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Observations of carbon export by small sinking particles in the upper mesopelagic

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ABSTRACT

Carbon and nutrients are transported out of the surface ocean and sequestered at depth by sinking particles. Sinking particle sizes span many orders of magnitude and the relative influence of small particles on carbon export compared to large particles has not been resolved. To determine the influence of particle size on carbon export, the flux of both small (11–64 μm) and large (>64 μm) particles in the upper mesopelagic was examined during 5 cruises of the Bermuda Atlantic Time Series (BATS) in the Sargasso Sea using neutrally buoyant sediment traps mounted with tubes containing polyacrylamide gel layers and tubes containing a poisoned brine layer. Particles were also collected in surface-tethered, free-floating traps at higher carbon flux locations in the tropical and subtropical South Atlantic Ocean. Particle sizes spanning three orders of magnitude were resolved in gel samples, included sinking particles as small as 11 μm. At BATS, the number flux of small particles tended to increase with depth, whereas the number flux of large particles tended to decrease with depth. The carbon content of different sized particles could not be modeled by a single set of parameters because the particle composition varied across locations and over time. The modeled carbon flux by small particles at BATS, including all samples and depths, was 39 ± 20% of the modeled total carbon flux, and the percentage increased with depth in 4 out of the 5 months sampled. These results indicate that small particles (<64 μm) are actively settling in the water column and are an important contributor to carbon flux throughout the mesopelagic. Observations and models that overlook these particles will underestimate the vertical flux of organic matter in the ocean.

1. Introduction

The biological pump leads to the uptake and sequestration of carbon by the ocean (Volk and Hoffert, 1985). The first step of the biological pump occurs when phytoplankton fix inorganic carbon into organic matter in the surface ocean, and the last step occurs when organic carbon sinks or is subducted into the deep ocean and is removed from contact with the atmosphere. Organic carbon is transported out of the surface ocean by particles, which include organisms, organic aggregates, and fecal pellets. Whether those particles reach the deep ocean before their carbon is consumed or respired depends on their individual characteristics and the influence of ecological processes as they sink through the mesopelagic zone (Buesseler et al., 2007b; De La Rocha and Passow, 2007). The amount of carbon that reaches the deep ocean is ultimately determined at the scale of the individual particle, so characterization of sinking particles and their ecological role is needed to determine the underlying mechanisms of carbon uptake by the ocean.

The size of a particle influences its fate as it sinks through the water column (Stemmann and Boss, 2012; Woodward et al., 2005), and for decades, great effort has gone toward identifying the particle size range contributing the most to carbon export (Dall'Olmo and Mork, 2014; Fowler and Knauer, 1986; Jacobs et al., 1973; McCave, 1975; Michaels and Silver, 1988; Richardson and Jackson, 2007; Riley et al., 2012). According to Stokes' Law, particle sinking speed scales with the square of particle size, and therefore large particles sink faster and are more likely to reach the deep ocean before being remineralized by bacteria. The importance of large particles (>100 μm) in transporting carbon to the deep ocean has been observed in multiple ocean environments (Guidi et al., 2009; Jackson et al., 2005; Riley et al., 2012) and explored in export models (Buesseler and Boyd, 2009; Giering et al., 2014; Siegel et al., 2014; Stemmann et al., 2004b). Observing small particles (<100 μm) at the same time as large particles is a methodological challenge because no single instrument or sampling device can resolve the entire size range of particles present in the water column (Jackson and Burd, 1998; Stemmann and Boss, 2012). Only a few studies have quantified suspended particle sizes spanning three orders of magnitude by combining instruments (Jackson et al., 1997; Stemmann et al., 2008). Differentiating sinking small particles from suspended small particles is even more challenging, and it is often assumed that small particles do not sink or sink so slowly that they are respired in the upper mesopelagic (Giering et al.,

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2014; Riley et al., 2012). These assumptions should be re-evaluated, since settling of small particles down to 1000 m and deeper has been observed (Dall'Olmo and Mork, 2014; Silver and Gowing, 1991).

Fast sinking speeds may not be required for small particles to contribute significantly to carbon export. In the Mediterranean Sea, the subarctic Pacific, and the subtropical North Pacific, approximately 50% of the carbon flux was attributed to particles sinking less than 100 m per day (Trull et al., 2008). During multiple sediment trap deployments near the Canary Islands, the largest fraction of bulk carbon flux was attributed to particles sinking between 0.7 and 5 m per day (Alonso-González et al., 2010). Although the size of these slowly sinking particles is unknown, particles sinking at these rates would either be small or have low density.

Small particles may be transported to depth at rates exceeding their own gravitational settling speeds through aggregation or because of physical mixing. Aggregates formed from small particles at the surface may sink below the surface layer rapidly and disaggregate at depth (Burd and Jackson, 2009; Jackson and Burd, 1998; Stemmann et al., 2004a). Several studies that combine modeling with particle measurements have concluded that small particles are transported to the deep sea by this mechanism of aggregation and disaggregation (Close et al., 2013; Giering et al., 2014; Richardson and Jackson, 2007; Stemmann et al., 2004a). This mechanism agrees with the established view that particles must be large to contribute to carbon flux, because the small particles in these models are exported only when part of larger aggregates. Alternatively, small particles could be transported by the "mixed layer pump", in which deep winter mixing transports small particles to depth and spring/summer shoaling of the mixed layer isolates these particles from the surface (Gardner et al., 1995). The mixed-layer pump was one of the proposed mechanisms for the observed vertical transport of particles smaller than 20 μm down to 1000 m in the Norwegian Sea (Dall'Olmo and Mork, 2014). Neither aggregation nor the mixed layer pump requires gravitational settling by individual small particles in order for them to contribute to carbon export.

Alternatively, small particles might be capable of sinking through the water column if shape and excess density contribute to enhanced settling speeds. McDonnell and Buesseler (2010, 2012) measured the sinking speed of various particle size classes in both the Southern Ocean and the Sargasso Sea, and found that smaller particles generally had slower sinking speeds than larger particles, as predicted by Stokes Law. However, they found an exception for the smallest observed particles (73–195 μm), which had faster sinking speeds than some of the larger particles. This apparent departure from Stokes Law was possible due to variation in the shape and density of different particle size classes, but the authors' observations did not extend to smaller particles (<73 μm) below the resolution of their observational techniques. If small particles sink faster than expected, they may have an unanticipated contribution to carbon export.

Small particles may contribute significantly to carbon flux due to aggregation and disaggregation, physical mixing, or direct gravitational settling. In the present study, we quantify the flux of both small and large particles in the Sargasso Sea and at various locations in the southern subtropical and tropical Atlantic Ocean with the use of polyacrylamide gels placed in the bottom of sediment traps, referred to here as gel traps (Ebersbach and Trull, 2008; Lundsgaard, 1995; McDonnell and Buesseler, 2010; Waite et al., 2000). Sinking particles gently settle into the gel layer at the bottom of the trap tube, retaining their original characteristics and maintaining their separation from one another. We observe sinking particles from a larger size range than in previous gel trap studies and quantify sinking particles as small as 11 μm. Particles that settle into the gel trap are by definition sinking, thus the fluxes we calculate are due to the sinking of individual particles at the depth at which they were collected. We calculate the contribution of both small (here defined as 11–64 μm) and large particles (>64 μm) to total carbon flux as they sink out of the surface and through the mesopelagic ocean.

2. Methods

2.1. Preparation of polyacrylamide gels

Polyacrylamide gel layers were prepared in 11 cm diameter polycarbonate jars (Thermo Fisher Scientific Inc., USA) using methods described in previous studies (Ebersbach and Trull, 2008; Lundsgaard, 1995; McDonnell and Buesseler, 2010) with slight modifications. To prepare 12% polyacrylamide gel, 7.5 g of sea salts (Sigma-Aldrich, USA) was dissolved into 400 mL of surface seawater from Vineyard Sound, MA, USA and filtered through a 0.2 μm polycarbonate filter (Millipore, Thermo Fisher Scientific Inc., USA). The filtered brine was boiled for 15 min to reduce the oxygen content and reduce the brine volume to 350 mL. The solution was bubbled with nitrogen gas through glass pipet tips attached to a pressurized tank while the solution cooled to room temperature. The container of brine was then placed in an ice bath on a stir plate and 150 mL of 40% acrylamide solution (Thermo Fisher Scientific Inc., USA) and 1 g of ammonium persulfate (Thermo Fisher Scientific Inc., USA) was added to the solution while stirring. After the ammonium persulfate dissolved, 1 mL of tetramethylethylenediamine (Acros Organics, Thermo Fisher Scientific Inc., USA) was added to catalyze polymerization. The gel jars deployed in ballasted, neutrally buoyant sediment traps were required to weigh 140 g. To achieve consistent weights, a large volume of polyacrylamide gel was prepared and then poured into each jar. Gels were stored at 4 °C until use.

2.2. Particle collection

Samples were collected during five Bermuda Atlantic Time Series (BATS) cruises in the western Sargasso Sea in July, August, September, and October 2013 and in March 2014 aboard the R/V Atlantic Explorer (Fig. 1). Neutrally buoyant sediment traps (NBSTs) (Valdes and Price, 2000) with modified burn-wire closure mechanisms were deployed at three depths for approximately 3 days during each cruise (Table 1). The polycarbonate trap tubes were 12 × 70 cm with a collection diameter of 0.0133 m^2. Four samples were collected in the southern subtropical and tropical Atlantic during March–May 2013 on the DeepDOM cruise aboard the R/V Knorr (1 deployment at Station 2, 2 deployments

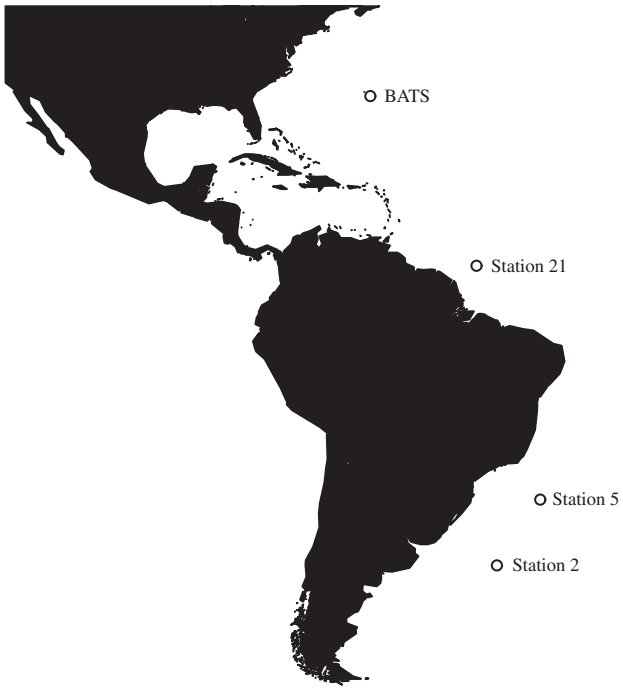

Fig. 1. Map of locations where sediment traps were deployed.

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