

## Do upper-ocean sediment traps provide an accurate record of particle flux?

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SEDIMENT traps are widely used to measure the vertical flux of particulate matter in the oceans. In the upper ocean, sediment traps have been used to determine the extent to which  $\text{CO}_2$  fixed by primary producers is exported as particulate organic carbon<sup>1-3</sup>. In addition, the observed decrease of particle flux with depth has been used to predict regeneration rates of organic matter and associated elements<sup>3</sup>. Over seasonal or annual timescales, the import of limiting nutrients into the upper ocean (new production) should be balanced by particle export<sup>4,5</sup>. Given the importance of accurately determining the sinking particle flux, it has been suggested that  $^{234}\text{Th}$  might be used to 'calibrate' shallow-trap fluxes<sup>6</sup>. Here I present a re-evaluation of existing  $^{234}\text{Th}$  data which indicates that trap-derived and model-derived  $^{234}\text{Th}$  particle fluxes can differ by a factor of  $\pm 3$ –10, suggesting that shallow traps may not provide an accurate measure of particle fluxes.

The activity of  $^{234}\text{Th}$  (half-life 24.1 days) in the oceans is primarily controlled by production from its soluble parent,  $^{238}\text{U}$  (half-life  $4.5 \times 10^9$  years), and losses through radioactive decay plus sorptive removal on sinking particles. A typical  $^{234}\text{Th}$  profile in the open ocean shows relatively low  $^{234}\text{Th}$  activities in surface waters and an increase with depth as the scavenging intensity decreases (Fig. 1). As  $^{238}\text{U}$  is conservative in sea water, the activity of  $^{238}\text{U}$  varies little with depth (Fig. 1) and is proportional to salinity ( $^{238}\text{U}$  (d.p.m.  $\text{l}^{-1}$ ) =  $0.069 \times \text{salinity}^7$ ). Secular equilibrium between  $^{238}\text{U}$  and  $^{234}\text{Th}$  usually occurs at depths of 50–200 m.

The deficiency of total  $^{234}\text{Th}$  relative to  $^{238}\text{U}$  has been widely used as a measure of the uptake and removal of  $^{234}\text{Th}$  through particle scavenging<sup>8-14</sup>. The magnitude of  $^{234}\text{Th}$  export from the surface ocean on sinking particles can be calculated from the following equation<sup>8-11</sup>

$$\partial^{234}\text{Th}/\partial t = ^{238}\text{U} \times \lambda - ^{234}\text{Th} \times \lambda - P \quad (1)$$

where  $^{234}\text{Th}$  is the measured activity of total  $^{234}\text{Th}$ ,  $^{238}\text{U}$  is determined from salinity,  $\partial^{234}\text{Th}/\partial t$  is the change in  $^{234}\text{Th}$  activity

with time,  $\lambda$  is the decay constant for  $^{234}\text{Th}$  ( $0.0288 \text{ day}^{-1}$ ) and  $P$  is the net removal flux of  $^{234}\text{Th}$  by particles. This equation can be solved for steady-state ( $\partial^{234}\text{Th}/\partial t = 0$ ) and non-steady-state conditions, and assumes that advection and diffusion terms can be neglected (see discussion). Using equation (1), it is possible to predict particle export at a given depth for  $^{234}\text{Th}$  by integrating total  $^{234}\text{Th}$  and  $^{238}\text{U}$  activities from the surface to the depth of interest<sup>12,15</sup> and calculating the unknown flux term  $P$ . The particle flux term will reflect the net sum of all biotic and abiotic particle formation, exchange, remineralization and export processes. This simple vertical  $^{234}\text{Th}$  scavenging model forms the basis for the calibration of sediment trap fluxes.

Figure 2 summarizes the results from a variety of open ocean, coastal, and semi-enclosed basin sites where it is possible to compare the measured trap flux of  $^{234}\text{Th}$  with the predicted particle  $^{234}\text{Th}$  flux calculated from water-column data using equation (1). All of the studies shown employed shallow sediment traps which are similar or identical to the VERTEX cylindrical design<sup>16</sup>. This is by far the most common trap design used in the upper oceans in the last decade, and few results for  $^{234}\text{Th}$  exist from studies using any other type of trap. The model  $^{234}\text{Th}$  flux data were either taken as reported from the original source, or calculated by this author (see Table 1 for details). The data are plotted as the logarithm of the ratio of the sediment trap  $^{234}\text{Th}$  flux to the model-derived  $^{234}\text{Th}$  flux. Relative to the model fluxes, data above  $\log 0$  (=1) suggest a positive collection bias and data below this line a negative collection bias. Roughly one third of the data suggests collection biases of at least a factor of three, and two thirds of the points lie at or beyond  $\pm 50\%$  (Fig. 2).

The extent to which the trap and model fluxes agree or disagree seems to be independent of the trap depth, total flux or research laboratory where the  $^{234}\text{Th}$  analyses were made (Table 1). Within a given site one tends to find consistently either under- or over-collection biases which are much larger than the error of any individual ratio. Given these data, one must conclude either that (1) shallow-trap particle fluxes can be substantially biased in either a positive or negative direction, and/or that (2) the simple  $^{234}\text{Th}$  scavenging model (equation (1)) is not appropriate for calibrating shallow-trap fluxes. I will re-examine the  $^{234}\text{Th}$  scavenging model first, as I propose that it is more likely that the trap fluxes are in error than the model-derived fluxes.

In most of the studies represented in Fig. 2, single profiles of  $^{234}\text{Th}$  and the assumption of steady state were used to calculate the  $^{234}\text{Th}$  particle flux (Table 1). The magnitude of the error introduced by assuming steady state ( $\partial^{234}\text{Th}/\partial t = 0$  in equation (1)) will depend upon the specific setting. For example, in the

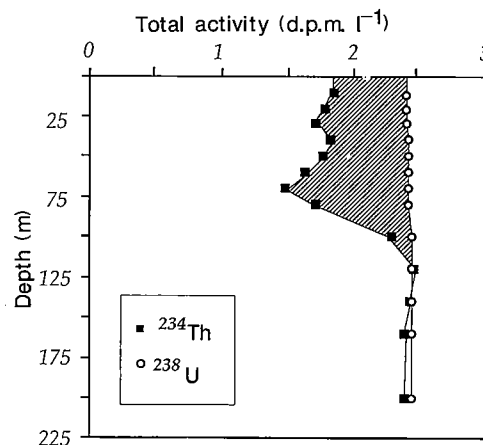


FIG. 1 Typical profile of  $^{234}\text{Th}$  in the upper open ocean. Shaded area represents disequilibrium between total  $^{234}\text{Th}$  and  $^{238}\text{U}$ . Data taken from VERTEX 3 (ref. 11).

TABLE 1 Compilation of  $^{234}\text{Th}$  flux data from traps and model

Identification number	Ref. number	$^{234}\text{Th}$ flux		Res-t (days)	Trap-t (days)	Depth (m)	Station ID	Model type	Location (and comments)
		Calc. (d.p.m. $\text{m}^{-2} \text{d}^{-1}$ )	Trap (d.p.m. $\text{m}^{-2} \text{d}^{-1}$ )						
1	8	1,500	800	19	13	50	VERTEX 1	SS	Different stations within California Current
2		1,500	2,100	19	13	50	VERTEX 1		
3		1,300	900	21	6	50	Cerop I		
4		1,700	2,000	18	5	50	Cerop II		
5		1,700	1,300	21	8	65	Cerop III		
6		1,800	2,200	20	6	60	MLML-2		
7	12	800	1,020	6	14	10	3/1-15/82	NSS	Funka Bay, Japan (March data provided best temporal comparison, other months show same range)
8		3,000	870	18	14	40	3/1-15/82		
9		5,000	2,390	16	14	80	3/1-15/82		
10	11	570	835	26	22	30	VERTEX 2	SS	Off Manzanillo, Mexico
11		1,222	1,878	30	22	120	VERTEX 2		
12		1,600	1,505	25	21	80	VERTEX 3		
13		1,861	730	27	21	120	VERTEX 3		
14	13 & 32	630	671	33	34	150	VERTEX 4	SS	900 kmN of Hawaii
15		1,660	175	31	10	200	Feb. 87		
16		604	148	33	10	200	Mar. 88		
17		316	181	34	15	200	Apr. 87		
18	14	744	1,960	30	3	80	sta-1	SS	Panama Basin (calculated fluxes from equation (1) by this author)
19		620	2,060	31	3	80	sta-2		
20		1,084	1,600	29	3	80	sta-5		
21	19	813	693	10	3	20	Feb.	SS	Dabob Bay, Washington, U.S.A. (calculated fluxes from equation (1) by this author, and data below 50 m are excluded because of evidence of sediment resuspension)
22		1,850	1,181	13	3	50			
23		797	365	13	3	19	March		
24		1,471	352	13	3	39			
25		1,133	168	8	3	25	May		
26		1,960	290	9	3	45			
27		969	635	8	3	23	June		
28		1,719	977	10	3	43			
29		942	722	9	3	23	July		
30		1,554	1,238	11	3	43			
31		869	168	8	3	20	Aug.		
32		1,575	970	10	3	40			
33		1,001	980	9	3	24	Sept.		
34		1,688	999	11	3	44			
35		969	632	10	3	25	Oct.		
36		1,708	1,160	11	3	45			
37		1,111	358	9	3	28	Nov.		
38		1,850	683	8	3	48			
39	20	253	380	29	3	36	BS3 sta-2	SS	Black Sea (calculated fluxes from equation (1) by this author)
40		480	822	29	3	71			
41		78	354	33	3	40	BS3 sta-6		
42		6.3	520	35	3	75			
43	15	4,565	1,867	25	11	150	late April	NSS	Northeast Atlantic
44		4,257	1,279	29	11	300			
45		3,093	2,145	27	14	150	early May		
46		7,745	1,485	28	14	300			
47		5,061	1,571	23	11	150	end May		
48		3,582	1,498	29	11	300			
49	18	949	4,537	25	13	50	VERTEX 5	SS	California Current (calculated fluxes from equation (1) by this author)
50		1,158	4,574	29	13	100			
51		1,900	692	25	13	100	VERTEX T7		Off Alaska (station Papa)

Identification numbers refer to Fig. 2. Calculated  $^{234}\text{Th}$  flux based on equation (1); trap  $^{234}\text{Th}$  flux from original reference. Res.-t is the residence time of  $^{234}\text{Th}$  with respect to decay and particle removal (see text). Trap-t is the trap deployment duration. Station ID provided as in original reference. Model type: SS, steady state; NSS, non-steady state.

Pacific gyre, seasonal variations in the  $^{234}\text{Th}$  inventory in the upper ocean are expected to be small and thus assumption of steady state is reasonable<sup>17,18</sup>. In contrast, at the onset of the spring bloom in the North Atlantic, the calculated particle flux can vary by as much as a factor of four if the change in  $^{234}\text{Th}$  activity with time is ignored<sup>15</sup>. Figure 2 includes studies where steady-state and non-steady-state solutions to equation (1) have been considered, and in both cases agreement with the trap fluxes is poor.

Neglected in equation (1) are vertical advective and diffusive fluxes of  $^{234}\text{Th}$ . Under average oceanic conditions these factors are small relative to the particle flux (for example, 5–10% of the particle flux<sup>15</sup>). An important point is that vertical mixing would always tend to supply  $^{234}\text{Th}$  to the surface layer given the increased  $^{234}\text{Th}$  activities at depth (Fig. 1). Ignoring this supply would cause the calculated fluxes from equation (1) to be too small. This would produce an overall systematic positive collection bias which is not seen in the data (Fig. 2).

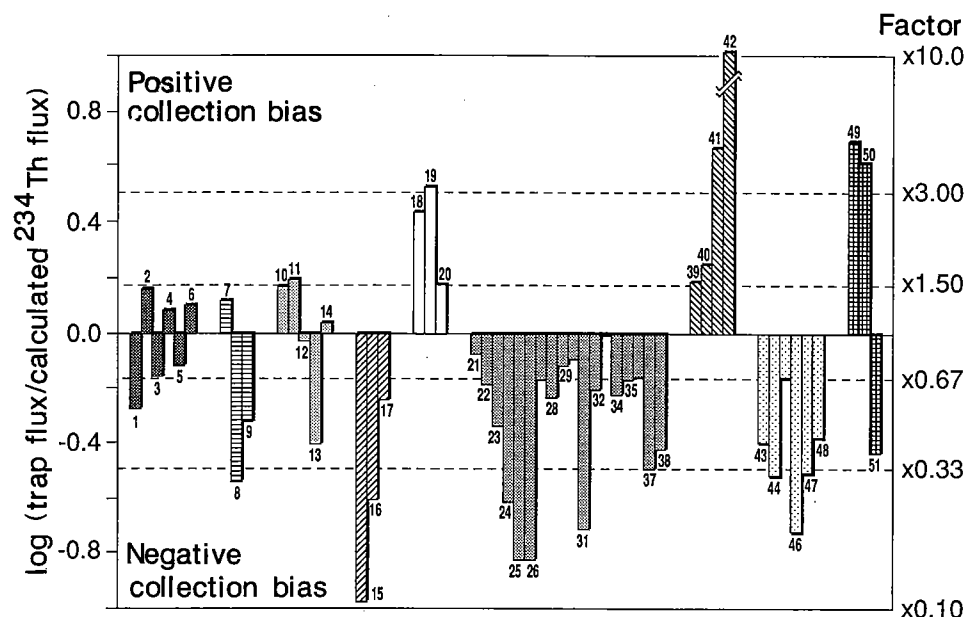


FIG. 2 Bar diagram showing the comparison between  $^{234}\text{Th}$  fluxes measured in shallow sediment traps, and that calculated for the same depth and time using the  $^{234}\text{Th}$  scavenging model (equation (1) in text). Data are plotted as the logarithm of the ratio of the trap flux to the model-derived  $^{234}\text{Th}$  flux. Each bar is numbered for reference to Table 1 and different fill patterns are used for each study. The left-hand vertical scale shows the ratio as the logarithm, and the right-hand scale converts this ratio to the factor of positive or negative collection bias suggested by the data (see text for details).

Finally, one must consider whether or not  $^{234}\text{Th}$  fluxes measured in traps and those determined from the water column  $^{234}\text{Th}$  distributions reflect particle export over the same scales. If the traps are deployed for only a few days (see Table 1) episodic particle fluxes may be missed, or alternatively short-term periods of low flux may not be represented. This factor alone should produce a random bias of over- and under-collection at a given site. It can be seen, however, that in traps deployed for only a few days, either in one season or throughout the year<sup>14,19,20</sup>, the calibration is not random and is biased in a single direction (Table 1).

If steady state is assumed, the deficiency in total  $^{234}\text{Th}$  reflects a temporal scale determined by the residence time of  $^{234}\text{Th}$  with respect to radioactive decay and scavenging ( $t = 1/(\lambda + k)$ , where  $k$  is the particle removal rate). This residence time ranges from 8 to 35 days for the studies compiled here (Table 1). In many cases this is comparable to the duration of the trap experiment. In the studies that applied a non-steady-state solution to equation (1)  $^{234}\text{Th}$  profiles are obtained at trap deployment and retrieval times and thus  $\partial^{234}\text{Th}/\partial t$  is measured to calculate the particle flux during the trap deployment<sup>12,15</sup>. In this case the temporal scale for the trap and model fluxes is the same. In general, the non-steady-state approach is preferred. The two non-steady-state studies referenced here suggest a negative collection bias for traps of up to a factor of three (Table 1).

There is still some uncertainty over whether the spatial scales of particle export over which the traps and  $^{234}\text{Th}$  measurements integrate are comparable. Patchiness in particle flux measured by traps would not, however, be expected to produce the unidirectional biases seen in the calibration at a given site (Table 1). Multiple traps and  $^{234}\text{Th}$  measurements over spatial scales of 10–100 km would be needed to answer this question directly.

It seems that the  $^{234}\text{Th}$  balance and hence particle export flux in the  $^{234}\text{Th}$  scavenging model is well constrained. The disagreement between the calculated and measured particle fluxes has not been eliminated or even reduced when more rigorous non-steady-state models have been used. Limitations in the model would tend to produce random biases in the flux estimates, but unidirectional trends are most often found within a given site. If the errors in the model are small, or at least random, then one must consider why the traps might over- or under-collect the true  $^{234}\text{Th}$  particle flux at a given site. The potential problems associated with using a shallow sediment trap as a collector of particle flux can be broadly divided into two areas, namely sample integrity and hydrodynamics.

Sample integrity issues will be of primary concern for carbon and organic constituents rather than for  $^{234}\text{Th}$ . For example, it has long been recognized that some organisms, the so-called swimmers<sup>6,21</sup>, will actively enter shallow traps. For  $^{234}\text{Th}$ , swimmers pose much less concern, as the specific activity of  $^{234}\text{Th}$  in potential swimmer fractions (salps and zooplankton) is lower by 1–3 orders of magnitude than that found in trap material<sup>22</sup>. Sediment samples remain in the trap for days or weeks depending on the duration of trap deployment. Consequently the loss of carbon and nutrients to the trap solution phases can occur<sup>23</sup>. As  $^{234}\text{Th}$  is strongly adsorbed on particle surfaces, sample integrity is ensured<sup>6</sup>.

Sediment traps of any kind will alter the flow field around them and thereby produce a hydrodynamic bias for collecting settling particulate matter. This would affect both the observed  $^{234}\text{Th}$  and organic matter fluxes. Considerable effort has been spent in evaluating various trap designs, and the VERTEX-style cylinders used in the  $^{234}\text{Th}$  fluxes referenced here were identified in early studies as having a minimal particle collection bias<sup>24,25</sup>. For a given design, however, it is known that variations in the magnitude of horizontal currents will affect the flow field, thus potentially biasing the overall collection efficiency<sup>26–28</sup>. Because multiple traps are typically hung from a single free-floating mooring, shallow traps in the field move at different speeds relative to the water in a complicated depth- (and time-) dependent pattern. Tilt and wave effects may also produce additional hydrodynamic biases for floating traps<sup>29</sup>.

In the oceans, a wide range of particle types has been found, with sinking speeds ranging from <1 m per day to >1,000 m per day<sup>30</sup>. Recent laboratory experiments<sup>27</sup> indicate that the bias due to fluid dynamics varies for different particle types under different horizontal flows. It can be postulated that the disagreement between trap and model-derived fluxes seen in Fig. 2 is due to differences in flow and particle type at a given location. Additional factors may, however, be significant. For example, vertical migrating organisms may actively remove particles from the upper ocean and bypass the traps during their descent to depth<sup>31</sup>. This would result in an apparent under-collection by the traps. It should also be noted that a calibration of particle flux using  $^{234}\text{Th}$  may not hold for organic carbon or other elements if the particle classes that carry these elements differ. On the other hand, if the traps cannot be shown to collect quantitatively the particles that carry  $^{234}\text{Th}$ , then there is good reason to question the accuracy of other flux measurements.

Sediment traps have contributed considerably to our understanding of sinking particles in the oceans. They provide samples for analyses, as well as what is thought to be reasonable flux information. A quantitative evaluation of trapping efficiency is needed, however, and the calibration of sediment trap fluxes using  $^{234}\text{Th}$  provides a powerful method of doing this. At present, the  $^{234}\text{Th}$  water column measurements and scavenging models suggest that over- or under-collection by a factor of three or more is common in shallow traps. A predicted flux within this uncertainty may be adequate for many purposes. But this calibration does not reflect artefacts due to swimmers and sample integrity, which will result in an additional collection bias for

organic constituents. For the calibration to hold, we must continue to examine the assumptions in the  $^{234}\text{Th}$  scavenging model. More time-series data and a three-dimensional grid of  $^{234}\text{Th}$  profiles and sediment traps will be needed to examine the spatial scale of particle export and to quantify any horizontal fluxes which are ignored in the simple vertical scavenging models. We may not yet be able to give a definitive answer to the question posed in the title. The disagreement between particle  $^{234}\text{Th}$  fluxes measured by traps and that predicted from water column data suggests, however, that the answer is not likely to be in the affirmative. □

Received 8 March; accepted 5 August 1991.

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ACKNOWLEDGEMENTS. Data for this manuscript were kindly provided by K. Bruland, J. Murray and C.-L. Wei before publication. Comments by A. Michaels, M. Bacon, B. Moran and E. Sholkovitz inspired and assisted me during the preparation of this manuscript. Financial support was provided by NSF.