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Carbon export associated with free-drifting icebergs in the Southern Ocean

K.L. Smith Jr.[1,*], A.D. Sherman[1], T.J. Shaw[2], A.E. Murray[3], M. Vernet[4], A.O. Cefarelli[5]

[1] Monterey Bay Aquarium Research Institute, 7700 Sandholdt Rd, Moss Landing, CA 95039, USA
[2] Department of Chemistry and Biochemistry, University of South Carolina, Columbia, SC 29208, USA
[3] Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA
[4] Scripps Institution of Oceanography, 8615 Discovery Way, La Jolla, CA 92037, USA
[5] Departamento Científico Ficología, Facultad de Ciencias Naturales y Museo, Universidad Nacional de La Plata, Paseo del Bosque s/n, 1900 La Plata, Argentina

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ABSTRACT

Enrichment of the pelagic ecosystem associated with the proliferation of free-drifting icebergs prompts questions about increased productivity and the export flux of organic carbon to the deep ocean with continued climate warming. Lagrangian Sediment Traps (LST) were deployed autonomously beneath a large tabular, free-drifting iceberg (C-18a) in the NW Weddell Sea during March and April 2009 to collect sinking particles at a depth of 600 m. Three LST deployments associated with C-18a, within a 30-km radius, collected sinking diatom frustules, dominated by *Corethron pennatum* and *Fragilariopsis nana*, euphausiid fragments, crustacean and fish fecal material, detrital aggregates and mineral grains. One LST deployment at a "control" site 74 km away in open water devoid of icebergs collected diatom frustules, euphausiid molts, crustacean fecal material and detrital aggregates. Phytoplankton abundance, microbial abundance and biomass were significantly higher in the LST samples than in open-water collections at 500 m depth. The mean mass flux and organic carbon flux associated with iceberg C-18a were twice as high, 124 mg m^{-2} d^{-1} and 5.6 mg C_{org} m^{-2} d^{-1}, respectively, than at the control site. A similar trend was observed in $C_{org}/^{234}Th$ activity, being highest near C-18a and lowest at the control site. Extrapolation of the area of enrichment to 30 km radius around C-18a, 2826 km^2, produces an estimated mass flux of 350 tons d^{-1} and carbon flux of 15.8 tons C_{org} d^{-1}. Five similar sized icebergs to C-18a were identified in satellite images in a surrounding 47,636 km^2 area at the same time of sampling. Assuming a 30-km radius as the area of influence around each of these five icebergs, 46% of the total area would be enhanced with an export flux at 600 m of 122.4 tons C_{org} d^{-1}. The large numbers of smaller icebergs identified visually in this area would only increase this area of influence. Icebergs serve as areas of local enrichment and with increased proliferation, must be considered in the cycling of carbon in the Southern Ocean.

1. Introduction

How important is the Southern Ocean in the global carbon cycle with increasing CO_2 levels and global warming? The importance of the draw-down of atmospheric carbon in the Southern Ocean and its ultimate sequestration are topics of considerable debate (Hoppema, 2004; Le Quere et al., 2007). The high-nutrient/low-chlorophyll (HNLC) waters of the Southern Ocean when artificially fertilized with iron, yield increased rates of primary production, thus increasing the amount of CO_2 drawn down into phytoplankton biomass. However, there are conflicting reports as to how much of this carbon is ultimately exported from the surface waters and reaches the deep sea. Artificial, mesoscale iron-enrichment experiments have enhanced diatom biomass (Boyd et al., 2000; Coale et al., 2004) and thus increased the drawdown of CO_2. However, over the short time periods of these experiments, the export of fixed carbon and its deep-sea sequestration are equivocal (Boyd, 2004; Buesseler et al., 2004; Lam and Bishop, 2007). Natural iron fertilization experiments, where upwelled iron provides the enrichment source, have provided good evidence that the increased phytoplankton biomass production is exported to deeper depths in the Southern Ocean at significantly higher rates than adjacent areas not fertilized by iron (Pollard et al., 2009; Blain et al., 2007). It is argued that under natural conditions, there is ample time for food chain transfer of this carbon through zooplankton grazing and fecal material export into the deep ocean (e.g., Ebersbach and Trull, 2008).

Other sources of iron include aerosols and glacially derived icebergs. Aerosol iron can enhance primary production in the Southern Ocean, especially in areas downwind of dry continental areas (Cassar et al., 2007). However, given the slow dissolution of iron in seawater, such dust mediated enhancement of primary

* Corresponding author. Tel.: +1 831 775 1710.
E-mail address: ksmith@mbari.org (K.L. Smith Jr.).

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production is considered rare (Boyd et al., 2009). Recent evidence suggests that free-drifting icebergs in the Southern Ocean contain significant concentrations of terrigenous material and are areas of enriched phytoplankton and zooplankton production (Smith et al., 2007). This terrigenous material, of glacial and aeolian origin, contributes significant concentrations of iron into the surrounding water (Lin et al., 2011), thus forming a natural enrichment experiment with a pelagic foodweb capable of processing photosynthetically derived organic carbon. Gen the increased number of icebergs in the Southern Ocean (Ballantyne, 2002), we hypothesized that there should be substantial carbon export and sequestration associated with these enrichment sites compared to open water some distance away.

2. Methods

To measure the flux of carbon associated with an iceberg, we developed an autonomous instrument that would collect sinking particulate matter while floating below the iceberg at a predetermined depth (Sherman et al., 2011). The Lagrangian Sediment Trap (LST) was designed around an existing neutrally buoyant SOLO float (Sounding Oceanographic Lagrangian Observer; Davis et al., 2001) and then adding four sampling funnels and opening-closing cups to collect sinking particles at a pre-determined depth of ~600 m. Each collection funnel had a mouth opening of 0.08 m^2 for a total collection surface area of 0.32 m^2. The LST was deployed autonomously from the RVIB Nathaniel B. Palmer in March and April 2009 to sample at a depth of 600 m under and in the vicinity of a large tabular iceberg, C-18a, in the northwestern Weddell Sea.

Prior to each deployment, each LST sample cup (125 ml) was filled with filtered surface seawater. No preservative was added to the LST sample cups since the deployment periods were less than four days (2.5 to 3.8 d) with assumed slow degradation at < 0.5 °C. The descent of the LST with a disposable weight of 7 kg was sufficient to attain a sinking speed of 8 m s^{-1}, reaching 600 m in ~62 s. Upon release of the descent weight at ~600 m depth, the sample cups sprung open for collection of particles. At the end of the collection period, the sample cups were then closed with a burn-wire release just before the LST ascended to the surface after releasing the ballast weight. The closure mechanism failed to rotate completely on three deployments (Stas. 95,96,142) and thus the cups were partially open at the base of the collection funnels contributing possible contaminants or winnowing the collected material during the ~96-minute ascents to the surface from 600 m. Once the LST was visually located on the surface, a small boat was deployed and the sample cups removed while the instrument was still vertically oriented in the water to prevent possible loss of samples. The period from surfacing to sample recovery was < 30 minutes. The capped sample cups and LST were returned to the ship and the samples kept on ice until further processing.

One sample cup from each deployment was subsampled for microscopy and bacterioplankton analyses of the freshly collected material. A low magnification stereomicroscope (6.5X to 50X) was used to examine and photograph the larger particulate matter in etched-glass grid petri dishes. The particulate matter in a small 5-ml subsample was examined and photographed with finer resolution using a high-magnification compound microscope. Samples in water mounts were analyzed at either 100, 200 or 400X in bright or phase contrast with a Zeiss Axioscop 50. Photographs were taken with a digital camera SPOT RT slider. Small subsamples were preserved in formalin for further microscopic analysis ashore. Mineral phases in these samples were determined by microscopic examination but sample size limitations precluded separate digestions for mineral content. In addition, a 50-ml subsample was taken for bacterioplankton analyses. The remaining three samples were filtered onto quartz membrane filters, conspicuous swimmers removed, and frozen at −80 °C. In the laboratory the filters were dried at 60 °C for 24 hours and then weighed to determine total mass. Half of each filter was then analyzed for total carbon and nitrogen using a Control Equipment Corporation Elemental Analyzer (Model 240XA). The other half of each filter was moistened with 10% v/v HCL, held in a closed container for 24 hours and then placed in a 60 °C drying oven for an additional 24 hours. The loss of mass measured after HCl treatment was considered inorganic carbon. The dried samples were then analyzed for carbon, and nitrogen using the elemental analyzer above with the resulting carbon concentrations assumed to be organic.

Samples from a single LST cup from each deployment were mixed then subsampled for cell counts and leucine incorporation rate determination. The leucine incorporation method (Kirchman et al., 1986) was adapted to the microcentrifugation method (Smith and Azam, 1992). Triplicate 1.5 ml subsamples and a single TCA-killed control sample were prepared for each LST sample, 20 nM final concentration 3 H-leucine was added, and the samples incubated at 0 °C in water baths for 2-3 hours. Following incubations, the samples were stopped by addition of TCA (5% final concentration), and following centrifugation and washes with 5% TCA, the pellets were dried with 80% ethanol. Due to the low volumes available from the LST sample, 1–1.5 ml were prepared for microscopy. Samples were vortexed, and enumeration of DAPI-stained bacterial cells following fixation in formalin using standard methods (Porter and Feig, 1980).

One sample cup from each LST deployment was filtered on a Quartz Membrane Filter (QMF) and dried for determination of the organic carbon to ^{234}Th activity ratio as a proxy for organic carbon export (see Shaw et al., 2011a). The ^{234}Th activity was measured on a shipboard Riso Beta counter with backgrounds determined later in the laboratory. CHN analyses were conducted as described above after background counts were complete.

3. Results

Four deployments of the LSTs were achieved, sampling beneath and around iceberg C-18a and then at a "control" station ~74 km distance. These deployments were conducted in the NW Weddell Sea from 18 March through 7 April 2009 while C-18a was free-drifting between 61° and 62° S and between 49° and 52° W (Fig. 1). The overall water depth during the four deployments ranged from 2918 to 3277 m over the Powell Basin.

Iceberg C-18a was formed in the Ross Sea during a calving event in 2003. This tabular iceberg then drifted counterclockwise around the Antarctic continent before reaching the NW Weddell Sea and being entrained in a northerly flow dubbed "Iceberg Alley" (Smith, 2011; Stuart and Long, 2011). The estimated dimensions of C-18a were 35 km long and 6 km wide with an aerial height of 28 m at the time of sampling (Helly et al., 2011). Although the iceberg draft was not accurately measured, it was estimated from ROV dives to extend ~200 m below the surface (Sherlock et al., 2011) which is consistent with other Antarctic iceberg studies (Dowdeswell and Bamber, 2007). Iceberg C-18a rotated as much as 60° while maintaining a general north-south orientation in a northeasterly direction at 0.2 to 0.4 km hr^{-1} (Helly et al., 2011).

3.1. Description of particulate matter:

On the first deployment (Sta. 43), the LST was launched in front of C-18a, as it drifted over the instrument which was