 mmol C m^{-2} d^{-1} (Figure 5). Model-estimated flux is greater than the measured flux at 3000 m as well, although the "Pace model" (Pace et al., 1987) shows a trend that is similar to the data trend and overestimates flux by less than a factor of two. It is notable that the Southern Ocean data are in reasonable agreement with all the model estimates, both at 1000 m and at 3000 m. The offset between the U.S. JGOFS data and the earlier models could be explained if earlier estimates of PP were low because of trace-metal contamination effects (Martin et al., 1993).

The assembled U.S. JGOFS data define a trend in primary production vs. POC rain that is roughly linear through an order of magnitude change in primary production and the same range of variability in POC flux. The Southern Ocean data add considerable scatter to such a trend. As POC export is positively correlated

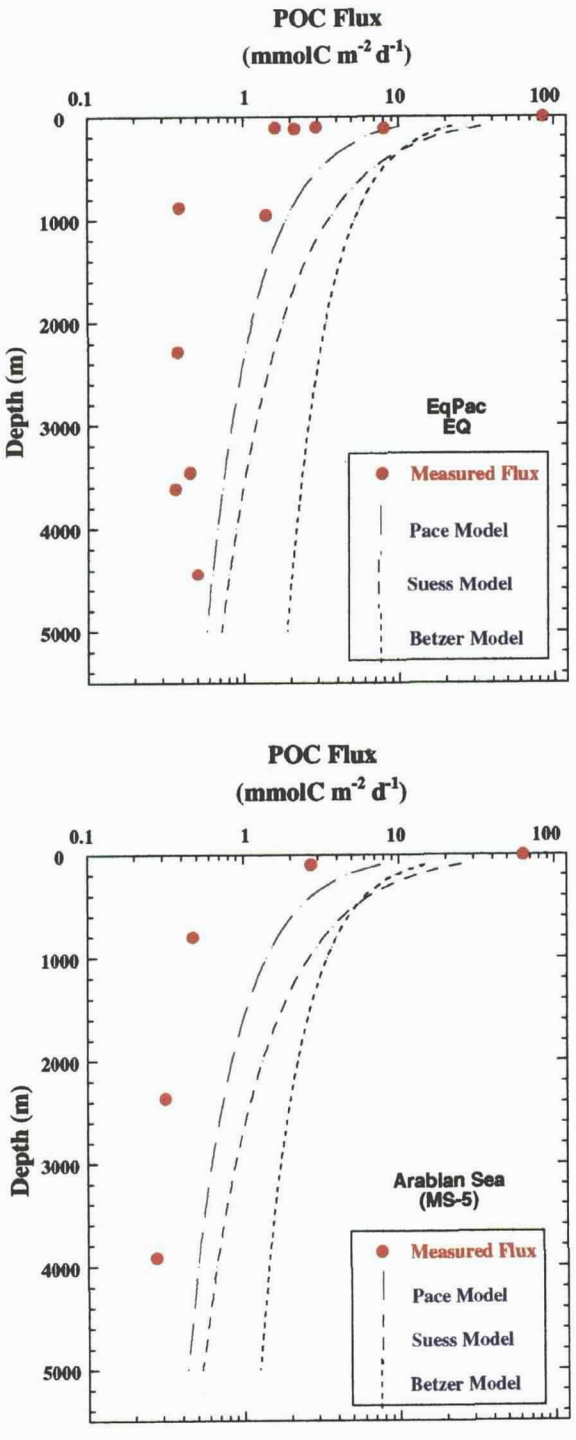

Figure 4. POC flux vs. depth at two U.S. JGOFS field sites, on the equator in the Pacific and MS-5 in the Arabian Sea. Also plotted on these figures are model predictions of POC flux as suggested by equations published by Pace et al. (1987), Suess (1980) and Betzer et al. (1984). The predicted patterns are based on the surface primary productivity values indicated in the figure. The measured POC fluxes for both stations are less than those predicted by the models.

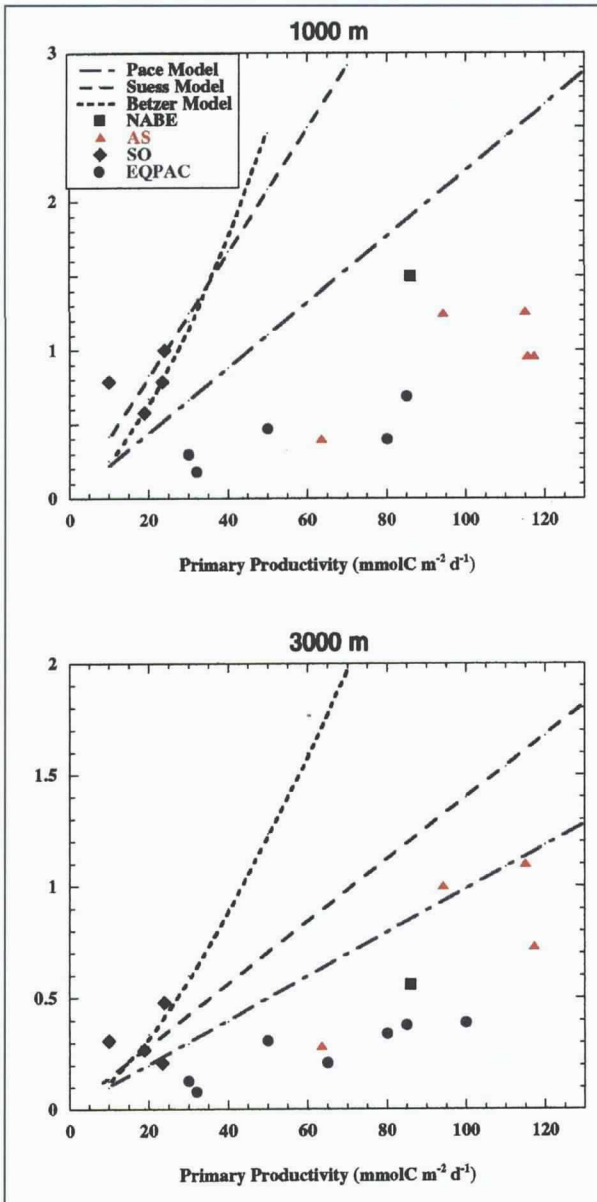

Figure 5. The relationship between primary productivity and POC rain to a depth of 1000 m (upper panel) and 3000 m (lower panel). The data are sorted by regional study area. Three model predictions are shown, one by Pace et al. (1987), one by Suess (1980) and the other by Betzer et al. (1984). The U.S. JGOFS data define a trend in primary productivity vs. POC flux that is generally linear and has a smaller slope than the model trends. Note how the SO data fall off the trend line.

with PP, a linear fit suggests that PP can account for about 70% of the variability in export of POC at 1000 m and about 80% of the variability in POC export at 3000 m. A linear fit between PP and POC export that passes through the origin defines a slope of approximately 120:1 (mmol C m^{-2} d^{-1} / mmol C m^{-2} d^{-1}) at 1000 m and approximately 150:1 at 3000 m. However, these slopes misrepresent the Southern Ocean data.

The Martin equation (Equation 1) is a commonly used parameterization in global biogeochemical models. In our analysis of this fitting equation, we find that the value chosen to represent POC export at 100 m is very important to the evaluation of the curve fit and the curve-fitting exponent b. For all 17 sites described, the total range of b values varied by a factor of 2, between 0.59 and 1.28. The greater the value of this parameter, the sharper the curvature in POC rain vs. depth. The distribution of b values shows some regional differences: for NABE, b = 1.28±0.06; for SO, b = 0.88±0.12; for AS, b = 0.79±0.11; and for EqPac, b = 0.74±0.11. The NABE export value at 100 m was derived from an average of estimates from thorium and floating-trap data and is larger than the floating-trap estimate alone; therefore the b value determined in this paper is greater than the value (0.946) reported by Martin et al. (1993), which considers only the trap data.

The shape of the Martin curve for sites from the U.S. JGOFS process studies is not significantly different from the curve fit for data from the time-series stations in the subtropical gyres. The fitting exponent b equals 0.81 for the Hawaii Ocean Time-series (HOT) site and ranges from 0.61 to 0.95 for the Bermuda Atlantic Time-series Study (BATS) site.

The uncertainty (± one standard deviation) in the regional value of b is large relative to the difference between regions. As a test of the sensitivity of this formulation, we fitted data from the equatorial Pacific, grouping all data within the latitudinal zones 2°N, equator and 2°S. Three different estimates of POC export at 100 m were fitted to the deep trap and sediment recycling data. Each method yields a different value of POC export at 100 m: 2.5 mmol C m^{-2} d^{-1} (Buesseler et al., 1995); 7.3 mmol C m^{-2} d^{-1} (Murray et al., 1996), and 3.1 mmol C m^{-2} d^{-1} (Wakeham et al., 1997). These different export values predict b values of 0.53, 0.97 and 0.61, respectively. Clearly, curvature in the Martin function is sensitive to the value chosen to represent export at 100 m, and a factor of 3 difference in flux at 100 m can affect the value of b by a factor of 2.

The fact that b values for Southern Ocean and North Atlantic sites are greater than b values for Arabian Sea and equatorial Pacific sites suggests that there may be some control on POC degradation vs. depth that is regionally specific. Although it seems counterintuitive, at sites where export below 100 m is high, degradation within the upper 1000 m occurs at an especially high rate. This relationship is shown by the positive correlation between the amount of POC export from 100 m and the b value (Figure 6). Although this trend is defined by the cumulative data set and is manifested only within the Southern Ocean regional data, the relationship between POC export and intensity of shallow degradation warrants further consideration.

There are numerous possible explanations for the correlation described above. The rate constant for POC degradation may vary regionally in association with some inherent differences in molecular composition; kinetic effects influenced by temperature structure, oxygen concentration or mineral associations may play a role. Various sites may simply develop different microbial and heterotrophic communities capable of processing POC with a greater or lesser efficiency. One might hypothesize that settling velocity is related to b, such that high b values are indicative of more slowly settling POC. We propose these hypotheses as a means of promoting further thought about the significance of the Martin equation and its application in various global models, as well as the significance of processes occurring in the "twilight zone," the region of the water column between 100 m and 1500 m where particles undergo intense remineralization.

An average of all 17 U.S. JGOFS sites yields a mean value of b = 0.82±0.16 (one standard deviation), remarkably close to the mean value defined by Martin

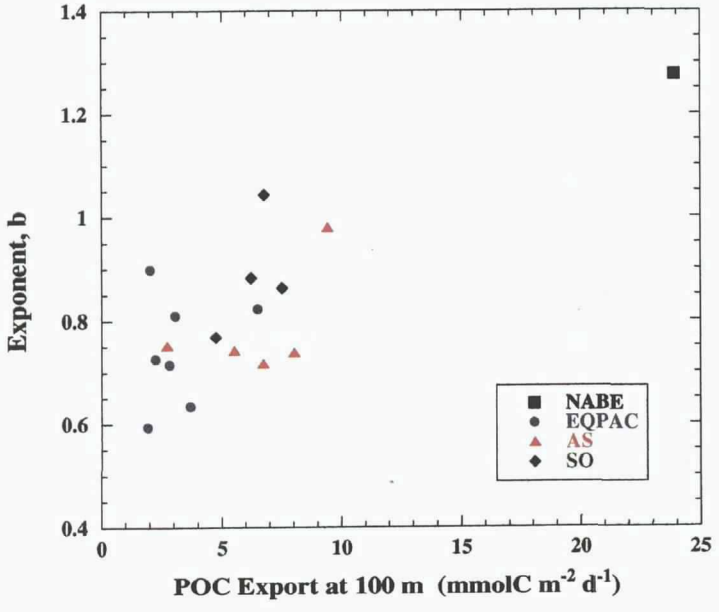

*Figure 6. The solution for the exponent b (from Equation 1), plotted as a function of POC export at 100 m. There is a positive correlation between these parameters such that b = 0.666 + 0.0255 * (POC flux). Although the correlation coefficient r-value is 0.799, the correlation is strongly driven by the NABE data value. Nevertheless, the cluster of EqPac, SO and AS points still define a positive relationship and one that has a similar slope.*

Catching The Rain Of Particles: How Accurate Are Deep-Sea Moored Sediment Traps?

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The deployment of sediment traps moored to the seafloor has been an integral part of all JGOFS programs (Honjo, 1996). Developed initially in the 1970s, moored sediment traps are still our primary means for sampling and quantifying the settling flux of particles to the deep sea, one of the key factors that regulate the global carbon cycle.

Although moored sediment traps are widely used, questions have been raised as to whether they record the vertical flux of particles accurately. The interactions between fragile particles settling through a moving fluid and intercepting conical funnels, the sediment-trap receptacle most often used for deep-sea deployments, are very complex. Controlled laboratory and field experiments have demonstrated that sediment traps may significantly under- or overestimate the vertical flux of particles, depending on their shape, size and density, the shape of the intercepting receptacle and the velocity and eddy fields surrounding it.

Two natural radionuclides (^{230}Th and ^{231}Pa) produced by radioactive decay of uranium dissolved in seawater provide an *in situ* means of assessing the efficiency of sediment traps. Uranium concentration in seawater is essentially constant. Therefore the rate of formation of ^{230}Th and ^{231}Pa is uniform throughout the water column and accurately known. Both nuclides are particle-reactive and rapidly removed from seawater by adsorption on settling particles. The two isotopes differ slightly in particle reactivity, with ^{230}Th being removed by settling particles faster than ^{231}Pa and the latter being more effectively transported laterally by eddy diffusion and advection toward regions of higher particle flux. This differential partitioning during the removal of two nuclides with identical source function can be used to predict the vertical flux of ^{230}Th from the ratio of ^{231}Pa to ^{230}Th in the intercepted settling mate-

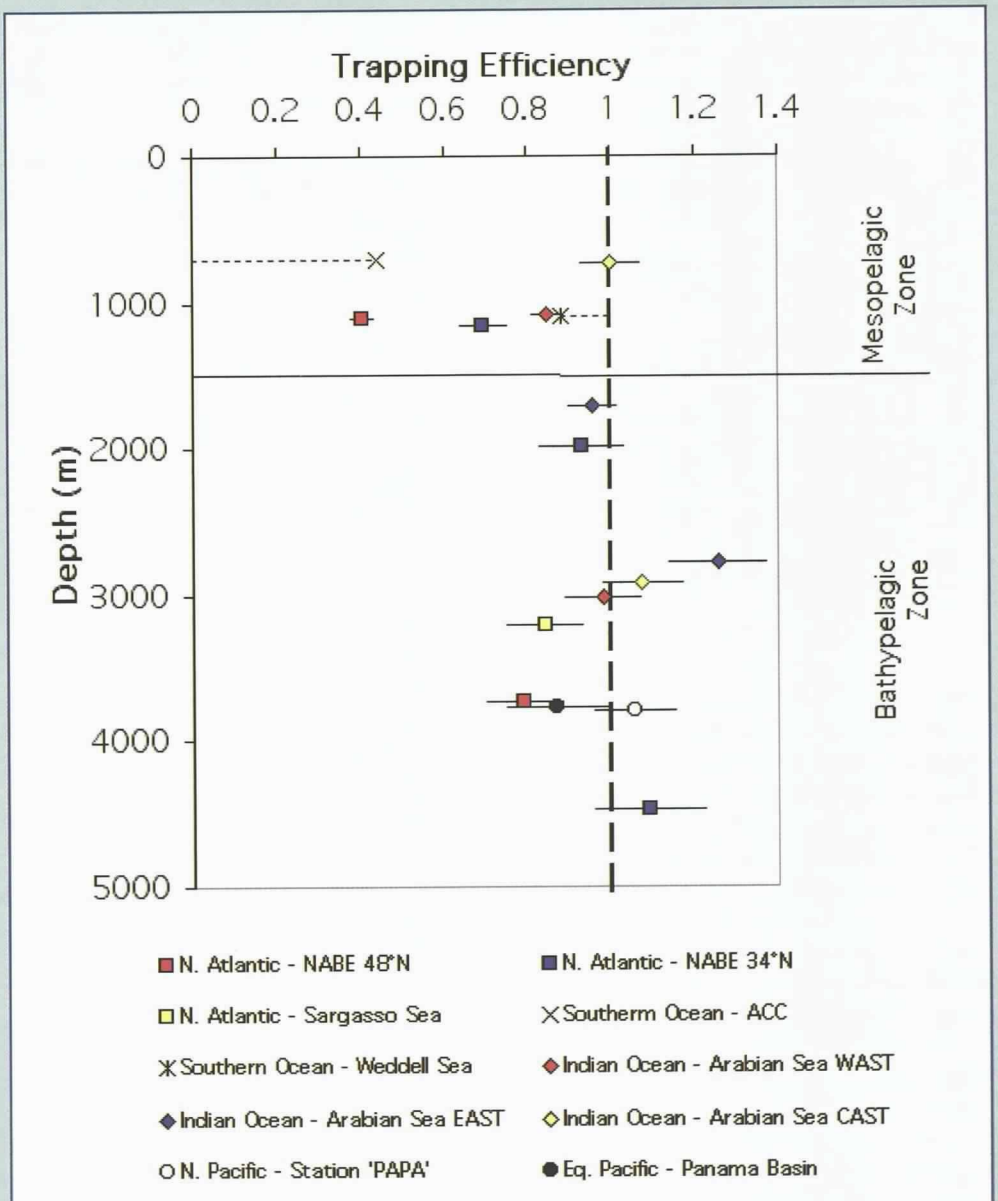

Figure a. Trapping efficiency of moored deep-sea sediment traps located at various depths and in a variety of ocean basins estimated using the differential partitioning of ^{231}Pa and ^{230}Th in settling material (adapted from Yu et al., 2001). An efficiency of 1 (x-axis) indicates 100% collection efficiency.

rial and estimates of the lateral ^{231}Pa:^{230}Th transport ratio.

Using this approach, Yu et al. (2001) have estimated the trapping efficiency of deep-sea moored sediment traps deployed in different oceanic regions (Figure a). The results show that when the traps are deployed in the bathypelagic zone (at depths >1500 m), E is approximately 1 (0.98 ± 0.14; n = 10, 1 σ), indicating that the sediment traps intercept the vertical flux of particles accurately. At shallower depths, however, trapping efficiencies are sometimes low.

Using a slightly different approach, Scholten et al. (2001) reached a similar conclusion. The reasons for the more erratic behavior of sediment traps in the mesopelagic zone are not yet clear. The low trapping efficiencies are not uniquely associated with higher current velocities, although that is a likely contributing factor. The nature and hydrodynamic properties of the settling particles, which appear to change with depth as particles lose organic matter and become more consolidated through cycles of aggregation and disaggregation, could also be an important factor.

From these results, we conclude that deep-sea moored sediment traps (in contrast to the conventional shallow surface-tethered floating traps) accurately measure the vertical flux of particles when deployed in the bathypelagic zone of the ocean. When they are deployed at intermediate depths, however, or at any depth in regions with high current velocity (typically > 10 cm s^{-1}), significant undertrapping may occur. It is thus advisable that ^{230}Th and ^{231}Pa be measured routinely with every sediment trap deployment. Once trapping efficiency is estimated, it can be used to correct the measured settling flux of important biogeochemical constituents.

Deep-sea moored sediment traps have been a very important tool and contributor to the success of JGOFS. Combining their use with radiochemical analysis will further enhance their usefulness in future programs.

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et al. (1987) of 0.86. The similarity in these values suggests great flexibility in the application of the Martin equation. However, as it is arbitrary to define export flux as beginning at 100 m, the use of a universally defined export and decay equation is also arbitrary. The U.S. JGOFS data shown here demonstrate that the fitting parameter b is not a global constant and is in many cases significantly greater or less than 0.86.

This analysis leaves many other major questions for future consideration. One is whether the sediment trap data are accurate. Work by Yu et al. (2000) indicate that some traps, especially those located at depths less than 1500 m, tend to undertrap the rain of particles (see sidebar by François, this issue). The correction of such a systematic error would shift b toward a lower value. Another uncertainty in the trap data involves the contribution of "swimmers," especially in the shallower traps. The development and use of indented rotating sphere traps (Peterson et al., 1993) and the good agreement between these and other trap data (Lee et al., 1998) suggest that many of the "swimmer" problems can be greatly reduced. Sediment recycling rates provide an excellent check for deep trap flux values. Although these rates depend on assumptions about diagenetic reaction stoichiometries and transport mechanisms, these two approaches converge in defining the POC rain into the deep sea.

Summary

The picture of POC transport through the entire water column has sharpened as a direct result of U.S. JGOFS research. Although carbon export into the deep water is positively correlated with primary productivity, the relationship we see may be regionally dependent. Small changes in PP result in greater differences in POC flux into the ocean interior in the Southern Ocean than occurs in temperate and tropical regions.

The Martin equation, a function that describes the flux of POC below 100 m, has been applied to data assembled from 17 locations. This formulation is very sensitive to the value assigned to POC export at 100 m. While one of the virtues of the data set discussed in this paper is that at most sites the same methods were used to determine POC export, great uncertainty still exists about how best to quantify export at 100 m. Therefore great uncertainty exists about the significance of the Martin equation fit.

Regions with greater export from 100 m have larger values for the curve-fitting exponent b (Figure 6).

Many global circulation models rely on equations describing the respiration of POC as a function of depth. This process is particularly important in the upper 1000 m of the water column. Thus the formulation and mechanistic explanation of the Martin equation will require the analysis of more regional data than has been attempted thus far. Although the b value of 0.86 that was defined by Martin et al. (1987) is very close to the average value for all the U.S. JGOFS regional sites considered (b = 0.82), there is a factor of 2 in the range of this parameter, from 0.6 to 1.3. The global average value hides important differences in controls of b, and the U.S. JGOFS regional studies have opened a door to the further examination of these differences.

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