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Particle size distributions in the upper 100 m water column and their implications for animal feeding in the plankton

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ABSTRACT

We deployed autonomous particle-sensing SOLOPC floats more than eight times during five cruises, amassing almost 400 profiles of particle size ($d > 90$ μm) and abundance between the ocean surface and 100 m. The profiles consistently had subsurface maxima in particle volume. The median (by volume) equivalent spherical diameter for the particle distribution was 0.4–0.8 mm and increased with depth in a manner similar to that observed in coagulation simulations. There was a sharp cutoff at the bottom of the high particle concentration region. Estimation of particle fluxes made using the size distributions show an increasing downward movement through the particle field above the sharp particle cutoff. The increase of particle flux with depth through the euphotic zone implies a partial spatial separation of production and consumption. The sharp drop in particle volume and flux implies that the base of the particle-rich zone is a region of active particle consumption, possibly by zooplankton flux feeding. Our data show greater concentrations of zooplankton-type particles relative to marine snow-type particles below the particle maximum. Such behavior could explain why zooplankton are frequently observed at and immediately below the particle maximum rather than the productivity maximum and suggests an important role for flux feeding in carbon and nutrient cycling at the base of the particle maximum. This implies that zooplankton act as gatekeepers for the movement of organic matter to the mesopelagic. The ability of the SOLOPC to sample hourly with high resolution in the upper 100 m of the ocean provides a powerful complement for the study of particles where it has been difficult to use sediment traps.

1. Introduction

A dominant goal of biological oceanography during the last two decades has been to understand the factors that control the fate of organic matter in the ocean. The particulate nature of marine organisms has profound implications for how they find each other, how they grow and die, and how they sink. Dominant processes that affect particle concentrations include growth, coagulation, consumption, and settling. Size is an important particle property controlling all of these processes.

While the euphotic zone is the source of organic matter for the deep ocean, all the problems associated with the direct measurement of flux using sediment traps are accentuated there (e.g., Buesseler et al., 2007). Indirect measurements provide insight into the processes around the euphotic zone. For example, Buesseler et al. (2005, 2008) made fine-scale measurements of ^{234}Th distributions near the ocean surface to infer the sources and sinks of falling organic matter. Typically they found a relative deficiency in ^{234}Th in the euphotic zone caused by the adsorption to and subsequent settling loss of organic matter from it. Buesseler et al. (2008) observed regions of enhanced ^{234}Th activity at the base of the euphotic zone, which they ascribed to the capture, consumption, and remineralization of falling particles by zooplankton. Again, localized interaction of zooplankton and falling particles was invoked to explain these observations.

Particles have been counted and measured directly near the surface using in situ imaging techniques (*e.g.*, Walsh and Gardner, 1992, Lampitt et al. 1993a,b, MacIntyre et al., 1995; Stemmann et al., 2000). Invariably, there is a maximum in particles near the base of the surface mixed layer. This maximum has been associated with turbulent processes (MacIntyre et al., 1995) and with zooplankton feeding (*e.g.*, Lampitt et al., 1993b).

Gehlen et al. (2006) tested various biogeochemical models to determine the fate of organic matter leaving the near-surface and how it influenced the deep ocean. They argued that aggregation processes that alter the particle size distribution and, hence, the particle flux, are essential "to initiate an intense biological pump."

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Table 1
Particulars of SOLOPC deployments. t_0 is deployment time, hours local time; lat_0 and $long_0$ are the latitude and longitude at deployment; z_{max} is the maximum sampling depth.

Cruise	deploy #	ID	launch d	t_0	lat_0	$long_0$	# prof	z_{max}(m)
Sproul 05	1	sp05	28-Sep-05	0906	33.01° N	−118.01°	63	100
New Horizon 06	1	nh06	14-Sep-06	1701	34.28	−121.14	86	100
Sproul 07	1	sp07_1	23-Mar-07	2024	34.77	−117.56	9	100
	2	sp07_2	23-Mar-07	1738	32.78	−117.55	12	100
Thompson 07	1	th07_1	4-Apr-07	0821	34.26	−120.88	70	100
	2	th07_2	9-Apr-07	1744	33.62	−123.09	72	100
	4	th07_4	16-Apr-07	0205	34.20	−121.16	76	100
Knorr 08	1	bl08	2-May-08	2020	61.15	−25.37	10	150

They also noted that "Below the wind mixed layer, POC fluxes are most sensitive to the intensity of zooplankton community composition." Their analysis highlights the importance of both aggregation and zooplankton grazing to the vertical flux for the euphotic zone.

We have developed and deployed the autonomous SOLOPC float to measure the concentrations of particles, including aggregates and zooplankton, in the upper 100–150 m of the water column (Checkley et al., 2008). We have deployed SOLOPC floats more than eight times during four cruises off Southern California and one in the North Atlantic (Table 1). We now have almost 400 profiles of particle size and abundance in the ocean surface layer.

The conditions of our deployments ranged from eutrophic to oligotrophic and from near-coastal to open ocean. Four of the deployments (sp05, nh06, and sp07_1 and sp07_2) were described in Checkley et al. (2008). Three of the deployments (th07_1, th07_2, and th07_4) occurred during the CCE LTER process cruise on the R/V Thompson, which was described in Landry et al. (2009). The final deployment (bl08) occurred at the start of a cruise of the R/V Knorr to study the North Atlantic Bloom.

In this paper we use our results from the SOLOPC to calculate particle abundance as a function of depth and particle size. We also use particle properties to infer particle type (aggregates and zooplankton) and how these relate to other water properties at multiple locations. We use spectra of particle abundance to estimate the fluxes of different size classes throughout the upper water column, assuming a size-dependent sinking rate.

We present a detailed set of results for one deployment, th07_1, in an upwelling region off Point Conception, California (Table 1). This deployment had the highest particle volume that we observed. We then compare observations among all of our deployments. Lastly, we discuss the implications for the particle flux and its control by animals.

2. Methods

2.1. The SOLOPC float

The SOLOPC is an autonomous biological profiler which combines a Sounding Oceanographic Lagrangian Observer (SOLO) float, reporting vertical profiles of temperature, salinity, and depth, with a Laser Optical Plankton Counter (LOPC) and a WET Labs ECO Puck. We used either a fluorescence or a backscatter ECO Puck sensor for each deployment. The LOPC senses individual plankters and other particles over a size range of 0.09–35 mm as they pass through a sheet formed by 70 adjacent 1 mm × 1 mm beams of red (640 nm) light (Herman et al., 2004). The particle-sensing region has a cross-sectional area of 49 cm^2 and thickness of 1 mm. For a 100 m vertical profile, the total volume sampled for particles is 0.49 m^3. The SOLOPC has been described in detail by Checkley et al. (2008).

2.2. Data collection

The LOPC handles small and large particles differently. Small particles (single-element particles, SEPs) are detected by the attenuation of one or two light beams as objects pass through the light field. Each SEP is assigned an equivalent spherical diameter (d_{esd}) and a count is added to the appropriate d_{esd} bin. The number of counts in the size bins is saved every 3 s, equivalent to about a 60 cm depth interval. Larger particles (multiple-element particles, MEPs) intercept more than two light beams; for each beam, maximum light attenuation and duration is recorded. We designate the width of the beams they intercept as the occluded diameter (d_{od}). In our data analysis, we calculated the d_{esd} from the total light attenuation for each MEP (Checkley et al., 2008) and added this count to the appropriate d_{esd} bin to create a size-frequency distribution for all (SEP+MEP) particles observed by the LOPC in each time interval. (Note that symbols are defined in Table 2.)

2.3. Data interpretation

2.3.1. Particle type

MEPs, particles with $d_{od} > 2000$ μm, are composed of at least two types, relatively opaque animals and relatively amorphous and transparent aggregates, distinguished by their ratios of d_{esd} to d_{od}. The relationships used to calculate d_{esd} were determined using opaque spheres and, thus, d_{esd} is closer to the mass-equivalent diameter than is d_{od}. Aggregates tend to have much larger values of d_{od} than d_{esd} because of their amorphous natures (*e.g.*, Jackson et al., 1997). We calculated the number of MEPs for bins of each 1 mm d_{od} increment and 0.1 mm d_{esd} increment. That is, we calculated a two dimensional histogram for size distributions using d_{od} and d_{esd} for each MEP. We determined the mean d_{esd} value ($\hat{d}_{esd}$) for the $\hat{d}_{esd}$ bin having the largest number of particles for each d_{od} bin value. We fit a curve of the form

$$\ln\hat{d}_{esd} = \alpha + \beta \ln d_{od} \tag{1}$$

If all particles were opaque, β would be 1; β decreases with increasing transparency of particles. This is equivalent to fitting

$$\left(\frac{\hat{d}_{esd}}{\hat{d}}\right)^3 = \left(\frac{d_{od}}{\hat{d}}\right)^f \tag{2}$$

where $f = 3\beta$ is the fractal dimension and $\hat{d} = e^{\alpha/(1-f/3)}$ is a scaling constant, which can be interpreted as the diameter of a single source particle, i.e., where $\hat{d}_{esd}$ equals d_{od}. Thus, f is maximal (3) for opaque particles and decreases with increasing transparency of particles.

We used Eq. (1) to calculate $\hat{d}_{esd}$ and classify MEPs as either *z*-particles (zooplankton) or *s*-particles (marine snow). MEPS with $d_{esd} > 2\hat{d}_{esd}$ were classified as *z*-particles; particles with