Biogenic sinking particle fluxes and sediment trap collection efficiency at Ocean Station Papa

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Comprehensive field observations characterizing the biological carbon pump (BCP) provide the foundation needed to constrain mechanistic models of downward particulate organic carbon (POC) flux in the ocean. Sediment traps were deployed three times during the EXport Processes in the Ocean from RemoTe Sensing campaign at Ocean Station Papa in August–September 2018. We propose a new method to correct sediment trap sample contamination by zooplankton “swimmers.” We consider the advantages of polyacrylamide gel collectors to constrain swimmer influence and estimate the magnitude of possible trap biases. Measured sediment trap fluxes of thorium-234 are compared to water column measurements to assess trap performance and estimate the possible magnitude of fluxes by vertically migrating zooplankton that bypassed traps. We found generally low fluxes of sinking POC ($1.38 \pm 0.77 \text{ mmol C m}^{-2} \text{ d}^{-1}$ at 100 m, $n = 9$) that included high and variable contributions by rare, large particles. Sinking particle sizes generally decreased between 100 and 335 m. Measured $^{234}$Th fluxes were smaller than water column $^{234}$Th fluxes by a factor of approximately 3. Much of this difference was consistent with trap undersampling of both small (<32 μm) and rare, large particles (>1 mm) and with zooplankton active migrant fluxes. The fraction of net primary production exported below the euphotic zone (0.1% light level; Ez-ratio = 0.10 ± 0.06; ratio uncertainties are propagated from measurements with $n = 7–9$) was consistent with prior, late summer studies at Station P; as was the fraction of material exported to 100 m below the base of the euphotic zone ($T_{100}$, 0.55 ± 0.35). While both the Ez-ratio and $T_{100}$ parameters varied weekly, their product, which we interpret as overall BCP efficiency, was remarkably stable (0.055 ± 0.010), suggesting a tight coupling between production and recycling at Station P.

Keywords: Biological carbon pump, Ocean Station Papa, Sediment traps, Carbon flux, Particle size distribution, Swimmers

1. Introduction

The downward transport of particulate organic matter in the ocean plays a critical role in the long-term sequestration of carbon dioxide and contaminants as well as serving as a food source for benthic foodwebs (McKinley et al., 2017). These biologically mediated mechanisms of organic matter transfer, collectively known as the “biological carbon pump” (BCP), vary in space and time. Their relative importance depends upon the structure of the ecosystem as influenced by chemical and physical ocean properties. Observations that sufficiently resolve the dynamic processes that comprise the BCP are challenging to make, which limits our ability to predict how BCP efficiency changes as ocean properties shift.

The transfer of carbon to depth via gravitationally sinking particles is generally thought to be the single largest flux pathway in most marine settings (Boyd et al., 2019). Carbon can also be exported from the surface ocean by vertically migrating organisms that feed at the surface and transfer carbon to depth and by physical mixing or subduction of suspended particulate organic carbon (POC) and dissolved organic carbon (DOC) from enriched surface
waters into deeper depths (Levy et al., 2013; Steinberg and Landry, 2017). The fraction of exported carbon that is sequestered over long timescales is dependent on the depth penetration below the winter mixed layer (Palevsky and Doney, 2018). Slowly sinking particles and nonsinking POC and labile DOC are thought to be remineralized near the surface and returned to the atmosphere, while carbon delivered by more rapidly sinking particles and by vertical migrators is retained in the ocean interior over millennium to longer timescales (Boyd et al., 2019).

The traditional tool used to measure sinking fluxes of particles in the upper mesopelagic zone is the drifting sediment trap (Gardner, 1977; Buesseler et al., 2007). Buesseler et al. (2007) reviewed the advantages, disadvantages, and designs of upper ocean sediment traps comprehensively; we summarize a few relevant points here. Among sediment trap advantages are their unequivocal separation of sinking from suspended material, their return of samples for detailed laboratory analyses, and their relatively well-constrained sampling periods. Among their disadvantages are potential hydrodynamic sorting effects, their short collection timescale, their inability to measure fluxes of carbon actively transported by vertical migrators, and their susceptibility to contamination by zooplankton “swimmers” that enter traps during collection (Buesserl et al., 2007). These considerations, as well as the diversity of sampling objectives in BCP research programs, have led to an assortment of trap designs currently in use (Buesseler et al., 2007; Baker et al., 2020). These include different collector shapes (cylindrical and conical), trap lids, sample preservatives, and supporting platforms (moored or drifting arrays and neutral floats).

Here, we describe a series of sediment trap deployments conducted as part of the EXport Processes in the Ocean from RemoTe Sensing (EXPORTS) program in the vicinity of Ocean Station Papa (Station P; 50°N, 145°W) in August and September 2018 (Siegel et al., n.d.). The goal of the EXPORTS program is to characterize comprehensively all of the component processes of the BCP, while simultaneously collecting a full suite of inherent and apparent optical properties that together can be used to develop predictive models of BCP fluxes driven by ocean color remote sensing observations (Siegel et al., 2016). The trap sampling plan was designed to provide information on the biological and chemical character of the sinking particles, their size distributions, and how their fluxes vary in time. To achieve these goals, we utilized multiple, complementary methods including different trap designs (Baker et al., 2020), simultaneous bulk sample collection and gel collectors (Durkin et al., 2021), and time-resolved, 3D sampling of thorium-234 activities (Buesserl et al., 2020a). This combination of methods also allowed us to examine potential biases in each measurement. Here, we describe the deployments and their results and contextualize them relative to other observational components of the EXPORTS study. We also discuss the trap fluxes in the context of historical observations from Station P.

2. Methods

2.1. Deployment design

The EXPORTS study design (described in detail in Siegel et al., n.d.) consisted of a suite of measurement tools operating in different spatiotemporal sampling modes. Autonomous platforms provided continuity with the time periods preceding and following ship occupations in August–September 2018. Spatially distributed hydrographic, chemical, and optical measurements were made from the R/V Sally Ride, while longer term measurements, including sediment trap deployments, were made in a water-following frame of reference from the R/V Roger Revelle, which tracked a Lagrangian float deployed at a drift depth of 100 ± 10 m (Siegel et al., n.d.). All measurements were conducted in repeated, 8-day cycles, referred to as “epochs.” During the cruise, the depth of the euphotic zone (defined as the 0.1% light level with respect to the surface) was determined from a series of radiometer profiles (Compact Optical Profiling System, Biospherical) conducted from the Revelle. The deployment and analysis details are described by Siegel et al. (n.d.). Sediment traps were deployed once per epoch for 3–6 days. Deployment locations, times, and depths are summarized in Figure 1 and Table 1.

Two sediment trap designs were utilized in the study. A drifting, five-depth, surface-tethered trap (STT) array collected sinking particles at 95, 145, 195, 330, and 500 m in Epoch 1. A repair of the STT array after weather damage during Epoch 1 increased all STT trap depths by 10 m in Epochs 2 and 3. Six neutrally buoyant sediment traps (NBSTs; Estapa et al., 2020) were also deployed alongside the STT array. Two NBSTs were deployed at 95 m and 195 m, and one each at 145 m and 330 m. Figure 1 shows trajectories of the NBSTs at different depths in each epoch. A handful of NBST deployment irregularities occurred in Epochs 2 and 3 and are described in detail by Estapa et al. (2020). For example, in Epoch 2, NBST-304 (targeted at 195 m) had its initial depressor weight become entangled during deployment. The trap, therefore, did not immediately resurface, although trap lids closed on schedule. NBST-304 resurfaced later, partway through Epoch 3. In Epoch 3, NBST-302 and NBST-303 (targeted at 195 and 145 m, respectively) resurfaced on time, but due to a communication problem, repeated their dive cycle a second time (with trap lids closed) prior to recovery.

Regardless of SST versus NBST platform, four trap tubes of the “CLAP” design (Lamborg et al., 2008) were deployed at each trap depth and consisted of a polycarbonate tube with a collection area of 0.0113 m², and a lid attached with an elastic bungee. Lids were deployed open, then were released from a timed burnwire to snap closed at the end of the planned deployment period. On each platform, two tubes carried 500 mL of 70 ppt salinity, 0.1% formaldehyde-poisoned brine buffered with borate to pH 8.5 that was overlain by 1-µm filtered surface seawater. A third tube carried homemade RNAlater (Malmstrom, 2015) overlain by filtered seawater to preserve genetic material, and a fourth tube carried a polyacrylamide gel collector overlain by filtered surface seawater (Durkin et al., 2015; Durkin et al., 2021). Each NBST carried
a transmissometer (C-Rover 2K, WET Labs Inc., Philomath, OR, USA) used as an optical sediment trap (OST; Estapa et al. 2017). At each of the upper three STT depths, the array also included a RESPIRE trap used to measure particle-attached microbial respiration rates and is discussed in detail by Santoro et al. (2020). An acoustic current meter was deployed immediately below the 500-m STT depth to measure relative water motions.

2.2. Sample analysis

2.2.1. Bulk sample processing and analysis

After recovery, each trap tube was removed from its host platform and allowed to stand in the lab for at least an hour to allow particles to finish settling to the bottom of the tube. Replicate formalin-poisoned brine tubes at each depth were combined and drained through a 335-μm polyester screen. Tubes and screens were rinsed thoroughly with filtered seawater. Then, screens were manually picked clean of recognizable zooplankton “swimmers” under 7× magnification. The remaining material on each screen, presumed to consist of passively settling material only, was recombined with the sample fraction that passed through the 335-μm screen, which was not picked. The sample was then passed through a rotary wet splitter inside a flow bench (Lamborg et al., 2008; Owens et al., 2013) and divided into eight equal fractions (A–H). Fractions A, B, and C were filtered through precombusted, 25-mm diameter, quartz microfiber filters (QMA, nominal...
Table 1. Summary of sediment trap deployments. DOI: https://doi.org/10.1525/elementa.2020.00122.t1

<table>
<thead>
<tr>
<th>Trap Type</th>
<th>NBST ID</th>
<th>Epoch</th>
<th>Depth (m)</th>
<th>Date/Time in 2018 (UTC)</th>
<th>Deployment Position</th>
<th>Recovery Position</th>
<th>Distance (km)</th>
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<td></td>
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<td>Resurfaced</td>
<td>Latitude (°N)</td>
<td>Longitude (°E)</td>
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<td>1</td>
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<td>105, 155, 205, 340, 510</td>
<td>August 31, 16:58</td>
<td>September 6, 08:17</td>
<td>50.5996</td>
<td>-144.8657</td>
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</tbody>
</table>

SOLO = SOLO-NBST; APEX = APEX-NBST; STT = surface-tethered trap array; NBST = neutrally buoyant sediment traps; UTC = Coordinated Universal Time.

aData were published originally in table 3 of Estapa et al. (2020). © American Meteorological Society (used with permission).
bEndpoint-to-endpoint distance. See Figure 1 for travel paths of STT arrays.

cTrap completed more than one mission cycle (see text). In Epoch 3, these traps are shown on separate lines because the floats resurfaced and transmitted positions after both cycles. In all cases, trap lids closed after the first cycle.
pore size 1 μm) and analyzed for total carbon and nitrogen, particulate inorganic carbon (PIC), and 234Th activity. Fractions D, E, and F were filtered through pretreated, 25-mm polycarbonate membrane filters (Nuclepore, nominal pore size 1 μm), rinsed with pH 8.5-buffered Milli-Q water to remove salts, and analyzed for gravimetric mass and biogenic silica (bSi). Fractions G and H were filtered onto either precombusted glass fiber or Supor filters for additional chemical analyses that will be described elsewhere. Filters from the A–F fractions were dried on board the ship and stored dry until analysis.

Dried filters A–C were immediately mounted and counted on board the ship using low-level Riso beta detectors. At sea, a subset of filters was recounted for quality control purposes. Post cruise, the “A” filters were then unmounted and split gravimetrically into quarters, and two quarters immediately consumed for analysis of 210Pb/210Po (Roca-Martí et al., 2020). Filters B and C were stored for at least 6 months (approximately 7 half-lives of 234Th, 24.1 days) and recounted to obtain background beta emissions. The 234Th activity on sinking particles at the time of collection was calculated as the difference between the initial and final background counts (or for “A” filters, the mean of Filters B–C background counts) and corrected for decay between the time of collection and the first count (Buesseler et al., 2020a). After background activities were determined, all remaining QMA filters were unmounted and split gravimetrically into halves, thirds, or quarters. At least one subfraction of each A–C filter was analyzed for total C and N content via elemental analysis and for PIC via acidification and coulometric titration (Honjo et al., 2000). Analyses on filter subfractions were scaled to whole-filter equivalents using the masses of the filter subfractions. The amount of POC per filter was determined by the difference between total C and PIC.

Filters D–F were stored dry until analysis on shore. Filters were weighed repeatedly on a microbalance until stable weights to within ±0.005 mg were achieved. The mass of accumulated particles on each filter was computed by difference from the filter tare weight. These filters were subsequently analyzed for bSi following alkaline digestion (1 h at 95 °C in 0.2 N NaOH followed by neutralization with 1 N HCl; similar to Nelson and Brzezinski, 1989) and spectrophotometric detection using standard methods.

For each of the analyses described above, uncertainties were computed on a platform-by-platform basis, as the standard deviation among triplicate splits. Fluxes were computed by normalizing to the trap collection period (from deployment until trap lid closure), the number of splits averaged, and the combined area of tube collection. Below, we report the means and uncertainties (usually n = 3) determined in this manner for each trap depth (Table 2; Estapa, 2019). In certain cases, only two splits were available, as noted in Table 2 and where applicable in the text. Individual split data are available in the NASA SeaBASS repository (Estapa et al., 2020).

2.2.2. Gel sample processing and image analysis

Gel sample processing and image analyses as well as particle types and modeled carbon fluxes are described in detail by Durkin et al. (2015; 2021). Here, we focus on the sinking particle size distributions (PSDs) to support interpretations of bulk trap fluxes and summarize the relevant subset of analytical procedures. After the recovery steps outlined above, overlying seawater was vacuumed out of the tubes with gel collectors, leaving behind the last 1–2 cm of water in each collector jar. Gel jars were removed from tubes and then the last layer of seawater was carefully removed via pipette. Identical blank gels kept in the laboratory for the duration of each deployment were treated in the same way as samples. The samples were imaged on board ship with a stereomicroscope (Olympus SZX16) and digital camera (Teledyne Lumenera Infinity 2) at varying magnifications (7×–115×) and focal planes and then frozen. In approximately half of the samples, ship motion precluded high-resolution (50×–115×) imaging at sea, so this step was performed on shore after thawing. In prior studies, the freeze-thaw process did not impact the detection or measurement of particles (Durkin et al., 2021). Median background values from process blanks were subtracted from the images. A thresholding and edge detection algorithm was applied to detect and measure particles in gel images. Particle duplicates detected in multiple focal planes were discarded and then equivalent spherical diameters (D) of particles were computed from their 2D imaged areas as described by Durkin et al. (2015; 2021). Every particle image was sized, counted, and manually classified into a passively sinking particle category or into various nonsinking or “noise” particle categories (e.g., zooplankton swimmers, fibers, imaging noise). Intact zooplankton “swimmers” were presumed to have actively entered the trap (Knauer et al., 1979; Lee et al., 1988; Table 2). Blank gels did not contain any particles that could be classified into the passively sinking particle categories identified in the sample gels nor were there any particles classified as “swimmers.” In the subsequent analyses described below, we disregarded the nonswimmer, “noise” particles identified in both the samples and blanks, negating the need to subtract the process blanks from the samples.

Particles classified as passively sinking were binned by diameter into logarithmically spaced size bins ranging from 10.7 to 8,192 μm. Similar to the procedure described by Durkin et al. (2015), size bins smaller than 32 μm were computed from particle images detected at 115× magnification, particles 32–90 μm at 50×, particles 90–362 μm at 20×, and particles larger than 362 μm at 7× magnification. These size ranges target the optimal detection limits of the microscope and camera combination at each magnification. This approach eliminates the underestimation of fluxes by particles smaller than the optimal detection limits of each magnification. However, the fluxes of particles smaller than 32 μm detected at 115× appear to be at the limit of the microscope and camera resolution and are likely underestimated (Durkin et al., 2015). Area fluxes (units of μm2 or mm2 m–2 d–1) and number fluxes (units of particles m–2 d–1) were computed, respectively, by normalizing the total projected area of particles, and the number of particles counted, to the imaged area and the deployment length. Differential number fluxes (N(D);
<table>
<thead>
<tr>
<th>Trap Typea</th>
<th>Date in 2018 (UTC)</th>
<th>Depth (m)</th>
<th>Uncorrected POC Flux (mmol C m⁻² d⁻¹)</th>
<th>Mass Flux (mg m⁻² d⁻¹)</th>
<th>²³⁴Th Flux (dpm m⁻² d⁻¹)</th>
<th>Corrected POC Flux (mmol C m⁻² d⁻¹)</th>
<th>Swimmer Area Flux (individ-ual m⁻² d⁻¹)</th>
</tr>
</thead>
<tbody>
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<td>SOLO</td>
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<td>96</td>
<td>2.71 ± 0.80</td>
<td>549 ± 57</td>
<td>89.00 ± 3.76</td>
<td>2.93 ± 1.16</td>
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<td>2.83 ± 0.09</td>
<td>497 ± 50</td>
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<td>2.066 ± 0.92</td>
<td>6,813 ± 3,785</td>
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<td>1 August 15</td>
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<td>4.47 ± 0.77b</td>
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<td>4.35 ± 0.45</td>
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<td>1.53 ± 0.19b</td>
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<td>27.48 ± 8.69b</td>
<td>2.212 ± 0.45</td>
<td>1628 ± 1,310</td>
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<td>116.55 ± 8.62</td>
<td>1.658 ± 0.57</td>
<td>8,436 ± 4,685</td>
</tr>
<tr>
<td>APEX</td>
<td>2 August 24</td>
<td>203</td>
<td>6.51 ± 1.71</td>
<td>386 ± 23</td>
<td>149.76 ± 17.98</td>
<td>9.35 ± 0.69</td>
<td>4,917 ± 1,612</td>
</tr>
<tr>
<td>APEX</td>
<td>2 August 24</td>
<td>337</td>
<td>1.53 ± 0.74</td>
<td>175 ± 49</td>
<td>31.60 ± 5.49</td>
<td>0.65 ± 0.38</td>
<td>305 ± 824</td>
</tr>
<tr>
<td>STT</td>
<td>2 August 24</td>
<td>105</td>
<td>1.49 ± 0.55</td>
<td>428 ± 57</td>
<td>66.31 ± 17.18b</td>
<td>3.599 ± 1.19</td>
<td>1,014 ± 3,344</td>
</tr>
<tr>
<td>STT</td>
<td>2 August 24</td>
<td>155</td>
<td>1.70 ± 0.25</td>
<td>374 ± 38</td>
<td>66.64 ± 14.72</td>
<td>2.111 ± 0.87</td>
<td>834 ± 3,242</td>
</tr>
<tr>
<td>STT</td>
<td>2 August 24</td>
<td>205</td>
<td>1.70 ± 0.75</td>
<td>254 ± 19</td>
<td>96.70 ± 26.83</td>
<td>2.489 ± 0.95</td>
<td>1,976 ± 3,405</td>
</tr>
<tr>
<td>STT</td>
<td>2 August 24</td>
<td>340</td>
<td>1.27 ± 0.41</td>
<td>240 ± 46</td>
<td>58.46 ± 9.81</td>
<td>16.37 ± 0.56</td>
<td>1,215 ± 1,101</td>
</tr>
<tr>
<td>STT</td>
<td>2 August 24</td>
<td>510</td>
<td>0.95 ± 0.24</td>
<td>412 ± 12</td>
<td>44.72 ± 9.89</td>
<td>2.629 ± 0.95</td>
<td>1,447 ± 1,060</td>
</tr>
<tr>
<td>SOLO</td>
<td>3 August 31</td>
<td>104</td>
<td>2.39 ± 0.48</td>
<td>678 ± 62</td>
<td>129.65 ± 33.31b</td>
<td>4.795 ± 2.39</td>
<td>840 ± 4,159</td>
</tr>
<tr>
<td>SOLO</td>
<td>3 August 31</td>
<td>104</td>
<td>2.78 ± 0.57</td>
<td>562 ± 46</td>
<td>106.93 ± 8.01</td>
<td>3.484 ± 1.61</td>
<td>1,141 ± 3,093</td>
</tr>
<tr>
<td>APEX</td>
<td>3 August 31</td>
<td>147</td>
<td>2.50 ± 0.17b</td>
<td>391b ± 79b</td>
<td>NA NA</td>
<td>2.525 ± 1.16</td>
<td>5,966 ± 4,201</td>
</tr>
<tr>
<td>APEX</td>
<td>3 August 31</td>
<td>198</td>
<td>1.36 ± 0.39</td>
<td>149b ± 53b</td>
<td>NA NA</td>
<td>1.752 ± 0.59</td>
<td>1,487 ± 2,957</td>
</tr>
</tbody>
</table>
units of particles m\(^{-2}\) d\(^{-1}\) \(\mu m\) were computed by dividing the binned number fluxes by size bin widths. Counting uncertainties were propagated into the different flux estimates. Number and area “fluxes” of swimmers were also computed from the number of pixels occupied by each individual to support the interpretation of bulk elemental fluxes (see Swimmer Correction section).

PSDs were modeled from differential number fluxes by fitting a simple power-law function (Equation 1; e.g., McCave, 1984) to the number fluxes of passively sinking particles using a nonlinear least-squares minimization (Matlab function “fminsearch”; Press et al., 2007):

\[
N(D) = A(D_{ref}) \times \frac{(D/D_{ref})^S}{C^2}
\]

where \(A(D_{ref})\) gives the PSD amplitude at a reference diameter \((D_{ref})\), and \(S\) gives the PSD slope. The parameter \(S\) is sensitive to the particle size range used in fitting the model. We fit Equation 1 to the entire resolvable size spectrum (32–5,792 \(\mu m\)) across all samples collected during the cruise (Figure S1). Uncertainties in the \(A(D_{ref})\) and \(S\) parameters were estimated using a Monte Carlo propagation of counting uncertainty.

2.3. Analytical methods
2.3.1. Particle source funnel modeling
In order to contextualize trap flux measurements within the upper water column, source regions were estimated for particles sinking from the mixed layer to trap collection points (Siegel and Deuser, 1997; Siegel et al., 2008).

Velocity fields during the cruise period were determined as follows: Both the *Ride* and *Revelle* carried 150 kHz acoustic Doppler current profilers (ADCPs), which resolved velocity profiles down to approximately 300 m. The *Revelle* additionally carried a 75-kHz instrument, which measured velocities down to approximately 600 m. Velocity profiles from all three instruments were interleaved and decomposed into tidal and inertial components, a low-frequency mean, a linear trend, and a high-frequency residual component. The low-frequency components were similar in magnitude and direction to satellite altimetry-derived geostrophic velocities (AVISO). The spatially gridded, AVISO-derived surface velocities were therefore attenuated with depth in proportion to the attenuation of the time-averaged, low-frequency portion of the current magnitudes from the ADCP. This depth-attenuated AVISO field was then summed with the mean tidal and inertial velocity profile time series. For comparison purposes, a spatially invariant velocity time series was also computed from the *Revelle* ADCP observations. Statistical source regions for sinking particles were modeled in order to constrain the spatial sensitivity of trap samples. Ten thousand sinking particles were advected backward in time from each point along each sediment trap trajectory (Figure 1). The actual location of the STT was used for this determination. NBST paths were modeled as a straight line and at a constant speed between the deployment and resurfacing locations and times. Estimates of particle sinking velocities (SVs) during EXPORTS await future modeling work. Here, source
regions were calculated using representative SVs of 100 and 500 m d$^{-1}$. Limited shipboard measurements of salp fecal pellets during EXPORTS showed SVs ranging hundreds of meters per day (D Steinberg, personal communication), similar to compilations of SV observations of sinking particles in the literature (e.g., Laurenceau-Cornec et al., 2019). Mean particle trajectories were computed from either the merged AVISO-ADCP velocity grid or the mean *Revelle* velocity time series. The high-frequency residual velocity profile from the decomposition described above was used to spread the particles up and outwards from their collection point at each model timestep, according to Equation 2 (Siegel et al., 2008).

$$u'(t) = \left(1 - \frac{\Delta t}{\tau}\right) u'(t_{i-1}) + \sqrt{2 \frac{\Delta t}{\tau} \sigma_u + r}$$

Above, $u'(t)$ is a random velocity imparted to each particle at each timestep, $\Delta t$ is the model timestep, which is small relative to the assumed decorrelation timescale, $\tau$, set to 10 days following Siegel et al. (2008). The random velocity of the particle, $u'(t_{i-1})$, is set at the previous timestep, $\sigma_u$ is the square root of the residual velocity variance, and $r$ is a random number between 0 and 1. Differences between the location and extent of the source regions computed using the AVISO-ADCP and *Revelle* ADCP velocity fields were negligible, and so the AVISO-ADCP-derived source regions were selected for use in subsequent analyses described below.

### 2.3.2. PSD modeling

The size distribution of sinking particles in the gel traps was used to model the amount of $^{234}$Th flux from particles that were too small to fully resolve with the microscope (i.e., smaller than 32 $\mu$m) or that were so rare that they had a low probability of collection during days-long trap deployments (see Discussion section, Comparison of Measured and Predicted $^{234}$Th Fluxes and Implications for Trap Efficiency section). The mean flux PSD slope was computed by averaging values at each of the five trap depths and extrapolated to give a particle number flux spectrum for sizes ranging from 1 $\mu$m to 1 cm (equivalent circular diameter; upper limit chosen to approximate the trap baffle opening). From the modeled flux PSD, we computed the number flux of particles smaller than 32 $\mu$m at each depth, converted this value to projected area flux ($A = \pi D^2/4$ mm$^2$ m$^{-2}$ d$^{-1}$ $\mu$m$^{-1}$), and integrated the area flux with respect to particle size. The $^{234}$Th flux from this modeled, <32-um particle pool was estimated using the mean area: $^{234}$Th relationship from the trap samples. For comparison to this model, the small-particle $^{234}$Th flux was also estimated on a per-trap basis from the observed number fluxes of particles smaller than 32 $\mu$m.

The modeled number flux size distribution was also used to compute the mean collection rate (particles d$^{-1}$) in the summed area of two trap tubes at each trap depth. Using these mean particle collection rates, a Poisson counting model was used to model the size-dependent probability of collecting at least five particles during a 3-day trap deployment (Figure S2). The number flux of particles with a less than 5% probability of collection (at the five particles per 3 days threshold) was computed from the counting model. This hypothetical number flux was integrated with respect to particle size, converted to an area flux, and used to estimate $^{234}$Th flux following the same procedure as described above.

### 2.3.3. Export ratios and transfer efficiency calculations

The Ez-ratio is defined as the export flux of carbon from a reference depth, ideally the base of the euphotic zone or mixed layer, whichever is deeper, divided by the net primary production (NPP) integrated to that depth. The 100-m transfer efficiency ($T_{100}$) is the downward flux of carbon at 100 m below the reference depth, divided by the export flux at the reference depth. We computed the Ez-ratio and $T_{100}$ metrics (Buesseler and Boyd, 2009; Buesseler et al., 2020b) from our sediment trap data on an epoch-by-epoch basis as well as over the entire cruise. Depth-integrated NPP was determined using the well-established $^{14}$C-based approach, following sample processing details reported by Fox et al. (2020), but with the addition of trace-metal clean techniques during all sample handling. Shipboard $^{14}$C bottle incubations were carried out for 24 h at light levels corresponding to targeted collection depths ranging from the surface to the 1% photosynthetically available radiation (PAR) depth, around 70 m. The volumetric NPP rates were then integrated to different depths. Here, we report integrated NPP to a depth of 100 m, and use this as our reference depth for Ez-ratio and $T_{100}$ calculations. While the shallowest sediment traps were about 12 m above the 0.1% light level (see below), this choice of reference depth avoids additional uncertainty associated with depth-interpolation of trap fluxes. Uncertainties in single-epoch NPP, Ez-ratio, and $T_{100}$ values were propagated from the standard deviation among the replicate measurements in each trap depth band. For the cruise-long average, we report the mean and uncertainty propagated from standard deviations in each trap depth band, over all three epochs ($n = 7$ for NPP; $n = 8$ or 9 for trap fluxes).

### 3. Results

#### 3.1. Trap deployments

A weak, anticyclonic mesoscale circulation dominated the mean trap motions during each deployment cycle (Figure 1; Siegel et al., n.d.). Superimposed on this larger pattern, the STT array was advected by inertial (period 18 h) and tidal motions and wind drag. While only the deployment and resurfacing locations were available for the NBSTs, they can be assumed to have been similarly affected by inertial and tidal oscillations. Compared to the NBSTs, the STT array drifted further to the north in Epoch 1, to the east in Epoch 2, and to the southeast in Epoch 3 (Figure 1). NBSTs had single-cycle endpoint-to-endpoint drift distances ranging from 4.8 to 21.1 km (Table 1), consistent with observed current speeds (Siegel et al., n.d.). The STT endpoint-to-endpoint distance (ranging from 16.0 to 30.4 km) was always greater than that of co-deployed NBSTs (except in the single case where an NBST took two cycle
periods to resurface; Table 1; Estapa et al., 2020). In situ velocities measured continuously every 10 min at the base of the STT array (Figure S3) had means and standard deviations of $6 \pm 3$ cm s$^{-1}$ (Epoch 1), $4 \pm 2$ cm s$^{-1}$ (Epoch 2), and $6 \pm 3$ cm s$^{-1}$ (Epoch 3).

During the cruise, the depth of the euphotic zone determined from radiometer profiles conducted aboard the Revelle had a mean and standard deviation of 112 $\pm$ 7 m (0.1% of surface PAR, $n = 11$), while the mixed layer was 31 $\pm$ 4 m ($n = 227$; using a 0.1 kg m$^{-3}$ criterion) during the sampling period (Siegel et al., n.d.). Prior work supports the interpretation of sinking particle flux data with reference to the primary production zone depth, which is defined as the depth where in vivo chlorophyll fluorescence drops to 10% of its maximum value (Owens et al., 2015). This depth, computed from daily chlorophyll fluorescence (FLNTU, WET labs Inc.) profiles of the Lagrangian float followed by the Revelle, was 116 $\pm$ 3 m, consistent with the 0.1% PAR depth and with other work supporting the use of a 0.1% PAR definition as the export reference depth (Marra et al., 2014; Buesseler et al., 2020b). As discussed above, the NBST deployment depths and the STT depths in Epoch 1 were targeted at 95, 145, 195, 330, and 500 m, while the STT depths in Epochs 2–3 were 10 m deeper. We have therefore grouped together all traps deployed in the same 10-m interval. For brevity, we refer below to these trap depth bands as 100, 150, 200, 335, and 505 m.

### 3.2. Bulk fluxes

#### 3.3.1. Swimmer correction

Sediment trap samples were highly impacted by zooplankton “swimmers,” with tens of milliliters of biomass removed in some cases. Often more swimmer material was removed from samples than the passive flux material left behind, with NBSTs more greatly impacted by swimmers than STTs (Figure S4). Qualitatively, the bulk of the swimmer biomass manually removed from samples was from Themisto and Vibilia amphipods (D Steinberg, personal communication). Large numbers of copepods and pteropods were also removed. Passively sinking material adhering to swimmers was carefully separated and returned to the bulk sample. The relative variability of swimmer fluxes before and after picking was computed as the relative difference between two traps, or relative standard deviation among three traps co-deployed at the same target depth. For triplicates, the RSD is the standard deviation among the three measurements divided by their mean. Error bars show propagated, split-to-split uncertainty from single platforms. The 1:1 line is shown for reference (solid black). DOI: https://doi.org/10.1525/elementa.2020.00122.f2.

![Figure 2. Relative variability in measures of swimmer flux. Relationship between measures of relative variability in swimmer area flux to gels, and relative variability in particulate organic carbon (POC) flux to bulk traps prior to statistical swimmer correction (see text). Black squares show relative differences (relative difference) between pairs of traps co-deployed at the same target depth, which is defined, for trap pairs, as the absolute difference between the two measurements, divided by the mean. White circles show relative standard deviations (RSDs) among sets of three traps co-deployed at the same target depth. For triplicates, the RSD is the standard deviation among the three measurements divided by their mean. Error bars show propagated, split-to-split uncertainty from single platforms. The 1:1 line is shown for reference (solid black). DOI: https://doi.org/10.1525/elementa.2020.00122.f2.](http://online.ucpress.edu/elementa/article-pdf/9/1/00122/466416/elementa.2020.00122.pdf)

Swimmers were generally small (less than 6 mm), swimmers that were small enough to pass through the screen, and possibly from unrecognized, fragmented, or cryptic swimmers (Michaels et al., 1990).

Relationships among the bulk elemental fluxes and magnitudes of some fluxes suggested nonnegligible contributions by swimmers to certain analytes (total and inorganic carbon, nitrogen, phosphorus, and total mass; Figure 3). For instance, ratios of carbon to $^{234}$Th in STT and NBST trap samples ranged from 2.1 to 29 µmol dpm$^{-1}$, with a median of 5.4 µmol dpm$^{-1}$. Previous work in the region has shown that C:$^{234}$Th values are almost always less than 6 µmol dpm$^{-1}$ (Charette et al., 1999; Kawakami et al., 2010; Mackinson et al., 2015). The higher values observed here are consistent with contamination by zooplankton, which typically have high C:$^{234}$Th ratios (Coale, 1990; Buesseler et al., 2006; Passow et al., 2006). The organic carbon (OC) weight fraction of the total mass flux ranged from 0.17 to 0.68 with a median of 0.34. Several samples had OC weight fractions above 0.5 (Figure 3b), consistent with enhanced contributions from components such as lipids and proteins (Hedges et al., 2002). We found that samples with high C:$^{234}$Th and high OC weight fractions also had high area fluxes of zooplankton swimmers...
to the gel trap on the same platform (Figure 3a and b). Swimmer-impacted analytes also showed high fluxes and inter-platform variability in the upper 195 m of the water column. In contrast, we found that fluxes of $^{234}$Th and bSi appeared to be less influenced by swimmer contributions as they were well-correlated to the area fluxes of nonswimmer particles (Figure 3c and d).

To correct for the additional POC flux contributed by swimmer material that passed through the 335-μm mesh, a statistical correction procedure was applied (Figure 4; Text S1). An unsupervised classification (Gaussian mixture cluster analysis; Press et al., 2007) was used to identify the subset of samples with high covariance among the following compositional ratios: bSi:POC, $^{234}$Th:POC, area:POC, and mass:POC. We assumed that these samples, which spanned the whole range of trap depths, were unlikely to be contaminated by swimmer material. The mean bSi:POC, $^{234}$Th:POC, and area:POC ratios from those samples were used to generate three independent, passive-only (i.e., swimmer-free) estimates of POC flux for the remainder of the samples. The estimated passive POC flux was insensitive to whether mean or depth-dependent compositional ratios were used, so we used the mean. Swimmer-corrected POC fluxes reported below were subsequently computed by averaging the three independent estimates. The uncertainty of this corrected POC flux is reported as the larger of either the standard deviation among the three estimates or the original observational uncertainty (mainly split-to-split variability; Table 2). DOI: https://doi.org/10.1525/elementa.2020.00122.f3

**Figure 3.** Bulk flux compositional ratios used for swimmer correction. Property-property plots for bulk flux samples illustrate the properties used to identify uncontaminated samples for statistical swimmer correction. In all panels, symbol colors correspond to the cross-sectional area “flux” of swimmers in gel collectors. Panel (a): Particulate organic carbon (POC) flux versus $^{234}$Th flux, no significant correlation. Dashed line shows POC:$^{234}$Th = 6 μmol dpm$^{-1}$. Panel (b): Mass fraction of organic carbon (see text) versus area flux of nonswimmer particles, $R^2 = .15$, $p < .05$. Dashed line shows mass fraction OC = 0.5. Panel (c): Area flux of nonswimmer particles versus $^{234}$Th flux, $R^2 = .56$, $p < 10^{-5}$. Panel (d): Area flux of nonswimmer particles versus biogenic silica (bSi) flux, $R^2 = .62$, $p < 10^{-6}$. Error bars indicate plus or minus one standard deviation ($n = 3$) or the range ($n = 2$) of directly measured splits (see Table 2). DOI: https://doi.org/10.1525/elementa.2020.00122.f3
Figure 4. Flowchart illustrating the modeling process for statistical swimmer correction. Dark gray box indicates observed quantities. Light gray boxes indicate modeled quantities, and white boxes indicate model steps. bSi = biogenic silica; POC = particulate organic carbon. DOI: https://doi.org/10.1525/elementa.2020.00122.f4

to larger swimmers that were removed manually from the screen prior to splitting and filtering.

Calculated swimmer POC contributions from material smaller than 335 μm in the screened and manually picked samples (Table 2) correlated positively with the area flux of swimmers of all sizes to the gel traps ($R^2 = .53, p < 10^{-5}$) but were not significantly related to area fluxes of swimmers smaller than 335 μm. Both the calculated swimmer POC correction and the total area flux of swimmers to gel traps were much larger in the NBSTs than in the STTs (Figure S4). However, the area fluxes of swimmers smaller than 335 μm were similar in NBSTs and STTs and comprised only a small fraction (median 6%) of the total swimmer area in the gels (Figure S4). These findings suggest that most of the swimmer material passing through the mesh originally entered the traps with larger swimmers and was detached during bulk sample handling. Swimmer POC from material smaller than 335 μm contributed between 0 and 91% of the measured, uncorrected POC flux (mean ± standard deviation of 45 ± 31%, n = 32). Above 200 μm, significant differences were observed between trap types in Epochs 1 and 2 (but not Epoch 3), with much higher swimmer POC contributions observed in NBST samples (paired-sample t test, 95% confidence; Table 2). No epoch-to-epoch differences were observed in contributions of <335 μm swimmer POC in the STTs, and for NBSTs only Epochs 1 and 3 differed significantly from one another (paired-sample t test, 95% confidence). The mean elemental ratios of the swimmer-free sample subset are reported below. Corrected profiles of the other swimmer-contaminated analytes besides POC (N, P mass, PIC) can be estimated by scaling passive POC flux estimates by the appropriate elemental ratios.

3.2.2. Flux profiles, bulk composition, and BCP efficiency

The corrected sediment trap-derived POC fluxes observed here were low and somewhat variable, with a cruise-wide average ($±$ standard deviation, n = 9) of 1.38 ($±$ 0.77) mmol C m$^{-2}$ d$^{-1}$ at the uppermost trap depth (100 m), attenuating significantly to 0.76 ($±$ 0.20) mmol C m$^{-2}$ d$^{-1}$ by a depth of 200 m (n = 8; t test, 95% confidence; Figure 5. Table 2). Surface-tethered sediment traps generally had a higher POC flux than NBSTs deployed at the same time and depth ($39 ± 18\%$ overall, Type-II linear regression, n = 12). POC fluxes also varied from epoch to epoch, increasing significantly (t test, 95% confidence) from 0.94 ($±$ 0.30, n = 6) mmol C m$^{-2}$ d$^{-1}$ in Epochs 1 and 2 to 2.27 ($±$ 0.61, n = 3) mmol C m$^{-2}$ d$^{-1}$ in Epoch 3. All nonswimmer impacted fluxes (bSi, $^{234}$Th, and area flux to gels) also increased significantly at 100 m from Epochs 1 and 2 to Epoch 3 (Figure 5). Significant epoch-to-epoch changes were not observed below 100 m, except for bSi at 145 m where fluxes in Epoch 3 increased to 0.43 ($±$ 0.10, n = 2) mmol Si m$^{-2}$ d$^{-1}$ from 0.17 ($±$ 0.03, n = 4) mmol Si m$^{-2}$ d$^{-1}$ in Epochs 1 and 2.

We assumed that the samples determined to be uncontaminated by POC from swimmers also had negligible swimmer contributions to measured N, PIC, and mass fluxes. We computed median compositional ratios from this small subset (n = 7; Table 2), which spanned all trap depths, epochs, and trap types, but which was not sufficient to examine variability within those categories. The median (interquartile range) of the POC: N molar ratio determined for this subset was 7.0 ($±$ 1.5), the PIC: POC molar ratio was 0.035 ($±$ 0.011), and the PIC:mass ratio was 0.25 ($±$ 0.03). The POC:P molar ratio was 264 ($±$ 187), although this ratio was higher than observed in samples from in situ pumps (M Roca-Martí, personal communication) and could indicate enhanced solubilization of P prior to sample filtration (e.g., Lamborg et al., 2008). The bSi:POC molar ratio increased from 0.15 ($±$ 0.03, n = 2) in Epoch 1 to 0.29 ($±$ 0.02, n = 4) in Epochs 2 and 3 (Figure 6b). The POC:$^{234}$Th ratio did not change significantly among the three epochs and had a mean of 2.2 ($±$ 0.2) μmol dpm$^{-1}$, consistent with >51 μm particulate samples collected via in situ large-volume pumps (Figure 6a; Buesseler et al., 2020a).

Epoch averages of NPP integrated to the uppermost trap depth ranged from 13.0 to 14.1 mmol C m$^{-2}$ d$^{-1}$ with a cruise mean of 13.8 ($±$ 1.9, n = 7) mmol C m$^{-2}$ d$^{-1}$ (Table 3). We use the Ez-ratio (here computed as the flux at the reference depth, 100 m, normalized to NPP) and the $T_{100}$ (flux at 200 m normalized to flux at 100 m) as metrics to describe the BCP efficiency (Buesseler and Boyd, 2009; Buesseler et al., 2020b). We found Ez-ratios ranging from
Figure 5. Fluxes of swimmer-corrected particulate organic carbon, biogenic silica (bSi), $^{234}$Th, and passively sinking area in gels. Open circles show fluxes to neutrally buoyant sediment traps, and filled squares show fluxes to surface-tethered traps. Panels a, b, and c show Epochs 1, 2, and 3, respectively. Error bars indicate plus or minus one standard deviation ($n = 3$) or the range ($n = 2$) of directly measured splits (see Table 2). POC = particulate organic carbon; bSi = biogenic silica. DOI: https://doi.org/10.1525/elementa.2020.00122.f5
propagated from the observations of Guidi et al. (2009; Table 3) or the range (n = 2) of directly measured splits (see Table 2). We also computed T\textsubscript{100} values for the fluxes without apparent swimmer contamination (bSi, 234Th, and gel area; Table 3; n = 3 except n = 2 in Epoch 2 at 200 m). For bSi, T\textsubscript{100} ranged from 0.4 to 1.1 with a mean of 0.6 (± 0.5); for 234Th, T\textsubscript{100} ranged from 0.4 to 1.0 with a mean of 0.5 (± 0.4); and for gel area flux, T\textsubscript{100} ranged from 0.4 to 0.8 with a mean of 0.6 (± 0.4). Among all analytes, T\textsubscript{100} varied the most in Epoch 1, was largest in Epoch 2, and varied the least and was lowest in Epoch 3 (Table 3).

3.3. Size distribution of sinking particles

PSD slopes (± propagated particle counting uncertainty) of sinking particles ranged from −2.15 (± 0.07) to −3.31 (± 0.16). For comparison, an equal volume distribution across all size classes may arise when mass redistribution among particles reaches a steady state, which would result in a theoretical PSD slope of −4 (Sheldon, 1972). Observed size distribution slopes of marine suspended particles typically fall between −2 and −4 (e.g., Guidi et al., 2009). Our sinking particle observations are therefore consistent with an increase in larger versus smaller particles, relative to typical distributions of suspended particles. The slope parameter S also generally decreased (became steeper) with increasing depth from 100 to 335 m, indicating a shift from larger to smaller particles over that depth range, albeit with substantial variability, consistent with the observations of Guidi et al. (2009; Figure 8). Among all samples, the median particle size (i.e., the equivalent spherical diameter calculated from the median area) ranged from 75 to 1,461 µm with a median of 282 µm. Particles smaller than 51 µm in diameter contributed between 0.57% and 42% of the total area flux, with a median of 11%. No significant trends in the median particle diameter or contribution of particles smaller than 51 µm were observed as a function of depth.

In spite of the relative importance of the largest particles to overall fluxes, they were not numerically abundant in the gel traps. Among size bins with median diameters larger than 437 µm, some samples had fewer than 10 particles (i.e., relative counting error greater than 32%) collected during a deployment. In size bins larger than 874 µm, some samples had zero particles collected. No particles larger than 5,792 µm were observed. The power-law model (Equation 1) gave a reasonable fit to the particle size data over the entire size range, with relative uncertainties in S determined by Monte Carlo propagation of counting uncertainty ranging from 2% to 10% (Figure 8). However, the observed size distributions included local minima and maxima that deviated from the model (Figure S1).

The estimated fluxes of 234Th carried by observed particles smaller than 32 µm had a mean (± standard deviation) of 26 (± 13, n = 30) dpm m\textsuperscript{-2} d\textsuperscript{-1}. The modeled fluxes of 234Th carried by 1–32 µm particles, computed by extrapolation of number flux size distributions to small sizes not well-resolved by microscopy, were larger and ranged from 119 to 376 dpm m\textsuperscript{-2} d\textsuperscript{-1}. Averaging the observations by depth and taking the difference from the model led to a conservative estimate of "missed" small particle 234Th flux ranging from 89 to 350 dpm m\textsuperscript{-2} d\textsuperscript{-1}, with the maximum observed at 150 m and the minimum

Figure 6. Thorium-234 and biogenic silica (bSi) ratios to particulate organic carbon (POC). Colors indicate epoch and correspond to Figure 1. Samples from the low-swimmer subset (see text and Table 2) are shown in larger triangles with heavy outlines. Small swimmer-corrected samples are shown with circles. (Left) 234Th versus swimmer-corrected POC. Mean POC:234Th ratio (± standard deviation) computed by Type-II linear regression is 2.2 (± 0.2) µmol dpm\textsuperscript{-1}; R\textsuperscript{2} = 0.86, \( p < 10^{-11} \), n = 32. (Right) bSi versus swimmer-corrected POC. Mean bSi:POC ratio (mol/mol) computed by Type-II linear regression is 0.29 (± 0.02); R\textsuperscript{2} = 0.90, \( p < 10^{-15} \), n = 32. Error bars indicate plus or minus one standard deviation (n = 3) or the range (n = 2) of directly measured splits (see Table 2). DOI: https://doi.org/10.1525/elementa.2020.00122
The modeled 234Th flux carried by rare particles with less than 5% probability of reaching a collection threshold of five particles in 3 days ranged from 120 to 456 dpm m\(^{-2}\) d\(^{-1}\), with the maximum observed at 100 m and the minimum at 330 m. The summed, modeled fluxes of 234Th carried by rarely collected and 1–32 mm particles ranged from 287 to 567 dpm m\(^{-2}\) d\(^{-1}\).

Durkin et al. (2021) classified passively sinking particles imaged in the gel traps that were approximately 10 mm or larger into nine morphological categories. Using literature values and prior, independent field measurements, modeled, size-dependent carbon contents were assigned to each particle class. The details of this model are presented elsewhere (Durkin et al., 2021), but we summarize a subset of the results here in order to support comparisons to the measured bulk fluxes. The POC fluxes modeled from particles identified in the gel traps agreed with the measured POC fluxes presented here (Figure 9; see also figure 13 in Durkin et al., 2021), with a linear regression (± parameter 95% confidence intervals) of

\[
\text{Modeled POC} = 1.2\pm0.6 \times \text{Measured POC} + 0.006 \pm 0.7; R^2 = 0.38, P < 10^{-3}.
\]

When large but infrequent contributions from salp fecal pellets were excluded from the modeled POC fluxes, the scatter in the relationship improved, but the slope did not change ($R^2 = 0.73$, slope $= 1.2 \pm 0.3$).

Table 3. Particulate organic carbon (POC) fluxes, export ratios, and POC, biogenic silica, and 234Th transfer efficiencies. DOI: https://doi.org/10.1525/elementa.2020.00122.f7

<table>
<thead>
<tr>
<th>Sampling Period</th>
<th>Sampling Period (2018)</th>
<th>Fluxes (mmol C m(^{-2}) d(^{-1}))</th>
<th>Transfer Ratio ($T_{100}$)(^{bc})</th>
<th>Area (^d)</th>
<th>POC at 100 m</th>
<th>POC at 200 m</th>
<th>NPP(^a)</th>
<th>PO2 at 100 m</th>
<th>PO2 at 200 m</th>
<th>NPP at 200 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoch 1</td>
<td>August 15-20</td>
<td>1.10 (0.16, n = 3)</td>
<td>0.69 (0.32, n = 3)</td>
<td>0.74 (0.20, n = 3)</td>
<td>0.88 (0.41, n = 3)</td>
<td>0.76 (0.24, n = 3)</td>
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</tr>
<tr>
<td>Epoch 2</td>
<td>August 24-28</td>
<td>0.78 (0.35, n = 3)</td>
<td>1.14 (0.76, n = 2)</td>
<td>1.10 (0.56, n = 2)</td>
<td>1.17 (0.66, n = 2)</td>
<td>1.10 (0.56, n = 2)</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Epoch 3</td>
<td>August 31 to September 5</td>
<td>2.27 (0.61, n = 2)</td>
<td>1.03 (0.21, n = 2)</td>
<td>0.41 (0.22, n = 2)</td>
<td>0.40 (0.23, n = 2)</td>
<td>0.40 (0.23, n = 2)</td>
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<tr>
<td>Cruise</td>
<td>August 15 to September 7</td>
<td>1.38 (0.77, n = 3)</td>
<td>0.76 (0.24, n = 3)</td>
<td>0.76 (0.24, n = 3)</td>
<td>0.76 (0.24, n = 3)</td>
<td>0.76 (0.24, n = 3)</td>
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</table>

\(^{a}\)All values reported as mean (with standard deviation).

\(^{b}\)Export ratios of POC, biogenic silica, and 234Th.

\(^{c}\)Transfer ratios of POC, biogenic silica, and 234Th.

\(^{d}\)Area refers to the total cross-sectional area flux of passively sinking particles into the gel traps (see text).
3.4. Trap source regions

Consistent with similar source region modeling work in prior studies (e.g., Siegel et al. 2008), trap source areas increased with trap depth (Figure S5). Areas of source regions were similar between NBST and STT traps, likely because the mean flow was small relative to higher frequency motions responsible for spreading and divergence of the source regions. For modeled particles sinking at 100 m d−1, source regions were offset from trap locations by 3–8 km and the diameters of source regions ranged from 9 to 20 km, both increasing with depth. In general, passively sinking particle size decreased with depth through 335 m but then increased slightly at 505 m. Error bars show particle counting uncertainty propagated into the PSD model using a Monte Carlo technique (see text). DOI: https://doi.org/10.1525/elementa.2020.00122.f8

Figure 8. Power-law particle size distribution (PSD) slopes measured from particles in gel traps. Colors correspond to epoch and match Figure 1. Circles show neutrally buoyant sediment trap (NBST) samples and squares show surface-tethered trap (STT) samples. Less negative power-law slopes for PSD correspond to larger particles, and more negative slopes correspond to smaller particles. In general, passively sinking particle size decreased with depth through 335 m but then increased slightly at 505 m. Error bars show particle counting uncertainty propagated into the PSD model using a Monte Carlo technique (see text). DOI: https://doi.org/10.1525/elementa.2020.00122.f8

4. Discussion

4.1. Method–method intercomparisons

Sediment traps have been a standard tool for measuring sinking particle flux for decades, yet uncertainties about their collection efficiencies and biases relative to other methods still persist. These issues were reviewed comprehensively by Buesseler et al. (2007). More recently, Lamborg et al. (2008), Owens et al. (2013), and Baker et al. (2020) reported field intercomparisons of different trap designs. The sediment trap deployments conducted here take into account many of the lessons learned in the earlier studies: minimizing hydrodynamic bias by utilizing NBSTS alongside STTs (Buesseler et al., 2007), employing cylindrical trap tubes to avoid funnel effects associated with conical traps (Baker et al., 2020), collecting process blanks for every analyte to control for the effects of sample handling (Owens et al., 2013), and ensuring that STTs were deployed below the mixed layer (Owens et al., 2013). Sediment traps remain the only way to isolate and concentrate sinking particles from the suspended pool for laboratory analysis. However, because there is no absolute standard for sinking particle fluxes, the only way to
evaluate the accuracy of sediment traps is to compare observations to other methods. The EXPORTS field campaign is one of the most comprehensive efforts to date in terms of simultaneous, independent particle flux measurements. In addition to the direct measurement of bulk carbon fluxes reported here, the program included sinking particulate carbon fluxes estimated from gel trap imagery (Durkin et al., 2021), from water column $\text{^{230}U-^{234}Th}$ (Buesseler et al., 2020a) and $\text{^{210}Pb-^{210}Po}$ disequilibria (Roca-Martí et al., 2020) and from Marine Snow Catcher samples (Rocamadour et al., 2020). We, therefore, have an unprecedented opportunity to explore the underlying causes for mismatches among methods as well as to describe the functioning of the BCP in this subpolar gyre setting.

### 4.1.1. Trap—trap reproducibility and platform differences

This study was consistent with prior observations of an approximate 10% overcollection of sinking POC flux by STTs relative to NBSTs (Estapa et al., 2020). The STT array was subject to wind stress on the surface buoy, which led to its divergence from the co-deployed NBSTs in all epochs (Figure 1). However, the measured relative velocities at the base of the STT array in each epoch mostly remained below the 10 cm s$^{-1}$ threshold at which hydrodynamic effects have been shown to become important (Buesseler et al., 1979; Lee et al., 1988). Solutions have run the gamut of platforms aimed at deploying sediment traps to minimize swimmer intrusion (e.g., “the labyrinth of doom” and “indented rotating platform” by Coale, 1990; Peterson et al., 2005), simple size-based separations such as those used in the Hawaii Ocean Time-series (HOT) program (Karl et al., 1990) and by the Bermuda Atlantic Time-series Study (BATS) program (Knap et al. 1997). The types and intensity of swimmer intrusion into sediment traps are highly variable and difficult to predict in advance of deployments. For instance, the NBSTs employed in this study attracted more swimmers than did co-deployed STTs (Figure 4), even though in prior work the reverse has occurred (Buesseler et al., 2000). Owens et al. (2013) discussed multiple examples where the same trap design performs differently (in terms of swimmer collection) in a variety of settings. Disentangling hydrodynamic effects from zooplankton behavioral influences remains a complex challenge.

Here, we have added a novel swimmer correction technique to the trapper’s toolbox, which, uniquely, is available for use after traps are retrieved and samples are analyzed. It is not, of course, a substitute for full exclusion of swimmers during trap deployment, or their removal from samples after retrieval, and information about the variation of sample composition with depth and time is lost. A direct validation of this approach awaits future study. However, this method allows retention of information about the overall sinking flux magnitude (here reported as POC flux), and critically, it can reveal the effectiveness of other swimmer exclusion treatments applied during sample collection and processing.

The statistical swimmer correction technique presented here relies on the availability of a handful of samples from the same site and time period, with similar multielement compositions (POC, mass, $\text{^{234}Th}$ activity, $\text{bSi}$, and nonswimmer composition), and flux profiles will be useful to measure in general because high POCl$\text{^{234}Th}$ ratios of swimmer biomass have been reported widely (Buesseler et al., 2006; Passow et al., 2006;
Buesseler et al., 2020a) and because swimmers can be identified easily and excluded from gel trap analyses.

4.1.3. Comparison of measured and predicted 234Th fluxes and implications for trap efficiency

In parallel with the trap sampling conducted here, over 20 spatially distributed profiles of total 234Th were collected during each epoch (Buesseler et al., 2020a). Under steady-state conditions, and in the absence of fluxes carried by vertically migrating zooplankton that bypass sediment traps, fluxes of 234Th computed from the water column deficit of particle-reactive 234Th relative to its conservative parent isotope 238U (termed “predicted 234Th fluxes”) should agree with measured fluxes of 234Th into sediment traps (e.g., Buesseler, 1991). However, in several prior studies with high-frequency sampling for 234Th in both the water column and in sediment traps, the difference between predicted 234Th fluxes and trap measurements is positive and typically increases as the total predicted flux increases (Buesseler et al., 2007). In this study, we similarly found measured 234Th fluxes in traps whose mean (+ standard deviation) values were 33 ± 19% (n = 32) of the “best estimate” fluxes (mean of steady-state and non-steady-state models; Buesseler et al., 2020a) predicted from water column activities (Figure 10). Buesseler et al. (2007) hypothesized that this pattern might be explained by hydrodynamic bias leading to preferential undercollection by traps of the smallest particles that contribute the most to the water column 234Th deficit, or alternatively by episodic, high-flux events that are missed by traps but captured by the longer integration timescale of 234Th measurements. The data collected during EXPORTS include 3D, time-resolved 234Th activities (Buesseler et al., 2020a), simultaneous neutrally buoyant and surface-tethered sediment trap deployments, and measurements of the sinking PSD over particle diameters ranging over three orders of magnitude. Therefore, we have the unique opportunity to evaluate quantitatively the possible drivers of this globally observed pattern.

We first consider timescale because water column-derived 234Th fluxes in this study likely integrated over approximately 20 days preceding sample collection (Buesseler et al., 2020a), while trap samples integrated over 3–6 days. Therefore, one possible explanation of predicted versus measured 234Th flux mismatches could be a high export event preceding the cruise. However, there is no evidence for such an event. Thorium-234 activities stayed relatively constant in Epochs 1 and 2 and increased 6–10% in the upper 60 m by Epoch 3, which leads to a decrease in flux predicted from water column 234Th deficits over the course of the cruise (Buesseler et al., 2020a). Also, no large changes in production indices were observed by autonomous vehicles present prior to the ship arrivals on station in mid-August (Siegel et al., n.d.), nor did fluxes of longer timescale tracers (e.g., 210Pb-210Po) indicate higher export prior to the cruise (Roca-Martí et al., 2020). Horizontal advection of 234Th into surface waters, which cannot be distinguished from a temporal change, possibly could have accounted for some of this increase in 234Th activity by Epoch 3. However, predicted

**Figure 10.** Measured and predicted thorium-234 fluxes. Comparison of measured 234Th fluxes from traps (black circles) and predicted cruise-mean 234Th fluxes from water column deficits according to steady-state (SS; light gray lines; solid and dashed show mean ± uncertainty) and non-steady-state (NSS; dark gray lines) models. Left panels compare to neutrally buoyant and surface-tethered trap fluxes; right panels compare to surface-tethered trap fluxes. Panel row corresponds to epoch. Predicted 234Th fluxes are from Buesseler et al. (2020a). Error bars, which in many cases are smaller than the markers, indicate plus or minus one standard deviation (n = 3) or the range (n = 2) of directly measured splits (see Table 2). DOI: https://doi.org/10.1525/elementa.2020.00122.f10
$^{234}$Th fluxes from a steady-state model (Buesseler et al., 2020a) were unrelated to trap $^{234}$Th fluxes (paired t test, $p < 10^{-4}$) regardless of whether spatial averages were computed over the whole $^{234}$Th data set or over subsets of measurements specifically within the trap source regions (Figure S5). Overall, these observations suggest that a sampling mismatch over a spatial flux gradient was unlikely to be the main cause of the discrepancy and that export prior to our arrival on station would have made only a minor contribution to the observed mismatch. Below, we discuss comparisons to flux predictions from both the steady-state (SS) and non-steady-state (NSS) models reported by Buesseler et al. (2020a), where the latter model is in better agreement with measured fluxes to the traps (Figure 10). Each model carries different assumptions about horizontal advection of $^{234}$Th and the time variations in the $^{234}$Th flux, as described in detail by Buesseler et al. (2020a).

Another possible cause of the discrepancy between water column-derived and measured sediment trap fluxes was that $^{234}$Th-bearing particles adhering to the bodies of zooplankton swimmers could have been picked out of the trap samples, inadvertently decreasing the measured trap fluxes (Buesseler et al., 2007). However, in spite of substantial differences in the numbers of swimmers detected in and removed from the different samples (Figure S4), $^{234}$Th fluxes were consistent among different trap platforms deployed alongside one another (Figure 10; Table 2). Furthermore, an independent model predicting carbon flux from images of particles in the gel traps agreed well with the corrected bulk carbon fluxes, as presented by Durkin et al. (2021) and discussed above (Figure 9; Size distribution of sinking particles section and Statistical Swimmer Correction section).

A number of recent studies have indicated an important role for small (tens of microns and smaller), presumably slowly settling particles in the BCP (Richardson and Jackson 2007; Richardson, 2019). If sediment traps undercollect such particles, then the difference between measured and predicted $^{234}$Th fluxes would be expected to grow with an increasing contribution of these small, $^{234}$Th-enriched particles to the total flux. We interpret the difference between the modeled and measured fluxes of $^{234}$Th carried by 1–32 μm particles (Figure 11; Size Distribution of Sinking Particles section) as the flux potentially missed by both the bulk and gel traps due to hydrodynamic effects (Buesseler et al. 2007) or by the gel traps, but not the bulk traps because of microscope resolution limits (Durkin et al., 2015). However, this interpretation of the model rests on the assumption that flattening of the sinking PSD at the small end of the size spectrum (Figure S1) was due to platform or detection effects and not to an actual decrease of the number fluxes of small particles relative to larger ones. While numerous studies support the idea that PSDs of nonsinking particles follow a power-law function at sizes below 32 μm, our ability to confirm this function for sinking particles remains limited at present. Even so, polyacrylamide gel traps and optical microscopy remain the best method for

![Figure 11](https://doi.org/10.1525/elementa.2020.00122.f11)

**Figure 11.** Measured, modeled, and predicted contributions to $^{234}$Th flux averaged during the cruise. Filled colored areas illustrate the cumulative contributions to the $^{234}$Th flux modeled from extrapolated sinking particle size distributions (see text). These include modeled flux of particles of diameter (D) larger than 32 μm collected by traps (blue, “Modeled trap-collected”), flux carried by smaller, potentially undercollected particles (orange), and flux carried by rare, infrequently collected particles (yellow). Also shown are the predicted $^{234}$Th flux from the steady-state (SS) model that assumes flux is constant in time (solid black line and shaded dark gray area showing uncertainty; see text discussion and Buesseler et al., 2020a) and from the non-steady-state (NSS) model that allows for time-varying flux (dashed black line and shaded light gray area; see text discussion and Buesseler et al., 2020a), as well as the measured flux in the neutrally buoyant sediment traps (NBSTs; magenta circles) and surface-tethered traps (STTs; magenta triangles), and the same trap fluxes with added, modeled contributions by small and infrequently collected particles (white symbols). DOI: https://doi.org/10.1525/elementa.2020.00122.f11
quantifying sinking particles with sizes below approximately 100 μm (e.g., Giering et al., 2020). In addition to the reasons given above, another reason to approach this model result with caution is the lack of any systematic difference between NBSTs and STTs in 234Th undercollection (Figure 10), even though NBSTs are expected to collect the smallest particles more readily due to their lower hydrodynamic biases (Baker et al., 2020). Finally, the model used a single, mean 234Th:area ratio, which may be inappropriate for particles ranging over orders of magnitude in diameter (e.g., Buesseler et al., 2006).

At the large end of the sinking particle spectrum (diameters roughly 1,000 μm and larger), particles may be less affected by the flow field around traps, given their assumed faster sinking speeds, but they also occur less frequently in low-flux settings such as Station P during the months of our study. The observed mean, size-resolved particle collection rates imply that if a power-law function accurately describes the size distribution of large sinking particles, then particles larger than about 2,000–3,000 μm had <5% probability of being collected during a 3-day deployment (Figure S2), even though modeled fluxes of those particles accounted for up to 9% of the total (Figure 11). The simple model of “undercollected, rare-particle flux” that is presented here is conservative in its calculation of the probability of collecting five particles in 3 days. Both increasing the deployment length and decreasing the required number of particles would decrease the magnitude of the modeled undercollection. Any departure of the true, sinking modeled PSD from the power-law model (Equation 1) at the large end of the spectrum would also add uncertainty to the modeled, undercounted flux from large particles. Unfortunately, the size distributions of large, sinking particles are not well constrained in general. The probability of collecting rare, large particles will increase, however, as the collection rates of these particles increase in higher flux settings. Therefore, undercounting is likely to be most problematic in low-flux settings with only occasional, outsized contributions of rare, large particles. Observations of salp patches, and occasional collection of salp fecal pellets that dominated modeled carbon flux to traps, suggest that such undercounting may have been the case during our study (Steinberg et al., 2020; Durkin et al., 2021).

The simple assumptions made in our model of 234Th fluxes carried by different particle classes allow us to coarsely evaluate the possible contribution of trap collection biases to the mismatch between trap and water column 234Th fluxes. Addition of the mean, modeled small-particle and rare-particle fluxes to the trap observations could plausibly close the gap between trap and predicted 234Th fluxes from the non-steady-state model at depths between 100 and 200 m (Figure 11). However, this approach did not work with respect to the steady-state model flux predictions or at depths below 200 m, where a gap of several hundred dpm m$^{-2}$ d$^{-1}$ remained (Figure 11).

In parallel with possible trap inefficiencies, fluxes carried by zooplankton vertical migrants could also be reflected in the water column 234Th deficits but not collected by the traps. Actively migrating zooplankton feed near the surface and then release 234Th at depth through respiration or excretion of the associated carbon, bypassing traps but contributing to the water column deficit (Longhurst et al., 1990; Steinberg et al., 2000; Steinberg and Landry, 2017). We next assess whether the magnitude of the observed trap-water column mismatch is consistent with an independent estimate of the carbon dioxide and DOC fluxes carried below 100 m by diel vertical migrants, which together averaged 0.4 mmol C m$^{-2}$ d$^{-1}$ (A Maas, personal communication).

The cruise-average, trap-water column 234Th flux mismatch at 100 m was 428 dpm m$^{-2}$ d$^{-1}$ (non-steady-state model) or 854 dpm m$^{-2}$ d$^{-1}$ (steady-state model). The conversion to carbon flux depends on the POC:234Th ratio (for brevity, C:Th ratio) of particles consumed by migrating zooplankton. In the mixed layer, particles smaller than 5 μm in diameter had a C:Th ratio of 3.95 μmol dpm$^{-1}$, while larger 5–51 μm particles at 100 m had a C:Th ratio of 1.62 μmol dpm$^{-1}$ (Buesseler et al., 2020a). These choices represent the high and low end of likely C:Th ratios. Depending on which flux model and C:Th ratio are chosen, the corresponding POC flux would range from 0.7 to 3.4 mmol C m$^{-2}$ d$^{-1}$. Therefore, only in the scenario where the non-steady-state model is used to predict 234Th flux, and a relatively low C:Th ratio is assumed, is the active flux by itself (0.4 mmol C m$^{-2}$ d$^{-1}$) of similar magnitude to the trap-water column 234Th flux mismatch. This comparison obviously rests upon a number of assumptions about the depth structure of zooplankton migration, the nature of food particles consumed, and the degree of actual undercollection and undercounting of particles by sediment traps. A more detailed exploration of these assumptions awaits further work, but this initial estimate suggests that part of the trap-water column 234Th flux mismatch could plausibly be due to active transport of carbon by vertical migrants, especially at the upper trap depths where their contribution should be the largest. However, this process does not address the larger trap-water column mismatch observed at deeper depths.

4.2. Characterizing the BCP during the EXPORTS North Pacific cruise

The overarching EXPORTS program goal is to characterize the BCP and related satellite observables across a range of ecosystem states, so that predictive, mechanistic models generalizable to the global ocean can be developed. To that end, the comparison of BCP strength and efficiency as measured here to other estimates will help to contextualize the North Pacific field campaign, which was meant to serve as one end-member of a broader comparison (Siegel et al., n.d.). Buesseler and Boyd (2009), and more recently Buesseler et al. (2020b), proposed the use of two metrics, the export ratio at the euphotic zone depth (Ez-ratio) and the 100-m transfer efficiency (T100), to describe and compare the BCP across regions and seasons.

The cruise-mean Ez-ratio observed here (0.10 ± 0.06) was consistent with an earlier measurement of 0.13 at Station P in August (Charette et al., 1999; Buesseler and Boyd, 2009). Our measured transfer efficiency (0.55 ±
0.35) is higher than the Charette et al. (1999) estimate of $T_{100} = 0.3$, although in that study $T_{100}$ was assessed at 40 m, which was likely well within the euphotic zone, resulting in a lower $T_{100}$ value (Buesseler et al., 2020a). Here, we have assessed the Ez-ratio and $T_{100}$ metrics at a depth slightly above the 0.1% light level. The difference between the upper trap depth (95–105 m) and $z_{eu}$ (112 ± 7 m, n = 11) is small, and interpolating the trap fluxes to 112 m would have introduced additional uncertainty. Parallel, independent estimates of the Ez-ratio and $T_{100}$ parameters were made using carbon flux predicted from $^{234}$Th deficits and C/$^{234}$Th ratios in large-volume pump samples (Buesseler et al., 2020a). For the “best estimate” of $^{234}$Th flux in that study, computed as the mean of the steady-state and non-steady-state models with an assumed euphotic zone depth of 120 m, the $^{234}$Th-based Ez-ratio was 0.13 (± 0.05; uncertainty from NPP and numerous $^{234}$Th flux measurements) indicates that the August–September period at Station P is one of generally low and declining export fluxes compared to earlier in the season (Timothy et al., 2013). Our observations are consistent with this finding. The shifts we observed in BCP strength and efficiency on weekly timescales are striking in comparison to the global range of similar measurements (Figure 7; see also a summary of global data in Buesseler and Boyd, 2009, updated in Buesseler et al., 2020b). For instance, our trap observations show that the first two sampling epochs had high and variable transfer efficiencies (0.6–0.9; Table 3) and low, relatively well-constrained Ez-ratios (0.06–0.08), which makes them more similar to subtropical, oligotrophic sites like HOT and BATS (Buesseler and Boyd, 2009). In contrast, the third sampling epoch saw an increase in both the magnitude and variability of the Ez-ratio (to 0.18 ± 0.06), coupled with a decrease in $T_{100}$ to 0.4 (± 0.2), which is more consistent with earlier observations at Station P in late summer (Charette et al., 1999). Shifts in proxies for biological stocks and rates, from Epochs 1 and 2 to Epoch 3, included increases in surface POC, phytoplankton pigments, and bSi concentrations (Siegel et al., n.d.). Forthcoming, more detailed investigations of the underlying biological processes and surface community composition will allow us to better contextualize these observed, temporal shifts in fluxes to the traps.

In spite of the larger week-to-week changes in Ez-ratio and $T_{100}$ measurements, their product, which gives the overall efficiency with which NPP is transferred to 100 m below the reference depth, was well constrained across sampling epochs (0.055 ± 0.010, n = 3). Compensation for an increase in the export efficiency with a decrease in the transfer efficiency during the course of the cruise is consistent with tight coupling between production and recycling in the ecosystem in the northeast, subarctic Pacific Ocean (Wassman et al., 1998; Buesseler and Boyd, 2009). Also suggestive of this coupling were the types of particles observed in gel traps and Marine Snow Catchers deployed during EXPORTS. Phytoplankton aggregates and cells made only minimal contributions to the sinking flux, which appeared to be heavily modulated by grazers (McNair and Menden-Deuer, 2020; Durkin et al., 2021; U Passow, personal communication). Future investigations will examine possible connections of these observations to biological rates and the ecosystem structure measured during EXPORTS.

5. Conclusion
We have presented the initial results from the EXPORTS North Pacific sediment trap sampling program, discussed the general patterns that were observed, and analyzed the major sources of uncertainty in our findings. This work includes the development of a novel method to correct for swimmer carbon in the sediment traps and the use of detailed measurements of sinking PSD to estimate $^{234}$Th fluxes via undercollected small particles and undercounted rare, large particles and to constrain potential $^{234}$Th fluxes due to active zooplankton transport. Future studies will examine more closely the role of active transport in carrying POC fluxes to depth; the spatiotemporal changes in physical drivers and ecosystem structure that might be responsible for changes in BCP efficiency on weekly timescales; and the detailed biological identities, fluxes, and attenuation with depth of sinking particles collected in gel traps (Durkin et al., 2021).

Data accessibility statement


Photosynthetically available radiation (PAR) data:

Supplemental files
The supplemental files for this article can be found as follows:

Text S1. Matlab code to carry out the swimmer correction procedure outlined in the main text and illustrated in Figure 4.

Figure S1. Composite figure showing particle size distribution spectra from all gel trap samples and fit of a power-law function to the data.

Figure S2. Figure showing the probability of collecting ≥5 particles during a trap deployment, as a function of particle size (1 μm to 1 cm) and depth (100–500 m).

Figure S3. Relative horizontal current speeds at the bottom of the surface-tethered trap array.

Figure S4. Profiles of proxies for swimmer intrusion into sediment traps.

Figure S5. Modeled particle source funnels for each trap, for particles sinking 100 m d−1.

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Competing interests
The authors declare that they have no conflict of interest.

Author contributions
Substantial contributions to conception and design: ME, KB, CAD, MO.

Acquisition of data: ME, KB, CAD, MO, CRBN, EB, RPK, SP, MRM.

Analysis and interpretation of data: ME, KB, CAD, MO, CRBN, EB, RPK, SP, MRM.

Drafting the article or revising it critically for important intellectual content: LE, KB, CAD, MO, CRBN, EB, RPK, SP, MRM.

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