Deep-Sea Research II 55 (2008) 1684–1695

Contents lists available at ScienceDirect

Deep-Sea Research II

journal homepage: www.elsevier.com/locate/dsr2

# *In situ* measurement of mesopelagic particle sinking rates and the control of carbon transfer to the ocean interior during the Vertical Flux in the Global Ocean (VERTIGO) voyages in the North Pacific

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ARTICLE INFO

*Article history:*
Accepted 16 April 2008
Available online 13 May 2008

*Keywords:*
Mesopelagic
Sinking rate
Settling velocity
Particle flux
Sediment trap
North Pacific

ABSTRACT

Among the parameters affecting carbon transfer to the ocean interior, particle sinking rates vary three orders of magnitude and thus more than primary production, *f*-ratios, or particle carbon contents [e.g., Boyd, P.W., Trull, T.W., 2006. Understanding the export of marine biogenic particles: is there consensus? Progress in Oceanography 4, 276–312, doi:10.1016/j.pocean.2006.10.007]. Very few data have been obtained from the mesopelagic zone where the majority of carbon remineralization occurs and the attenuation of the sinking flux is determined. Here, we report sinking rates from ~300 m depth for the subtropical (station ALOHA, June 2004) and subarctic (station K2, July 2005) North Pacific Ocean, obtained from short (6.5 day) deployments of an indented rotating sphere (IRS) sediment trap operating as an *in situ* settling column [Peterson, M.L., Wakeham, S.G., Lee, C., Askea, M.A., Miquel, J.C., 2005. Novel techniques for collection of sinking particles in the ocean and determining their settling rates. Limnology and Oceanography Methods 3, 520–532] to separate the flux into 11 sinking-rate fractions ranging from >820 to >2 m d$^{-1}$ that are collected by a carousel for further analysis.

Functioning of the IRS trap was tested using a novel programming sequence to check that all particles have cleared the settling column prior to the next delivery of particles by the 6-hourly rotation cycle of the IRS. There was some evidence (from the flux distribution among the cups and photomicroscopy of the collected particles) that very slow-sinking particles may have been under-collected because they were unable to penetrate the brine-filled collection cups, but good evidence for appropriate collection of fast-settling fractions.

Approximately 50% of the particulate organic carbon (POC) flux was sinking at greater than 100 m d$^{-1}$ at both stations. At ALOHA, more than 15% of the POC flux sank at >820 m d$^{-1}$, but low fluxes make this uncertain, and precluded resolution of particles sinking slower than 137 m d$^{-1}$. At K2, less than 1% of the POC flux sank at >820 m d$^{-1}$, but a large fraction (~15–45%) of the flux was contributed by other fast-sinking classes (410 and 205 m d$^{-1}$). PIC and BSi minerals were not present in higher proportions in the faster sinking fractions, but the observations were too limited to rule out a ballasting contribution to the control of sinking rates. Photographic evidence for a wide range of particle types within individual sinking-rate fractions suggests that biological processes that set the porosity and shape of particles are also important and may mask the role of minerals.

Comparing the spectrum of sinking rates observed at K2 with the power-law profile of flux attenuation with depth obtained from other VERTIGO sediment traps deployed at multiple depths [Buesseler, K.O., Lamborg, C.H., Boyd, P.W., Lam, P.J., Trull, T.W., Bidigare, R.R., Bishop, J.K.B., Casciotti, K.L., Dehairs, F., Elskens, M., Honda, M., Karl, D.M., Siegel, D., Silver, M., Steinberg, D., Valdes, J., Van Mooy, B., Wilson, S.E., 2007b. Revisiting carbon flux through the Ocean's twilight zone. Science 316(5824), 567–570, doi: 10.1126/science.1137959] emphasizes the importance of particle transformations within the mesopelagic zone in the control of carbon transport to the ocean interior.



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doi:10.1016/j.dsr2.2008.04.021

## 1. Introduction

Sinking particles structure ocean ecosystems. They cause the oligotrophic conditions that characterize most of the global ocean surface, induce chemical gradients that significantly reduce atmospheric carbon dioxide (Broecker and Takahashi, 1978; Volk and Hoffert, 1985; Sarmiento and Orr, 1991), couple pelagic and benthic ecosystems (Deuser, 1996; Jahnke, 1996), and provide a fast path for anthropogenic pollutants to reach the deep sea (Fowler and Knauer, 1986). As the particles sink they are rapidly remineralized, so that typically less than 10% of the particulate organic carbon leaving the surface reaches the deep sea (deeper than 1000 m) and less than 1% reaches abyssal sediments (Suess, 1980; Martin et al., 1987; Honjo, 1996; Jahnke, 1996; Oschlies and Kahler, 2004).

The attenuation of carbon flux with depth represents a balance between particle properties that aid transit (e.g., fast-sinking rates, protection of organic matter within minerals, aggregation) and those that retard it (e.g., slow-sinking rates, disaggregation, consumption by zooplankton and bacteria). While measurements of sinking rates are very sparse for the open ocean, it is clear that they vary greatly, with observed speeds ranging from less than 1 to more than 1000 m $d^{-1}$ (Fowler and Knauer, 1986; Asper, 1987; Asper et al., 1992; Honjo, 1996; Turner, 2002; Asper and Smith, 2003), and compilations of sinking rates are available (Diercks and Asper, 1997; Turner, 2002; Stemmann et al., 2004b).

Knowledge of the factors that control sinking rates is particularly poor. Studies with *in situ* cameras found rates varying from ($<$10 to several hundred m $d^{-1}$) and indicate a weak positive correlation of sinking rate with particle size (Asper, 1987; Diercks and Asper, 1997; Pilskaln et al., 1998; Asper and Smith, 2003), as does compilation of sinking rates determined from these and other methods (Stemmann et al., 2004b). However, for a given size, observed sinking rates vary by more than order of magnitude (Stemmann et al., 2004b). This variability is in agreement with the perspective that the biological origins and thus forms and porosities of the particles are also important (Alldredge and Gotschalk, 1988; Silver and Gowing, 1991; MacIntyre et al., 1995; Turner, 2002).

Mineral contents influence particle sinking rates and organic carbon transport. Particles collected by sediment traps moored in the deep sea exhibit correlations between organic carbon and mineral contents in both individual studies (Ittekkot et al., 1992; Ittekkot, 1993; Honjo, 1996) and global comparisons (Armstrong et al., 2002; Francois et al., 2002; Klaas and Archer, 2002), although these correlations are weaker or absent in seasonal and interannual variations at time-series sites (Dunne et al., 2005; Boyd and Trull, 2006). Whether these correlations reflect control of carbon export by mineral abundance via enhanced sinking rates (the "ballast" hypothesis), or more general influences of minerals on export such as protection of organic matter against remineralization (sometimes referred to as the "ballast ratio" hypothesis; Armstrong, 2006), or arise incidentally from relationships between ecosystem structure and carbon export is not yet clear (Ittekkot et al., 1992; Ittekkot, 1993; Honjo, 1996; Armstrong et al., 2002; Armstrong, 2006; Francois et al., 2002; Klaas and Archer, 2002). In near-surface waters, where particle organic matter contents are higher, it may be that organic matter production and aggregation controls mineral fluxes (Deuser et al., 1983; Passow et al., 1994; Passow, 2004; Passow and De La Rocha, 2006), and it is possible that organic matter control of mineral fluxes in the upper ocean grades through to mineral control of carbon flux at depth.

In this paper, we present sinking rates and mineral compositions for mesopelagic particle populations at ~300 m depth at two sites in the North Pacific, obtained with a zooplankton-excluding indented rotating sphere (IRS) sediment trap (M.L. Peterson et al., 1993) operated as an *in situ* settling column to collect fractions of sinking particles separated by their sinking rate (M.L. Peterson et al., 2005; T.D. Peterson et al., 2005). We compare our flux estimates to other trap designs used during VERTIGO, and our sinking rates to previous results from the MedFlux program in the northwest Mediterranean from bottom-moored IRS traps at ~300 m depth (Lee and Niiler, 2005; T.D. Peterson et al., 2005; Armstrong, 2006) and particles separated by sinking rate in the laboratory (Goutx et al., 2007). Finally, we offer brief speculations on the implications of varying sinking rates for carbon transport to the ocean interior.

## 2. Methods

### 2.1. VERTIGO trap deployments

We deployed the IRS sediment trap (described in detail below) at ~300 m depth beneath a free-drifting surface float (Fig. 1) for periods of approximately 1 week during the VERTIGO programs in the North Pacific. VERTIGO also examined particle fluxes at mesopelagic depths using cylindrical tube traps (0.127 m internal diameter, 0.7 m length, similar to "traditional" designs used in the HOT and BATS time-series programs (Karl et al., 1996; Michaels and Knap, 1996)). These were deployed in two ways: on rosette frames below the same surface-float mooring design as for the IRS, and on neutrally buoyant autonomous floats (Buesseler et al., 2007b).

Deployments were undertaken in oligotrophic subtropical waters in June 2004 (at station ALOHA—site of the HOT program north of Hawaii at 22.75°N, 158°W), and in mesotrophic waters of the western sub-arctic gyre in July 2005 (at the K2 time-series site operated by the Japan Agency for Marine-Earth Science Technology and collaborators, 47°N, 160°E). Overviews of the oceanographic conditions at these sites are available in companion papers (Buesseler et al., 2007b, 2008), as are particle flux results

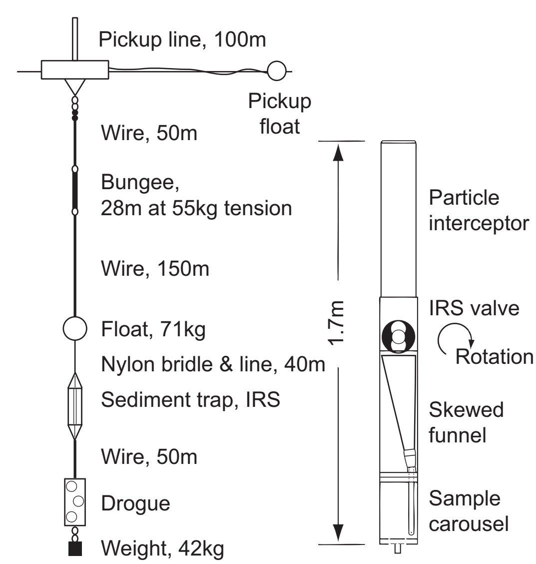


**Fig. 1.** IRS trap and deployment system. Key features of the IRS trap include the baffled particle interceptor tube (PIT) and the indented rotating sphere (IRS) that transfers the particles into the skewed settling funnel, for collection by 11 glass cups at the carousel (M.L. Peterson et al., 2005). The deployment system used an elastic decoupling link between the surface float and the trap to minimize vertical motion, a holey sock drogue to favor Lagrangian drift, and an Argos/GPS beacon for tracking. To minimize contamination, all bridle fittings above and below the trap were stainless steel, all wire was plastic jacketed, and the bridle and bungee were deployed directly from a plastic container to avoid deck contact. Drawing of the IRS trap modified from M.L. Peterson et al. (2005).