An improved "benchmark" method for estimating particle settling velocities from time-series sediment trap fluxes

by

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Abstract

A new method, based on fitting Fourier series to time-series (TS) data from sediment traps, has been developed to estimate the settling velocities (SV's) of sinking particles in the open ocean. This new method was applied to data from MedFlux, as well as from the US JGOFS NABE, EqPac, and ASPS studies. Fluxes of mass and of four chemical tracers, as well as the molar ratios of the latter, were plotted on logarithmic scales; Fourier series were then fit to these data. In each case we determined the most likely sinking velocity using a likelihood-based nonlinear fitting algorithm. Variation among estimates using single tracers was significantly less than variation using tracer ratios; we therefore concluded that estimates based on single tracers are to be preferred to estimates based on tracer ratios. Our results also showed no obvious differences among SV's estimated using different single tracers. The best estimate of settling velocity using single tracer fluxes with good temporal resolution (i.e, for sites with cup rotation times $\leq$ 8.5 days) is 205 m/d, with standard deviation 74 m/day. For MedFlux data alone (which has a resolution of 4-6 d), the estimate is 220 $\pm$ 65 m/d. This latter value is within 10% of the estimate of average sinking velocity (242 $\pm$ 31 m/d) made using MedFlux IRS traps in "sinking velocity" mode.

Keywords: settling velocity, sinking particles, benchmark method, Fourier series, time-series sediment trap, DYFAMED, US JGOFS, MedFlux

Running title: estimating particle settling velocities

1. Introduction

Sinking particles are major vehicles for transporting organic carbon from surface waters to the deep ocean. This transport reduces the partial pressure of carbon dioxide (the pCO_2) in the surface mixed layer, allowing the ocean to take up more atmospheric CO_2 than would otherwise be possible (Sarmiento and Gruber, 2006). Because it determines the residence time of sinking particles in the water column, settling rate is one of the major factors that determine the depth at which organic carbon is remineralized. Therefore, accurate estimation of settling velocity is critical for understanding mechanistically the role of the ocean in determining atmospheric CO_2.

Recently it has been conjectured that the flux of organic carbon is determined by its quantitative association with ballast minerals (opal for diatoms; calcite for coccolithophorids and foraminifera; aragonite for pteropods; and dust; see Armstrong et al., 2002; François et al., 2002; Klaas and Archer, 2002). In the MedFlux program we have been seeking to identify mechanisms that determine observed patterns, so that we can understand and predict their variability in space and time. A central focus of our research has developed around the use of Indented Rotating Sphere (IRS) sediment traps in "settling velocity" (SV) mode (Peterson et al., 2005, and this volume; see also Armstrong et al., this volume; Lee et al., this volume). These traps sort particles into settling velocity classes, enabling flux estimates and chemical analyses of particles as functions of settling velocity. In an analysis of mass fluxes during the eight deployments of these settling velocity traps, Armstrong et al. (this volume) estimated *modal* settling velocities (that is, settling velocities with the highest mass fluxes per settling velocity interval) of "fast settling" particles to be 353 m/d, with a standard deviation of 76 m/d, while the *average* velocities of the “fast sinking” fraction is much lower: 242 ± 31 m/d. These values are somewhat (but not radically) higher than the “canonical” range 80-200 m/d (Honjo, 1996; Siegel and Deuser, 1997; see also Armstrong et al., this volume).

The method of choice for assessing settling velocity using time-series trap data is to compare the time of arrival of a sediment peak at one depth to its time of arrival at a deeper depth; this approach has become known as the “benchmark” method (Deuser et al., 1981; Honjo, 1996). In the present case, a “benchmark” estimate of settling velocities is made possible by the fact that IRS traps can also be deployed in “time series” (TS) mode (Peterson et al., 2005). In TS mode, the IRS valve is rotated several times per day, and the sediment on the IRS valve is deposited in whichever cup is open at the time of rotation. We analyzed MedFlux time-series data statistically to give an estimate of sinking velocity at the DYFAMED site that was independent of the estimates from “settling velocity” (SV) mode. In addition, we reanalyzed data from the North Atlantic Bloom Experiment (NABE) (Honjo and Manganini, 1993) and from the US JGOFS Equatorial Pacific study (EqPac) and Arabian Sea Process Study (ASPS) used by Berelson (2002). This analysis was performed using a new, more powerful implementation of the benchmark method.

Using time-series trap data from the US JGOFS EqPac and ASPS studies, Berelson (2002) estimated particle settling velocities to be 83 – 331 m/day. Berelson used ratios of organic carbon (OC), biogenic Si (BioSi), Ca, and Al fluxes from different depths in the water column, arguing that ratios may have less measurement error than do measurements of individual tracers, and so would be more useful for assessing sinking velocity. While the first statement may be true, the second – that ratios are better for assessing sinking velocity – is not, as will be shown below.

For each tracer ratio at each site, Berelson (2002) regressed the ratio measured in cup n in a deep trap on the same ratio measured in cup m in a shallower trap; his goal was to estimate how much time (in terms of cup rotation intervals) it took for a pattern of fluxes in the shallower trap to reach the depth of the deeper trap. Berelson performed separate regressions for a range of integer cup delays $n - m = \{0,1,2\ldots\}$ between upper and lower traps. The "best" cup shift, which was used in calculating the settling velocity of particles from the upper depth to the lower depth, was determined (roughly) as the shift having the largest average regression coefficient across tracer ratios. Settling velocities were then calculated as (depth difference)/(("best" cup shift)*(cup rotation time)). However, in most cases (14 of 18 in Berelson's study), the no-shift case $n - m = 0$ showed the best correlation. To avoid the possibility of infinite settling velocity (= depth difference/($n - m$)), Berelson made the assumption that when the best shift was $n - m = 0$, he would use a cup shift of 0.5 cups. This assumption inflates the transit time between depths, and so biases Berelson's results towards lower settling velocities.

This problem notwithstanding, Berelson then compared settling velocities between "shallow" trap pairs to settling velocities between "deep" trap pairs. This comparison was made separately for EqPac and ASPS. However, within each of these data sets, he did not specifically compare deep and shallow estimates from the same site; e.g., for the EqPac comparison he used shallow settling velocities from the Equator, 5N. and 5S, while the deep velocities were from the Equator, 5N, and 12S. He concluded that settling velocity tended to increase with depth.

There are three problems with this conclusion. First, since most of the cup shifts were 0.5 cups, his sinking velocity estimates depend more on the spacing between traps than on their time offsets. Second, the composition of settling material, and hence its settling velocity, may depend as much or more on site than it does on depth; it would therefore be highly desirable to make depth comparisons only within sites. Third, in sites with traps at three depths, data from the middle trap were used to estimate time offsets between both the upper pair of traps and the lower pair of traps; any error in the middle trap thus shows up in both upper SV and the lower SV, causing them to be negatively correlated.

To avoid these problems, we devised a method whereby three Fourier series, differing only in their absolute timing, were fit simultaneously to data from shallow, middle, and deep traps at each site where data from three depths were available. (See Materials and Methods for details.) The estimated timing differences were then used in settling velocity calculations. In our method, timing differences can be any real number, and are not restricted to integer multiples of cup rotation time.

Here we apply this new method to data from MedFlux, from the US JGOFS NABE, and from the studies used by Berelson (2002). We also present results on whether measurements of single elements or ratios of elements are better indicators of settling velocity. We compare the estimated SV's to those found by Berelson (2002) and to estimates from MedFlux SV traps. Finally, we comment on the minimum timing between successive time-series cups needed to achieve satisfactory results.

2. Materials and methods

2.1 Sample collection

Particles in the MedFlux study were collected using IRS (Indented Rotating Sphere) time-series sediment traps (Peterson et al., 2005) at the DYFAMED site (43°25'N, 7°52'E) in the northwestern Mediterranean Sea (http://alpha1.msrc.sunysb.edu/MedFlux/). Separate collections were made from March to May in 2003, from May to June in 2003, and from March to April in 2005. IRS traps have 11 collection cups, plus a twelfth position that is open during trap deployment and retrieval. During deployment, each cup was open for a programmed interval of 4 to 6 days. Trap depths and deployment dates for each deployment are listed in Tables 1 and 2. Total mass and masses of ballast elements (inorganic carbon (IC), biogenic silica (BioSi), and aluminum (Al)) and organic carbon (OC) were measured after collection. Total Si, not BioSi, was measured in March to April 2005.

We also analyzed data from the US JGOFS North Atlantic Bloom Experiment (NABE), equatorial Pacific (EqPac), and Arabian Sea (ASPS) studies. These data were collected by Honjo and others (Honjo and Manganini, 1993; Honjo et al., 1995; Honjo et al., 1999) between 1989 and 1995; they are available on the US JGOFS website (http://usjgofs.whoi.edu/). Generally, time-series cups in NABE, EqPac, and ASPS were open for 14, 17, and 8.5 days, respectively. Many of these traps have continuous data for an entire year. For NABE 34N, fluxes at the shallow trap for the first half-year were much lower than those for middle and deep traps; many were close to zero, perhaps due to some technical problem during sampling. We therefore considered only data from the second half-year in our study.

2.2 Statistical Methods

We fit Fourier series expansions to the time-series data described in the previous section. We used Fourier series only to characterize the temporal patterns occurring at successive depths, so that these patterns could be aligned and their time-offsets estimated; we did not use these fits to estimate the "power" associated with each mode, or any other potential use of Fourier series.

Usually data from a triplet of traps, (a shallow trap, a mid-depth trap, and a deep trap), deployed during the same time period, were analyzed together. All data (either for a single tracer, or for ratios between two tracers) were pretreated by transforming onto a logarithmic scale, followed by subtracting the mean of TS sample for each depth before analysis, leaving only the temporal pattern. These three sets of pretreated time series data were then fit simultaneously to the following harmonic curves:

$$\begin{aligned}
\widehat{F}_s(t_j) &= \sum_{k=1}^{m} a_k \cos(k\omega(t_j - \phi_{sk})) \\
\widehat{F}_m(t_j) &= p_{sm} \cdot [\sum_{k=1}^{m} a_k \cos(k\omega(t_j - \phi_{sk} - \frac{\Delta z_{sm}}{SV_{sm}}))] \\
\widehat{F}_d(t_j) &= p_{sd} \cdot [\sum_{k=1}^{m} a_k \cos(k\omega(t_j - \phi_{sk} - \frac{\Delta z_{sm}}{SV_{sm}} - \frac{\Delta z_{md}}{SV_{md}}))] \quad .
\end{aligned} \tag{1}$$

In Eq. (1), $\hat{F}_s(t_j)$, $\hat{F}_m(t_j)$, and $\hat{F}_d(t_j)$ are model predictions of pretreated time series data at shallow (*s*), middle (*m*), and deep (*d*) traps, respectively, at the time of closing t_j of the *j*th collection cup. In equation (1), a_k is the amplitude and ϕ_{sk} is the phase shift for the *k*th Fourier component for the shallow layer; ω is the frequency (d^{-1}) of the first Fourier component at $k = 1$; Δz_{sm} and Δz_{md} are depth differences between shallow and middle, and middle and deep traps, respectively; and SV_{sm} and SV_{md} are the corresponding mean settling velocities (SV's) for particles in these two depth intervals. The ratios $\Delta z_{sm} / SV_{sm}$ and $\Delta z_{md} / SV_{md}$ are therefore the estimated delays (or offsets) of the fitted pattern between shallow and mid-depth traps, and between mid-depth and deep traps, respectively. Losses of material with depth are reflected in the parameters p_{sm} and p_{sd}. At the MedFlux DYFAMED site and at EqPac-12S, only two traps were deployed; therefore only the shallow and middle equations were considered in Eq. (1).

Since particle fluxes have well-defined annual cycles, we used one year as the fundamental period if the length of data set was equal to or more than one year. Otherwise, we chose the fundamental period to be the closest integer divisor of 366 days. For example, the fundamental period for a 61-day time series was taken to be 61 (= 366/6) days, and the fundamental period for a 170-day series was 183 (=366/2) days.

Maximum likelihood is a well-known statistical method for finding the most likely values for a set of parameters. The logarithm of the likelihood, log(likelihood), is usually used instead of likelihood itself because likelihood is often a very small value and it can be interpreted more easily with a logarithm scale (Edwards, 1992; Hilborn and Mangel, 1997; Burnham and Anderson, 1998; Armstrong et al., 2002). In this study, data points were fit by maximizing log(likelihood) values $\log(L)$ using the following equation:

$$\log(L) = -n\left[\log(\sigma) + \frac{1}{2}\log(2\pi)\right] - \sum_{j=1}^{n} \frac{(Y_j - \hat{Y}_j)^2}{2\sigma^2} \quad . \qquad (2)$$

Eq. (2) is based on a normal error distribution for the difference between the observed and predicted values: the Y_j are observed shallow, middle, or deep layer data points, the $\hat{Y}_j$ are predicted values at these points, *n* is the number of data points in the time series, and σ is the standard deviation for the difference between Y_j *and* $\hat{Y}_j$. The value of *m*, the number of Fourier components, was usually between 5 and 7; adding additional Fourier components increased $\log(L)$ very little. Estimated settling velocities SV_{sm} and SV_{md} were constrained to be in the range 10 – 1000 m/day.

Berelson (2002) used linear-scale molar ratios for SV estimation. Here we used log-transformed ratios to remove the asymmetry between A/B and B/A: fits using A/B may give different results than fits using B/A, whereas log(A/B) = log(A) – log(B) = –log(B/A), so that a fit of log(A/B) yields a temporal pattern that is identical (except for sign) to a fit of log(B/A). For the single-tracer fits, we used Inorganic Carbon (IC) rather than Ca, which was used by Berelson (2002) to represent $CaCO_3$, assuming that all IC is in $CaCO_3$. For comparing the use of single tracers to the use of ratios, we used only the three ratios OC/Al, OC/BioSi, and OC/IC because the other ratios are not independent. We also performed fits on log-transformed data using mass fluxes and fluxes of the four elemental tracers discussed above.

3. Results

3.1. Log-transformed (single tracers) or log(tracer ratios)?

3.1.1. Insights from MedFlux March – May 2003

Settling velocities (SV's) were estimated from log-transformed data on mass fluxes and fluxes of four chemical tracers, and on three different elemental molar ratios (OC/Al, OC/BioSi, and OC/IC), for time-series sediment traps data from the MedFlux DYFAMED site in March to May 2003 (Table 1, first row). Estimates of settling velocity based on molar ratios had a higher mean settling velocity (393 m/d) and a much larger coefficient of variation (*cv* = 0.82) than estimates from single tracers (mean 216 m/d and *cv* = 0.22). To explore the basis for these results, we plotted (Fig. 1) time series of fluxes, plus model fits, for both single tracers and their molar ratios at shallow (238 m) and middle depths (771 m). The top five panels in Fig. 1 show results using fluxes of mass and of the four chemical tracers. These figures show that different single tracers yield slightly different estimates of settling velocity. However, these differences are minor (range: 144 – 276 m/d), so that use of one tracer in preference to another should be made on scientific, as opposed to statistical, grounds.

The bottom 3 panels in Fig. 1 show that fits using molar ratios can produce SV estimates that vary widely (range: 181 – 761 m/d). There is almost no visible cup delay between upper and lower layers using OC/IC as the tracer; but the other two molar ratios (OC/Al and OC/BioSi) show obvious shifts between these two depths.

This difference may be explained as follows: use of molar ratios combines temporal patterns from two tracers; for example, log(OC/Al) = log(OC) – log(Al) depends on both OC and Al. If the two tracers in a ratio have contrasting temporal patterns, the resulting overall pattern will be enhanced; but if they have similar patterns, the signal will be reduced. This difference may help explain the large coefficient of variation in the fits using tracer ratios, and argues for choosing single elements for SV estimation. The using of molar ratios by Berelson (2002) for assessing sinking velocity may not an appropriate method.

3.1.2. Analysis of the complete data set

To investigate quantitatively how well single tracers and tracer ratios work for the complete data set, we estimated SV's at all the open-ocean sites (4 couplets and 11 triplets of traps; see Table 1) using the same tracers.   Data from EqPac 5S were excluded because the sediment traps at this station were too close to one another in depth. Estimated SV's are shown in Table 1, along with the summary statistics {mean, standard deviation *sd*, and coefficient of variation $cv = sd$ / mean}, both for SV's estimated using single tracers and SV's estimated using tracer ratios.

As shown in Table 1, most (21 of 26) of the *cv*'s estimated using elemental molar ratios are higher than those obtained using single tracers. A nonparametric one-sided binomial test was applied to this ratio (*cv*) shows $(cv)_{\text{single tracer}} < (cv)_{\text{ratios}}$ to be significant at $p < 0.001$. We conclude that use of single elements gives more consistent results across tracers; single elements were therefore used for the SV estimation in the rest of this paper.

3.2. Particle SV's estimated using log(single tracers)

Table 2 gives time offsets ($\Delta z_{sm} / SV_{sm}$ or $\Delta z_{md} / SV_{md}$) for sinking particles from 4 couplets and 11 triplets of time-series sediment traps, and the best-fit settling velocities estimated from them, for total mass and for the four chemical tracers, respectively. Examination of these results showed that not all estimates were of equal quality. For the MedFlux DYFAMED site, estimated cup shifts were between 0.87 and 10.5 days, with an average of 4.59 days; estimated delays were therefore comparable to the DYFAMED cup rotation time (4 – 6 days). In contrast, many of the deployments at NABE and EqPac had much longer cup rotation schedules; the estimated delay was often only a fraction of a cup.

To assess the importance of this resolution issue for our estimates of settling velocity, we divided the data set into three groups: the first group included only MedFlux data (15 estimates); the second group included all estimates made using data from traps with rotation times ≤ 8.5 d (75 estimates, including those from MedFlux); and a third group with rotation times ≥ 14 d (55 estimates). (Estimates from EqPac 5S, were again excluded.)

The cumulative distribution functions (cdf) for these three groups are shown in Fig. 2. First, the cdf from MedFlux data is S-shaped, which is typical of a unimodal distribution; this unimodality is confirmed in Fig. 3. In contrast, neither of the other two groups is ‘S’ shaped: both curves have a relatively flat region between 400 and 600 m/d, which means that few SV’s fall in this range. The histograms (Fig. 3) for SV’s of these two groups show clearly that both groups have two modes, centered at ~175 and 800 m/d for the high-resolution data and at ~100 and 850 m/d for the low-resolution data. The distribution for the total data set is also bimodal, with modes at ~150 and 875 m/d.

We interpret these results as implying that the MedFlux results, being of the highest resolution, are unimodal because their resolution is sufficient to allow the Fourier method to work well in almost all cases. In contrast, at many other sites the data are not sufficiently resolved to allow the method to pick out a pattern. In these cases, the fact that we imposed a maximum SV of 1000 m/d has caused results to pile up in an apparent second mode, which we deem to be an artifact.

To eliminate this artifact, we analyzed the data in Fig. 3 by excluding any SV > 400 m/d, which visually appears as a natural break point in Fig. 3. The means and standard deviations of the remaining data (also highlighted in gray color in Table 2 for settling velocities) are listed in Table 3. The average settling velocity increases with increasing resolution (from 126 m/d for low-resolution data, to 205 m/d for high-resolution data, to 220 m/d for MedFlux data), while the standard deviation and coefficient of variation decrease. We conclude that the relatively slow sinking speeds of classical studies (summarized in Honjo, 1996) are at least partly due to the low resolution of the data available at that time.

3.3. Do sinking velocities increase or decrease with depth?

In Table 4 we compare cup offsets and inferred sinking velocities for all data in our study. As noted in the Introduction, Berelson (2002) concluded that sinking velocity increases with depth. His conclusion is based on a comparison of SV's estimated at "shallow" and "deep" trap pairs; this comparison was made separately for ASPS and EqPac. In each of these regions, "shallow" SV's were pooled and compared to pooled "deep" SV's in the same region; no attempt was made to compare shallow and deep traps from the same site. Berelson's conclusion (his figure 5) was that settling velocity increases with depth. Comparing the error bars in his figure, it is clear that this trend was statistically significant at EqPac but not at ASPS.

Berelson's estimates of sinking velocities (Table 4; results taken from his Table 1, but excluding the result from EqPac 5S) support his conclusion: in 6 out of 8 cases, the SV between the deeper trap pair was greater than the SV between the shallower trap pair. However, Table 4 also contains SV's estimated using our Fourier technique, which allows an analysis based on shallow and deep trap pairs at the same site. Considering only the data from EqPac and ASPS used by Berelson (2002), our estimates indicate that the deep SV was greater than the shallow SV at only 3 of 9 sites; when the NABE sites are added, deep SV's were greater at only 5 of 11 sites. Our results stand in contradiction to those of Berelson (2002). However, since none of these results (including Berelson's) is statistically significant (exact binomial tests), we conclude that these data by themselves do not provide strong evidence for or against an increase of sinking velocity with depth.

Table 4 also contains a comparison of cup shifts estimated in the present paper with those reported in Berelson (2002). For EqPac and ASPS, Berelson reported 4 cup-shifts of 1.0 cup and 14 cup-shifts of 0.5 cup. Our procedure produced cup shifts between 0.10 and 1.10. For the 18 cup shifts that can be compared between studies, 12 of ours were shorter than those in Berelson (2002), and the other 6 were slightly longer than Berelson's.

4. Discussion

We estimated sinking velocities between 26 pairs of traps, in each case making 5 estimates using different tracers. In each case we determined the most likely value for the velocity at which signals are propagating down the water column. We then computed the averages of these velocities across tracers. Since estimates using different tracers are not independent, we cannot test whether results using different tracers differ significantly in a statistical sense. However, note that among the 15 couplets of high-resolution traps (3 from MedFlux and 12 from ASPS, indicated in bold in Table 2), settling velocities for all tracers were <400 m/d in 7 couplets, all SV's were >400 m/d in 3 couplets, and SV's were mixed in 5 couplets. More interesting, when aluminum is excluded as a tracer, all SV's are <400 m/d in 10 couplets, all are >400 m/d in 4 couplets, and estimates are mixed in only one couplet. These results suggest that even if differences among tracers do exist, they are usually unimportant (at least if Al is excluded as a tracer). They also suggest that use of Al in tracer ratios (Berelson, 2002) may lead to problems in SV estimation, perhaps because of the "excess aluminum" problem (see Lee et al., this volume). Excess aluminum was defined as the difference between total Al and the lithogenic Al (Dymond et al, 1997).

In the present study, we estimated the average SV to be slightly more than 200 m/day. Assuming that two traps are deployed 1000 m apart, it would take about 5 days for sinking particles to settle from the upper trap to the lower trap. To have an offset comparable with the cup rotation time, sampling would need to be done with 5-day or better resolution time for each cup. For the DYFAMED site, average cup shifts for each deployment interval were between 0.38 and 1.83, with a grand average of 0.89 cup, so that the estimated shift was comparable to the resolution of the data at DYFAMED (4 to 6 days). An interesting study would be to simulate sinking of a spectrum of particles, simulate sampling by a depth series of sediment traps, then see what resolution would be needed to capture the time delays in the patterns. However, to produce reliable results such a study would require use of a sophisticated model of particle interaction. Since the data on which such a model might be produced are only now becoming available (Armstrong et al., this volume; Trull et al., in press), such a study would at this point be premature.

Finally, one of the distinct advantages of our method is that it can be used to estimate SV's between 2 or more pairs of traps at the same time; it therefore provides a method for investigating whether sinking velocity increases with depth that is free from the statistical correlation problems outlined in the Introduction. In Table 5 we have listed all 11 triplet traps, with the difference for log(likelihood) between two cases: in case A we allowed two SV's, one between the upper and middle traps and one between the middle and lower traps; in case B we fitted only a single SV for the whole water column.

To justify an extra parameter (2 SV's instead of 1), the log(likelihood) in case B must be at least 2 log(likelihood) points above that for case A (Hilborn and Mangel, 1997). This criterion was met for all tracers at only one station (NABE 34N), and only for a few tracers at other two station (ASPS 2SW and ASPS 5). Curiously, both the NABE 34N and the ASPS 5 sites were "low resolution" (Table 2), with ≥ 14 d cup rotation times. We again conclude that there is no strong evidence for increased sinking velocities with depth.

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Station	deployment interval	Depth (m)		SV (m/d) by log(tracer)								SV(m/d) by log(tracer ratio)					
		upper	lower	mass	OC	IC	BioSi	Al	mean	sd	cv	OC/Al	OC/BioSi	OC/IC	mean	sd	cv
MedFlux	3/06/03-5/06/03	238	771	210	229	224	276	144	216	48	0.22	235	181	761	393	321	0.82
	5/14/03-6/30/03	117	1918	172	231	293	219	179	219	49	0.22	115	320	507	314	196	0.62
	3/4/05-4/28/05	313	924	169	180	165	389	702	321	233	**0.73**	212	283	49	181	120	**0.66**
NABE-48N	4/3/89-4/2/90	1110	2109	47	116	59	40	45	61	31	0.51	787	19	680	495	415	0.84
		2109	3734	145	252	176	52	61	137	83	0.61	825	49	778	550	435	0.79
34N	10/16/89-4/2/90	1248	1894	111	175	115	102	82	117	35	0.3	577	828	249	551	290	0.53
		1894	4391	615	571	350	688	987	642	230	**0.36**	498	527	711	579	116	**0.2**
EqPac-Equator	2/02/92-1/07/93	880	2284	930	878	883	780	851	864	55	0.06	28	29	61	39	19	0.48
		2284	3618	233	54	609	118	294	262	216	0.83	688	804	12	501	428	0.85
12S	2/02/92-1/07/93	1292	3594	142	879	109	47	53	246	356	**1.45**	79	151	386	206	161	**0.78**
5N	2/02/92-1/07/93	1200	2100	131	113	154	122	121	128	16	0.12	43	378	744	388	351	0.9
		2100	3800	859	829	950	859	717	843	83	0.1	27	914	43	328	507	1.55
ASPS-2NE	11/13/94-4/26/95	903	1974	252	818	719	782	682	650	229	0.35	84	965	931	660	499	0.76
		1974	3141	245	291	263	241	305	269	28	0.11	858	810	530	733	177	0.24
3NE	12/2/94-2/8/95	858	1857	833	657	719	908	768	777	98	0.13	348	249	699	432	236	0.55
		1857	2871	780	852	542	922	780	775	143	0.18	719	10	786	505	430	0.85
4NE	11/13/94-4/26/95	821	2229	190	167	139	232	749	296	256	**0.87**	258	891	741	630	331	**0.52**
		2229	3478	142	194	148	134	53	134	51	0.38	251	886	223	453	375	0.83
2SW	5/25/95-9/09/95	924	1996	153	275	166	188	71	170	73	0.43	949	531	270	583	343	0.59
		1996	3159	98	76	82	116	736	222	288	**1.3**	214	843	89	382	404	**1.06**
3SW	6/28/95-9/17/95	888	1882	297	262	365	271	290	297	41	0.14	103	450	127	226	194	0.86
		1882	2991	186	205	161	293	186	206	51	0.25	760	284	645	563	248	0.44
4SW	6/11/95-8/23/95	807	2215	880	787	880	833	674	811	86	0.11	805	204	127	379	371	0.98
		2215	3489	584	462	754	582	224	521	196	0.38	45	13	564	207	309	1.49
5	12/6/94-4/30/95	800	2363	145	90	191	134	94	130	41	0.32	965	44	930	646	522	0.81
		2363	3915	499	848	877	800	658	736	157	0.21	228	125	792	382	359	0.94

Table 1 Settling velocities (SV's) estimated using either single tracers or tracer ratios. Stations with triplets of traps (shallow, middle, deep) are highlighted in gray. Data from EqPac 5S were excluded because the sediment traps at this station were deployed too closely in depth. Summary statistics (mean, standard deviation (*sd*), and coefficient of variation $cv = sd$ / mean) are listed in each row. In 21 of 26 cases, the *cv* for single tracers was less than the *cv* for ratios; this proportion is significant at $p < 0.001$ (exact binomial test).

Station	deployment	Depth (m)		cup rotation	offset (d)					Settling velocity (m/day)				
	interval	upper	lower	period (d)	log(mass)	log(OC)	log(IC)	log(BioSi)	log(Al)	log(mass)	log(OC)	log(IC)	log(BioSi)	log(Al)
MedFlux	**3/06/03-5/06/03**	**238**	**771**	**5.5**	**2.54**	**2.33**	**2.38**	**1.93**	**3.71**	**210**	**229**	**224**	**276**	**144**
	5/14/03-6/30/03	**117**	**1918**	**4.5**	**10.5**	**7.8**	**6.14**	**8.21**	**10.08**	**172**	**231**	**293**	**219**	**179**
	3/4/05-4/28/05	**313**	**924**	**5**	**3.62**	**3.4**	**3.7**	**1.57**	**0.87**	**169**	**180**	**165**	**389**	**702**
NABE-48N	4/3/89-4/2/90	1110	2109	14	21.4	8.61	16.9	24.9	22.1	47	116	59	40	45
		2109	3734	14	11.2	6.45	9.21	31.3	26.6	145	252	176	52	61
34N	10/16/89-4/2/90	1248	1894	14	5.84	3.69	5.6	6.33	7.91	111	175	115	102	82
		1894	4391	14	4.06	4.37	7.13	3.63	2.53	615	571	350	688	987
EqPac-Equator	2/02/92-1/07/93	880	2284	17	1.51	1.6	1.59	1.8	1.65	930	878	883	780	851
		2284	3618	17	5.72	24.9	2.19	11.3	4.53	233	54	609	118	294
12S	2/02/92-1/07/93	1292	3594	17	16.2	2.62	21.2	49.2	43.7	142	879	109	47	53
5N	2/02/92-1/07/93	1200	2100	17	6.85	7.96	5.86	7.38	7.45	131	113	154	122	121
		2100	3800	17	1.98	2.05	1.79	1.98	2.37	859	829	950	859	717
ASPS-2NE	**11/13/94-4/26/95**	**903**	**1974**	**8.5**	**4.25**	**1.31**	**1.49**	**1.37**	**1.57**	**252**	**818**	**719**	**782**	**682**
		1974	**3141**	**8.5**	**4.76**	**4.01**	**4.44**	**4.84**	**3.82**	**245**	**291**	**263**	**241**	**305**
3NE	**12/2/94-2/8/95**	**858**	**1857**	**8.5**	**1.2**	**1.52**	**1.39**	**1.1**	**1.3**	**833**	**657**	**719**	**908**	**768**
		1857	**2871**	**8.5**	**1.3**	**1.19**	**1.87**	**1.1**	**1.3**	**780**	**852**	**542**	**922**	**780**
4NE	**11/13/94-4/26/95**	**821**	**2229**	**8.5**	**7.41**	**8.42**	**10.1**	**6.07**	**1.88**	**190**	**167**	**139**	**232**	**749**
		2229	**3478**	**8.5**	**8.81**	**6.43**	**8.44**	**9.35**	**23.6**	**142**	**194**	**148**	**134**	**53**
2SW	**5/25/95-9/09/95**	**924**	**1996**	**8.5**	**7.02**	**3.9**	**6.46**	**5.7**	**15.2**	**153**	**275**	**166**	**188**	**71**
		1996	**3159**	**8.5**	**11.9**	**15.4**	**14.2**	**10**	**1.58**	**98**	**76**	**82**	**116**	**736**
3SW	**6/28/95-9/17/95**	**888**	**1882**	**8.5**	**3.35**	**3.8**	**2.72**	**3.67**	**3.43**	**297**	**262**	**365**	**271**	**290**
		1882	**2991**	**8.5**	**5.95**	**5.4**	**6.89**	**3.79**	**5.95**	**186**	**205**	**161**	**293**	**186**
4SW	**6/11/95-8/23/95**	**807**	**2215**	**8.5**	**1.6**	**1.79**	**1.6**	**1.69**	**2.09**	**880**	**787**	**880**	**833**	**674**
		2215	**3489**	**8.5**	**2.18**	**2.76**	**1.69**	**2.19**	**5.7**	**584**	**462**	**754**	**582**	**224**
5	12/6/94-4/30/95	800	2363	17	10.8	17.4	8.2	11.7	16.7	145	90	191	134	94
		2363	3915	17	3.11	1.83	1.77	1.94	2.36	499	848	877	800	658

Table 2 Time offsets (days) estimated for sinking particles from 4 couplets and 11 triplets of time-series sediment traps, and their estimated SV's, from single tracers (total mass and four chemical constituents). Stations with triplets of traps are again highlighted in gray. Data are grouped into two classes by cup rotation times: cups rotating in $\leq$ 8.5 days in boldface, and cups rotating in $\geq$ 14 days. Settling velocities less than 400 m/d are highlighted in gray.

Data category	number of trap pairs	number of SV's < 400 m/d	mean	*sd*	*cv*
All data	26	83	172	83	0.48
Low resolution (rotation interval>=14d)	11	34	126	73	0.58
High resolution (rotation interval<=8.5d)	15	49	205	74	0.36
MedFlux	3	14	220	65	0.29

Table 3 Numbers of trap pairs and summary statistics, arranged by data-resolution class, for sites and tracers where the SV was estimated to be less than 400 m/d (these are highlighted in gray in the last 5 columns of Table 2). See text for further details.

Station	deployment interval	Depth (m) upper	Depth (m) lower	distance (m)	cup rotation period (d)	this paper SV(m/d)*	this paper offset cup#	Berelson(2002) SV(m/d)	Berelson(2002) offset cup#
MedFlux	3/06/03-5/06/03	238	771	533	5.5	216	**0.45**	-	-
	5/14/03-6/30/03	117	1918	1801	4.5	219	**1.83**	-	-
	3/4/05-4/28/05	313	924	611	5	321	**0.38**	-	-
NABE-48N	4/3/89-4/2/90	1110	2109	999	14	61	**1.16**	-	-
		2109	3734	1625	14	137	**0.85**	-	-
34N	10/16/89-4/2/90	1248	1894	646	14	117	**0.39**	-	-
		1894	4391	2497	14	642	**0.28**	-	-
EqPac-Equator	2/02/92-1/07/93	880	2284	1404	17	864	**0.1**	83	**1**
		2284	3618	1334	17	262	**0.3**	157	**0.5**
12S	2/02/92-1/07/93	1292	3594	2302	17	246	**0.55**	271	**0.5**
5N	2/02/92-1/07/93	1200	2100	900	17	128	**0.41**	106	**0.5**
		2100	3800	1700	17	843	**0.12**	200	**0.5**
ASPS-2NE	11/13/94-4/26/95	903	1974	1071	8.5	650	**0.19**	252	**0.5**
		1974	3141	1167	8.5	269	**0.51**	137	**1**
3NE	11/13/94-4/26/95	858	1857	999	8.5	777	**0.15**	235	**0.5**
		1857	2871	1014	8.5	775	**0.15**	261	**0.5**
4NE	11/13/94-4/26/95	821	2229	1408	8.5	296	**0.56**	331	**0.5**
		2229	3478	1249	8.5	134	**1.1**	294	**0.5**
2SW	5/25/95-9/09/95	924	1996	1072	8.5	170	**0.74**	252	**0.5**
		1996	3159	1163	8.5	222	**0.62**	274	**0.5**
3SW	5/25/95-12/15/95	888	1882	994	8.5	297	**0.39**	117	**1**
		1882	2991	1109	8.5	206	**0.63**	261	**0.5**
4SW	5/25/95-12/15/95	807	2215	1408	8.5	811	**0.2**	-	-
		2215	3489	1274	8.5	521	**0.29**	300	**0.5**
5	12/6/94-12/15/95	800	2363	1563	17	130	**0.7**	92	**1**
		2363	3915	1552	17	736	**0.12**	183	**0.5**

Table 4 Average settling velocities and cup shifts estimated using single tracers (total mass and 4 critical elements) are compared to results from Berelson (2002). The vertical distances between upper and lower depths, and the number of days each cup was open, are also noted.

Station	deployment interval	Depth (m) shallow	middle	deep	log(Likelihood) difference between Case A & Case B log(mass)	log(OC)	log(IC)	log(BioSi)	log(Al)
NABE-48N	**4/3/89-4/2/90**	**1110**	**2109**	**3734**	1.11	0.08	0.86	0.24	0.13
34N	**10/16/89-4/2/90**	**1248**	**1894**	**4391**	4.52	3.06	3.62	3.51	8.53
EqPac-Equator	**2/02/92-1/07/93**	**880**	**2284**	**3618**	0.11	0.66	0.05	0.02	0.07
5N	**2/02/92-1/07/93**	**1200**	**2100**	**3800**	0.61	0.63	0.22	0.98	0.29
ASPS-2NE	**11/13/94-4/26/95**	**903**	**1974**	**3141**	0.01	1.41	1.54	1.81	0.72
3NE	**11/13/94-4/26/95**	**858**	**1857**	**2871**	0.28	0.27	0	0.23	0.2
4NE	**11/13/94-4/26/95**	**821**	**2229**	**3478**	0.21	0.05	0	0.29	0.21
2SW	**5/25/95-9/09/95**	**924**	**1996**	**3159**	0.76	5.99	1.88	0.87	1.02
3SW	**5/25/95-12/15/95**	**888**	**1882**	**2991**	0.05	0.1	0.36	0.02	0.48
4SW	**5/25/95-12/15/95**	**807**	**2215**	**3489**	0.26	0.02	0.11	0.12	0.46
5	**12/6/94-12/15/95**	**800**	**2363**	**3915**	2.13	2.7	1.26	1.19	1.93

Table 5 Eleven triplets of time-series sediment traps analyzed by Berelson (2002) were reanalyzed to assess whether deeper particles sink faster than shallower particles. Data from EqPac 5S were again excluded. Case A: Sinking particles were allowed to have separate SV's for shallow/middle and middle/deep trap pairs. Case B: Sinking particles were constrained to have only a single SV for shallow/middle and middle/deep trap pairs. Likelihood differences must differ by at least two log(likelihood) points to justify an additional parameter (see text); only the NABE 34N site, and a few tracers at ASPS sites 2SW and 5, meet this criterion, and many sites have miniscule differences between fits made with one vs. two sinking velocities. This test provides little evidence that deeper particles sink faster.

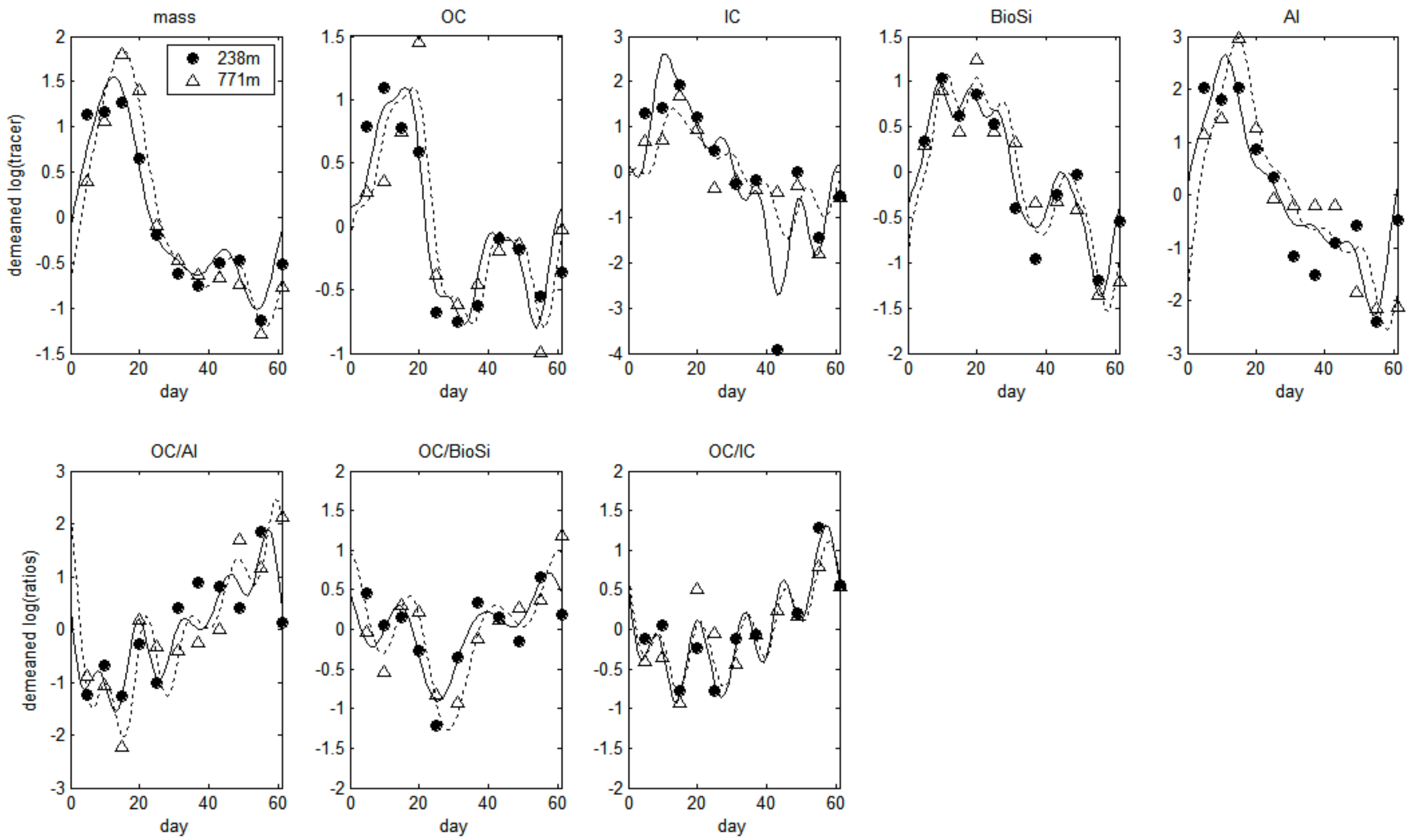

Figure 1 Fits of the model to demeaned log-transformed single tracers (top 5 subplots) and tracer ratios (bottom 3 subplots). Data are from MedFlux time-series sediment traps at 238m (upper depth) and 771m (lower depth) at the Mediterranean DYFAMED site, from March to May 2003; they were pretreated by transforming onto log scales, followed by subtracting the mean of each trap record before analysis.

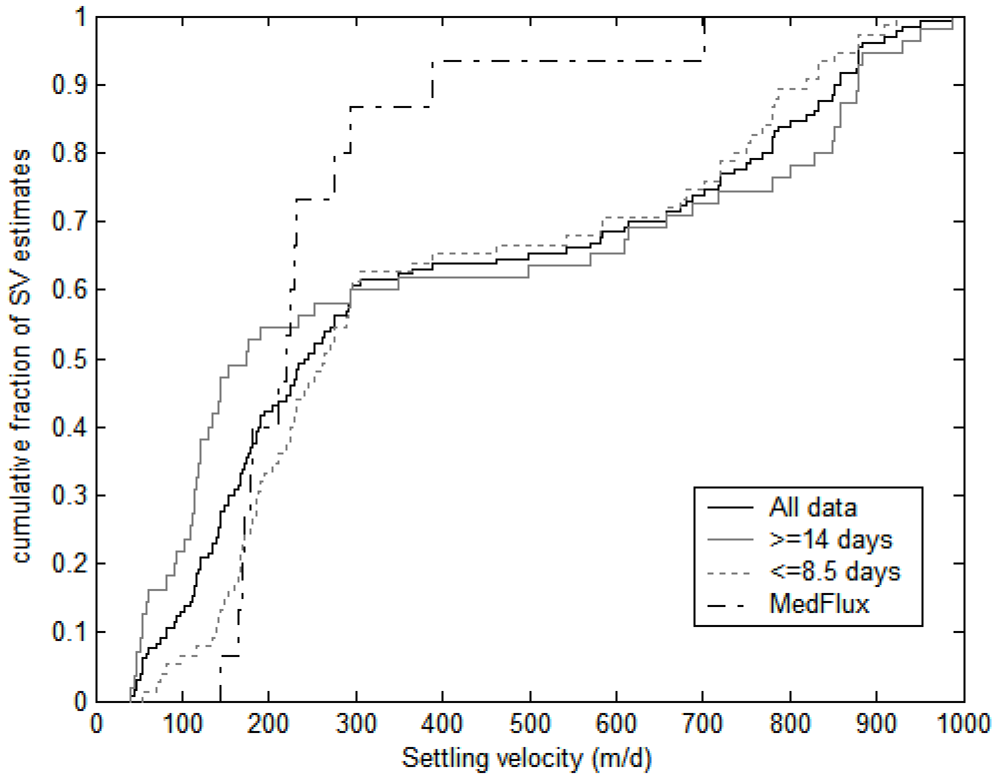

Figure 2 Cumulative distribution function (cdf) curves for the SV's for: (a) MedFlux data only; (b) data with cup rotation times ≤ 8.5 days (including MedFlux data); (c) data with cup rotation times ≥14 days; (d) all data in Table 2. The MedFlux data produce an S-shaped distribution, indicative of a unimodal distribution, whereas the other data sets produce cdf's indicative of bimodal distributions; see also Fig. 3. See text for further details.

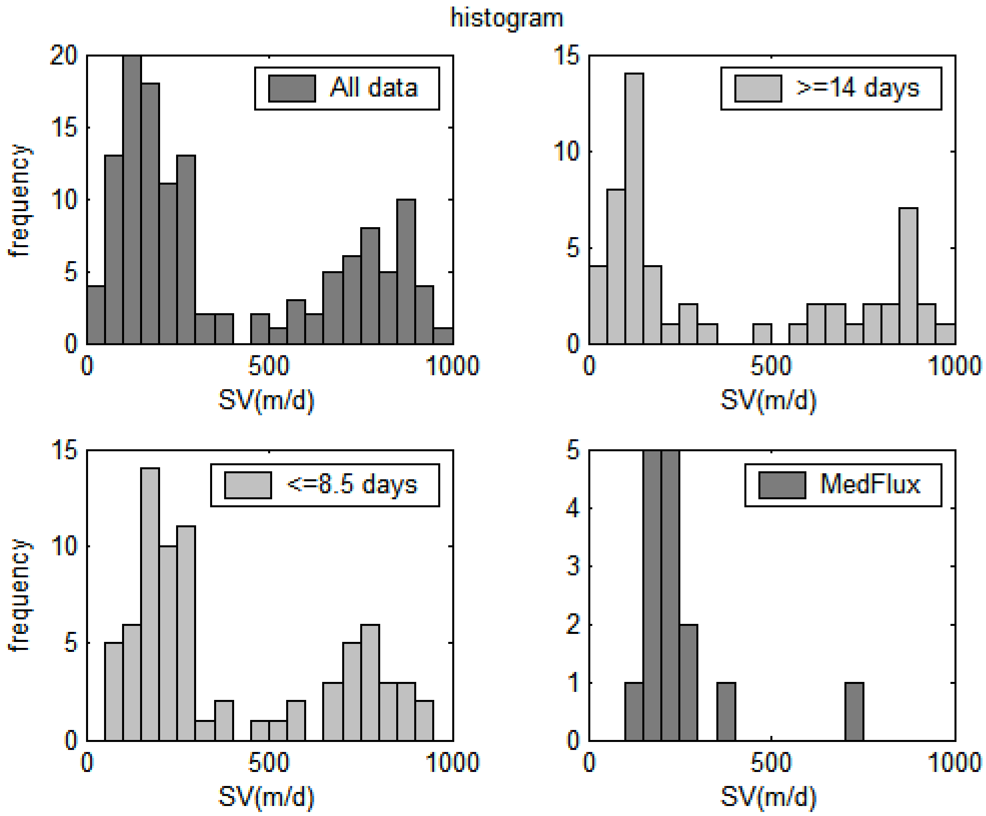

Figure 3 Histograms of SV estimates for the four data sets shown in Fig. 2.