High particle export over the continental shelf of the west Antarctic Peninsula

Ken O. Buesseler,[1] Andrew M. P. McDonnell,[1] Oscar M. E. Schofield,[2] Deborah K. Steinberg,[3] and Hugh W. Ducklow[4]

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[1] Drifting cylindrical traps and the flux proxy ^{234}Th indicate more than an order of magnitude higher sinking fluxes of particulate carbon and ^{234}Th in January 2009 than measured by a time-series conical trap used regularly on the shelf of the west Antarctic Peninsula (WAP). The higher fluxes measured in this study have several implications for our understanding of the WAP ecosystem. Larger sinking fluxes result in a revised export efficiency of at least 10% (C flux/net primary production) and a requisite lower regeneration efficiency in surface waters. High fluxes also result in a large supply of sinking organic matter to support subsurface and benthic food webs on the continental shelf. These new findings call into question the magnitude of seasonal and interannual variability in particle flux and reaffirm the difficulty of using moored conical traps as a quantitative flux collector in shallow waters. **Citation:** Buesseler, K. O., A. M. P. McDonnell, O. M. E. Schofield, D. K. Steinberg, and H. W. Ducklow (2010), High particle export over the continental shelf of the west Antarctic Peninsula, *Geophys. Res. Lett.*, *37*, L22606, doi:10.1029/2010GL045448.

1. Introduction

[2] The coastal zone and sea-ice margins of Antarctica exhibit high and variable rates of primary production [*Vernet et al.*, 2008]. This high production is important as the base of a food web for top predators [*Knox*, 2006], for its support of a rich benthos [*Smith et al.*, 2006], and for balancing a microbial demand for labile organic matter [*Ducklow et al.*, 2006]. In order to determine this region's role in the global carbon cycle and the Antarctic marine food web, it is necessary to make accurate measurements of particulate carbon (PC) fluxes. Unfortunately, the study of PC fluxes off Antarctica is complicated by its remote location, harsh conditions, sea ice, export variability in space and time, and by the limited tools we have to study the transfer of organic matter produced in the euphotic zone to the seafloor. Given these substantial impediments, few measurements of sinking PC fluxes have been made in this region and, as a result, the fate of the WAP's high phytoplankton production is poorly understood and quantified.

[3] Our present view of the WAP's biogeochemical function, variability, and ongoing changes is derived in large part from the Palmer Long-Term Ecological Research Project (PAL) which has provided a detailed time-series of observations of the marine ecosystem since 1990 [*Ducklow*, 2008]. As part of this program, sinking PC fluxes have been measured at 170 m depth with the use of a bottom-moored time-series sediment trap. These measurements have revealed the extreme seasonality of the C cycle at this location, with PC fluxes varying four orders of magnitude between the ice-covered winters and the moderately productive summers. The peak of the annual flux is also now occurring about 40 days later in the season than it did at the beginning of the record. Curiously, however, the mean annual flux derived from the PAL trap suggests an extremely low annual export ratio (e-ratio = trap flux/net primary productivity) averaging <4% between 1992–2007 [*Ducklow et al.*, 2008]. These e-ratios are much lower than what would be expected from a high-latitude ecosystem like the WAP, which is dominated by quickly-sinking diatom aggregates and krill fecal pellets [*McDonnell and Buesseler*, 2010]. This low e-ratio severely complicates our understanding and interpretation of the ecosystem function and carbon cycling along the WAP [e.g., *Ducklow et al.*, 2008]. With the rapid warming [*Vaughan et al.*, 2003] and associated changes in ecosystem structure and function [*Montes-Hugo et al.*, 2008] that are already being observed in this sensitive region, it is imperative that we resolve export fluxes.

[4] In this study, we present a new set of upper ocean particle flux measurements collected during a singular intercomparison opportunity conducted in January 2009 along the WAP. We conducted three independent measurements of particle flux using two trap designs as well as the particle flux proxy, thorium-234. Our results suggest that PC fluxes are more than an order of magnitude larger than those determined by the ongoing and multidecadal measurements of flux from a moored time-series sediment trap at this site. While the data are from a single set of observations in the WAP, we discuss how these new estimates have significant implications for our understanding of the magnitude, efficacy and function of the biological pump in this region.

2. Methods

[5] Three independent methods were used to quantify sinking particle fluxes at 64° 30′S latitude, 66° 00′W longitude, 130 km off shore on the continental shelf of the WAP. The first method was a moored conical shaped time-series trap (PARFLUX Mark 78H, 21 sample cup, McLane Research Lab) that has been deployed annually as part of

[1]Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.
[2]Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey, USA.
[3]Virginia Institute of Marine Science, College of William and Mary, Gloucester Point, Virginia, USA.
[4]The Ecosystems Center, Marine Biological Laboratory, Woods Hole, Massachusetts, USA.

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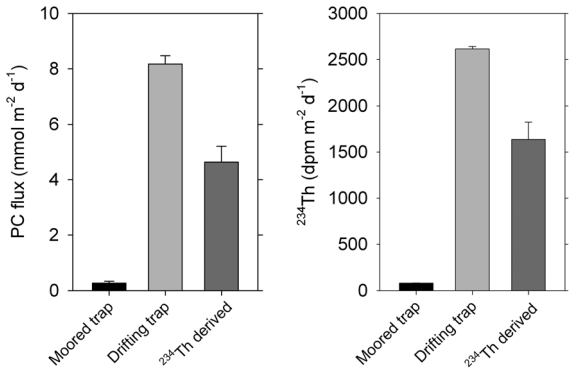

Figure 1. Comparison of average particulate sinking fluxes of (left) PC and (right) ^{234}Th during January 2009 as estimated by a moored time-series trap, a drifting cylindrical trap and as derived from the water column distribution of ^{234}Th. Data in Table 1.

PAL since 1992 [*Ducklow et al.*, 2008]. Sample cups were filled with buffered brine and formalin as a preservative and swimmers were removed under a microscope. The moored trap at 170 m (350 m water depth) was recovered January 10, 2009 after a one year deployment and ^{234}Th was analyzed immediately at sea on 1/8th splits of the 5 most recent sampling cups (programmed for 6–8 day intervals during peak flux periods, December 6, 2008–January 10, 2009). These splits were later analyzed for PC as described below for the drifting traps. A parallel set of sample splits was analyzed for organic carbon after acid fuming to remove carbonate.

[6] The second method was a surface-tethered, drifting cylindrical trap array deployed at the same site for 1.5 days between January 8–10, 2009 following *Lamborg et al.* [2008]. Trap tubes were deployed at 150 m with brine and formalin, and swimmers were removed under a microscope. Sample analyses for ^{234}Th on both traps were performed as described by *Lamborg et al.* [2008]. Carbon analyses at the Woods Hole Oceanographic Institution (WHOI) did not include acid fuming, however these should be equivalent to fumed samples since carbonate was <2% of total PC at 500 m in a nearby trap [*Palanques et al.*, 2002] and expected to be even less in shallow traps. Thus, we use PC to refer to both moored trap POC and drifting trap C fluxes, reported here in units of mmol C m^{-2} d^{-1}.

[7] The third method relied on the particle-reactive and naturally occurring radionuclide, thorium-234 (half-life 24.1 days), which has been widely used as a particle flux proxy [*Waples et al.*, 2006]. In general, lower ^{234}Th activities relative to its conservative parent, ^{238}U, indicate a higher export flux of particles. Total ^{234}Th samples (4 L) were collected with the CTD/Rosette and analyzed via methods described by *Pike et al.* [2005]. Uranium-238 is determined by its constant relationship with salinity [*Rutgers van der Loeff et al.*, 2006]. The flux of ^{234}Th is determined by a simple 1-D steady-state model [*Savoye et al.*, 2006]. In 2009, we measured total ^{234}Th at 10 depths in the upper 250 m in profiles collected within 1 km of the drifting trap site on January 8, 9, and 11, 2009 and report fluxes from those profiles calculated at 150 m in units of dpm m^{-2} d^{-1}.

[8] We also use the ^{234}Th flux approach to determine PC fluxes by multiplying the ^{234}Th flux by the C/^{234}Th ratio on particles [*Buesseler et al.*, 2006]. The C/^{234}Th ratio was determined here on three different sets of samples: the two trap systems and also particles collected via a large volume in-situ pumping system at 150 m on January 9th. That system filtered approximately 1000 liters sequentially through a 53 μm and 10 μm screen (142 mm diameter), which were then processed for ^{234}Th and PC, identical to the drifting trap samples.

3. Results

[9] Particle fluxes measured with the moored trap indicate substantially lower flux than measured by the drifting trap and as calculated from ^{234}Th profiles (Figure 1). On average, the moored trap fluxes are a factor of 30 lower than the drifting trap fluxes for both PC and ^{234}Th (Table 1). The low flux in the moored trap cannot be attributed to an anomalously low flux in the last moored trap cup (January 3–10), as the fluxes were similarly low in all of the 5 cups between December 6–January 10 (Table 1). For the drifting trap, replicate tubes agreed within 13% for fluxes of both PC (8.2 mmol C m^{-2} d^{-1}) and ^{234}Th (2600 dpm m^{-2} d^{-1}).

[10] The estimate of ^{234}Th fluxes derived from the total ^{234}Th profiles (1640 dpm m^{-2} d^{-1}) are in closer agreement with the drifting trap and on average about 20 times greater than the moored trap (Figure 1). The variability in ^{234}Th flux predicted from each of the three different profiles is small (±23%). PC fluxes can be calculated from the ^{234}Th flux derived from the water column data and an estimate of the C/^{234}Th ratio of sinking particles. We measured a similar C/^{234}Th ratio in the moored trap (4.2 ± 0.4 μmol dpm^{-1}), drifting trap (3.1 ± 0.2) and the particulate material collected via in situ pumps screens as the >53 μm (3.6 ± 0.1) or 10–53 μm size fractions (3.2 ± 0.1). No matter which ratio is used, the PC flux thus calculated is 18 to 25 times greater than found in the moored trap, indicating a similar PC collection bias as found for the two trap comparison.

4. Discussion

[11] Two decades ago *Karl et al.* [1991] stated: "Very little is known about the immediate fate of the Antarctic phytoplankton production". Despite some progress, our understanding of upper ocean export in the Antarctic remains limited not only because of the remote location and harsh sampling conditions, but also as we show here, due to important methodological issues. Time-series moored conical sediment traps are ideal for capturing the seasonal pattern of sedimentation in the deep sea and allow unattended sampling during ice-covered periods. However, biases in applying these traps as quantitative collectors in the upper ocean need to be considered [*Gardner*, 2000; *Buesseler et al.*, 2007]. This applies not just to the WAP, but also to other polar coastal waters and shelves, and in general to other upper-ocean settings.

[12] The (20–30×) higher PC and ^{234}Th flux in the surface-tethered drifting trap relative to the moored trap is supported by three water column profiles of ^{234}Th at the same site. These measurements result in computed ^{234}Th fluxes that are also more than an order of magnitude higher than in the moored trap. While the comparison between

Table 1. Summary of PC, ^{234}Th Fluxes and Export Ratios

Collection Dates	^{234}Th Flux (dpm m^{-2} d^{-1} ± error)	PC Flux (mmol C m^{-2} d^{-1} ± error)	Export Ratios[a]
	Moored Trap		
Jan. 3–10[b]	79 ± 1	0.33 ± 0.03	
Jan. 3–10[c]		0.20 ± 0.01	
average	79 ± 1	0.26 ± 0.06	0.3%
Dec. 6–Jan. 10[d]	59 ± 36	0.27 ± 0.11	
Dec. 6–Jan. 10[e]		0.19 ± 0.11	
	Drifting Trap		
Jan. 8–10[f]	2591 ± 38	7.7 ± 0.4	
Jan. 8–10[f]	2638 ± 37	8.7 ± 0.4	
average	2614 ± 27	8.2 ± 0.3	10%
	^{234}Th Derived		
Jan. 8[g]	1822 ± 185	5.3 ± 1.0	
Jan. 9[g]	1446 ± 196	4.2 ± 0.8	
Jan. 11[g]	1640 ± 239	4.4 ± 0.8	
average	1636 ± 188	4.6 ± 0.6	6%

[a]Export ratio = PC flux/primary productivity. Productivities averaged 82 mmol C m^{-2} d^{-1} on Jan. 9, 10, 12 using ^{14}C methods and 24 hour deck board incubations.
[b]1/8th split; WHOI CHN facility; ^{234}Th error from counting statistics, PC error from CHN analysis.
[c]7/8th split; MBL CHN facility; PC error from CHN analysis.
[d]Average and std. dev. for 5 sample cups- WHOI splits.
[e]Average and std. dev. for 5 sample cups- MBL splits.
[f]^{234}Th and PC flux and error are from two collection tubes from a single 150 m drifting trap.
[g]Flux of ^{234}Th and propagated error and PC flux derived from a single water column ^{234}Th profile on date indicated.

sediment trap ^{234}Th fluxes and fluxes estimated from a model of water column ^{234}Th data has its limitations [*Buesseler et al.*, 2009; *Cochran et al.*, 2009; *Savoye et al.*, 2006], a difference this large is hard to interpret other than as a large under-collection bias by the moored trap.

[13] Unfortunately, there are no other trap data for direct comparison from this site during its 17-year operation, but we can compare to a site 25 km away, where ^{234}Th fluxes at the seafloor derived from sediment inventories during different seasons and years were 400 to 2600 dpm m^{-2} d^{-1} [*McClintic et al.*, 2008]. Fluxes of <100 dpm m^{-2} d^{-1} as seen in all 5 cups of our moored trap do not match this sedimentary data. Although several hundreds of kilometers to the northeast and in more protected and coastal waters, two previous studies also deployed drifting cylindrical traps in the Gerlach and Bransfield Straits, and thus permit a generalized comparison to the fluxes we measured at the PAL trap site. The first study in 1986 found fluxes of 4 to >30 mmol C m^{-2} d^{-1} at 100 m in December through March [*Karl et al.*, 1991]. Another group in 1995 measured 10–60 mmol C m^{-2} d^{-1} at 60 m in December though January [*Anadón et al.*, 2002]. These fluxes are also more than an order of magnitude higher than the PAL moored trap, and even several-fold higher than our drifting traps that are further offshore.

[14] We know from other studies that there are multiple reasons why conical traps may undercollect sediment fluxes [*Buesseler et al.*, 2007]. First among the possible causes is trap hydrodynamics, whereby horizontal flow over the trap mouth makes these traps susceptible to collection biases due to resuspension of material before it reaches the trap cup. This is a greater concern in conical than cylindrical sediment traps [*Gardner*, 2000] and in the upper ocean in general where currents are faster. These hydrodynamic effects are difficult to separate from other possible collection biases, such as solubilization or loss of particulate material after collection, which is greater in longer deployments and at shallower depths [*Antia*, 2005]. Another factor that may contribute to lower fluxes is consumption of detrital particles by zooplankton feeding along the walls of a conical trap.

[15] The significance of the higher fluxes to the WAP ecosystem is profound for many reasons. First, one measure of the strength of the biological pump is the export efficiency, or ratio of flux to primary production. Our export ratio in January at 150 m is 10% for the drifting trap (Table 1). In contrast, the moored trap would indicate an e-ratio in January 2009 of 0.3% which seems unreasonably low for a site dominated by a short food chain with large diatoms and krill. Using a one-month lag between peak productivity and export, *Ducklow et al.* [2008] calculated e-ratios for the moored trap ranging from 0.3% to 2.6% between 1992–2007 (with one exception of 28% in 2002/2003 when primary production was extremely low). Such a low export ratio is equivalent or lower than seen in oligotrophic settings such as the Bermuda Atlantic Time-series Study site [*Steinberg et al.*, 2001].

[16] We believe that the higher e-ratios as seen in the drifting trap and as derived from ^{234}Th during January 2009 are more likely to be characteristic of this WAP region. In fact, our e-ratios may be an underestimate of the seasonal average because they are a snapshot of conditions prior to expected peak flux periods. *Anadón et al.* [2002] estimate a regional PC e-ratio of 26% at 60 m but that was only for the short Dec./Jan. growth season. E-ratios derived from ^{234}Th profiles for the Ross Sea were 25–70% during the summer of 1996/1997 [*Cochran et al.*, 2000] and are higher at high latitude sites in general [*Buesseler*, 1998]. While our new estimate of an e-ratio of 10% is substantially larger than suggested by the moored sediment trap, it still implies that

there is substantial recycling component to the foodweb of the upper ocean at WAP, an idea that is consistent with inverse model results of *Ducklow et al.* [2006].

[17] Higher fluxes measured at depth in the WAP also imply less PC attenuation and recycling in surface waters, and more energy to support subsurface and benthic food webs. Although the moored trap sampled flux at only one depth, the low fluxes imply significant recycling of PC as it settles to the sea floor. There is some support for the idea that sites of high seasonality in flux have low export/high attenuation [*Lutz et al.*, 2007]. However, with our new data, we must question that assumption at the PAL site and possibly for our broader understanding of the Southern Ocean, since many of the traps used in the Southern Ocean are moored conical traps in waters <1000 m (for example, 16 of 24 used by Lutz et al.). Looking in more detail at one example, in the Ross Sea, the flux of PC at 200 m estimated by a seasonal C budget exceeded the PC flux measured by a moored conical sediment trap by a factor of 6.6 [*Sweeney et al.*, 2000]. Additionally, seasonal ^{234}Th data, indicated more than 10 times lower fluxes in the moored trap during peak summer flux periods [*Cochran et al.*, 2000]. This was also supported by annual budgets of the longer-lived ^{230}Th and ^{231}Pa isotopes which indicated at least a factor of 3–6 higher export than the moored trap, and possibly by as much as an order of magnitude [*Fleisher and Anderson*, 2003]. Thus, low export efficiency assigned to these high latitude sites using shallow moored conical trap data would be in error.

[18] A final implication of higher particle fluxes in the WAP is that it calls into question the variability in flux, and the fundamental causes thereof, as measured by the moored time-series trap. This is important, as Antarctic PC fluxes in general are thought to be characterized by extreme seasonality and large interannual variability in particle flux [e.g., *Wefer et al.*, 1988]. In the moored PAL trap, on average 85% of the flux is caught in the one-month period between late December and January, and total annual fluxes range from 13 to 413 mmol C m^{-2} a^{-1} between 1993 and 2006 [*Ducklow et al.*, 2008]. Our data suggests that these summer fluxes could be even higher, though we can't necessarily extrapolate to winter conditions. That the moored trap shows seasonality is not surprising, as ultimately if total particle stocks in the water column are low, such as under ice conditions, then material caught in the trap will be low, and vice-versa during bloom conditions. The similarity in C/^{234}Th ratios mentioned above and C/N (data not shown) between the drifting and moored traps, as well as microscopic analysis of trap material (a dominance of krill fecal pellets in both traps) give some confidence that the quality of the material in the moored trap is not dramatically different, i.e., sorting is not apparent. However, we should be cautious about the certainty in the magnitude of the highest peak and lowest flux conditions as well as interannual variability in fluxes, until we understand more about the root causes of these potential biases.

5. Conclusion

[19] In this study, for the first time, two additional upper ocean particle flux methods, namely drifting cylindrical traps and the flux proxy ^{234}Th, were used to show more than an order of magnitude higher fluxes for both PC and ^{234}Th at 150 m compared to a moored time-series trap at the same WAP site. The implications of a stronger and more efficient biological pump are important, including a higher organic matter source to subsurface and benthic ecosystems. This is consistent with a short food chain and high C fluxes associated with blooms of large diatoms and fecal pellet production by krill characteristic of the WAP and many polar blooms. We expect that the highly periodic seasonal pattern in flux seen in the existing time-series trap data will hold, with extremely low fluxes under ice-covered conditions, though the magnitude of these fluxes and the interannual variability are difficult to quantify.

[20] To answer the question from *Karl et al.* [1991] regarding the fate of Antarctic phytoplankton production, we still need much better quantitative estimates of year-round export fluxes combined with new ecological and biogeochemical process studies, to determine the mechanisms that control the biological pump within the euphotic zone and especially the waters immediately below where the variability in flux attenuation between sites is greatest [*Buesseler and Boyd*, 2009]. Fortunately, alternatives to moored conical traps do exist for use in the mesopelagic and upper ocean, including moored time-series cylindrical designs that should be less susceptible to hydrodynamic biases [*Cochran et al.*, 2009; *Peterson et al.*, 1993]. Also, as shown here, short deployments of drifting traps, or better yet, use of untethered, neutrally buoyant sediment traps [*Buesseler et al.*, 2007; *Lamborg et al.*, 2008] can reduce even further collection biases due to flow around traps.

[21] Ultimately, the use of multiple methods (different traps designs, in-situ tracers, particle cameras and biogeochemical flux models) will be needed to both confirm the sedimentary fluxes and resolve the mechanisms that control flux in the WAP and other sites. Only with a mechanistic understanding of particle export will we be able to predict the consequences of global warming, changing ice dynamics, and plankton community shifts on the strength of the biological pump, and hence the impact of climate change on C sequestration, nutrient recycling, and food supply to top predators and benthic communities along these productive margins of the Antarctic.

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K. O. Buesseler and M. P. McDonnell, Woods Hole Oceanographic Institution, Mail Stop 25, Woods Hole, MA 02543, USA. (kbuesseler@whoi.edu)

H. W. Ducklow, The Ecosystems Center, Marine Biological Laboratory, Woods Hole, MA 02543, USA.

O. M. E. Schofield, Institute of Marine and Coastal Sciences, Rutgers University, 71 Dudley Rd., New Brunswick, NJ 08901, USA.

D. K. Steinberg, Virginia Institute of Marine Science, College of William and Mary, PO Box 1346, Gloucester Pt., VA 23062, USA.