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

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ARTICLE INFO

Article history:
Received 12 November 2010
Accepted 12 November 2010

Keywords:
Carbon export
Icebergs
Lagrangian sediment traps
Particulate organic carbon flux
Pelagic community
Weddell Sea

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\(_{org}\)/234Th 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.

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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 iron (Pollard et al., 2009; Blain et al., 2007)
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., this issue), 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 pre-determined depth (Sherman et al., this issue). 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 m² for a total collection surface area of 0.32 m². 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 sprang 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) 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 sprang open for collection of particles. 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 while floating below the iceberg at a pre-determined depth of ~600 m. Each collection funnel had a mouth opening of 0.08 m² for a total collection surface area of 0.32 m². 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.

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neutrally buoyant at ~600 m depth. The LST was then recovered 2.9 days later at a distance of 7.8 km north of the deployment site (Fig. 2A). The particulate material in the four collection cups consisted of eight taxa of diatoms (Table 1), which appeared dominated by *Corethron pennatum*, with frustules containing cellular material in varying stages of degradation (Fig. 3A). However, under more stable microscope conditions ashore, *Fragilariopsis nana*, a small diatom 2.4–15.5 μm in length was the most numerically abundant species. The diatom taxa, combined with silicoflagellates and radiolarians formed detrital aggregates (Fig. 3B). Fragments of euphausiids (Fig. 3C) and their cylindrical string fecal pellets (Fig. 3D) were abundant as well as fecal material from small crustaceans and fish (Table 1).

During each LST deployment, a series of transmissometer casts were taken in the vicinity to estimate particle density from light transmission as part of routine CTD casts (Smith, this issue). Fourteen transmission profiles during the first deployment showed percent transmissivity between 93.5 and 95.5 in the surface waters, rapidly increasing to ~98% below 100 m depth (Fig. 4). At 600 m depth the percent light transmission was consistently above 98%, indicating low suspended particle density in water with a salinity of 34.66 psu and temperature of 0.46 °C.

The second deployment (Sta. 95) of the LST was again set so that iceberg C-18a drifted over the instrument. The 3.8-day collection period of sinking particulate matter on this deployment resulted in the LST drifting 32.4 km southeast before recovery (Fig. 2B). Over this collection period at ~600 m depth, diatoms were prevalent and again numerically dominated by *F. nana* and *C. pennatum* of the six taxa present (Table 1). There was considerable diversity in zooplankton and micronekton fecal material with euphausiid string and ovoid pellets (Fig. 3F) being most numerous. Salp fecal material (Fig. 3G, H) was evident as well as the more amorphous fecal fluff. A euphausiid molt (Fig. 3E) and exoskeleton fragments (Fig. 3G) were conspicuous components.

The third deployment (Sta. 96) of the LST drifted under C-18a and continued for a total distance of 40.6 km at 600 m depth over the course of 3.5 days (Fig. 2C). The collected particulate matter was similar in composition to that in the previous deployments (Table 1). There was a greater diversity of diatom taxa totaling 11, dominated by *F. nana* and *C. pennatum*, but with many broken frustules amongst the phytodetrital aggregations (Fig. 3I). Fecal material was dominated by euphausiid string pellets (Fig. 3K, L) and ovoid crustacean pellets (Fig. 3J). Radiolarians were also numerous, serving as nuclei for agglutinating phytodetritus and...
amorphous fecal material (Fig. 3L). Transmissivity profiles from 10 transmissometer casts concurrent with Sta. 95 and Sta. 96 revealed high variability in light transmission in the upper 200 m while reaching 98% light transmission below 200 m depth (Fig. 4). Salinity at 600 m depth ranged from 34.53 to 34.75 psu while temperature was highly variable between 0.36°C to 0.41°C.

The fourth deployment (Sta. 142) of the LST was established as a control, positioned 74 km southeast of C-18a and not in the near vicinity of other icebergs at the time of deployment (Fig. 2D). This LST drifted 15.7 km over the course of the 3.7-day deployment. Particulate matter collected during this deployment had the most diverse assemblage of diatoms of the four deployments, consisting of 12 species which were still dominated by F. nana and C. pennatum (Table 1). Many of the C. pennatum frustules were empty (Fig. 3M, N). Euphausiid molts were present in the samples (Fig. 3M) along with aggregated masses of phytodetritus. Fecal material consisted of a dense ovoid fecal pellet containing phytodetritus (Fig. 3O) and large numbers of string euphausiid fecal pellets (Fig. 3P). Five transmissometer profiles taken during the fourth LST deployment exhibited a sharp precipitous drop in particle density below 50 m, reaching light transmission >98% from 100 m to >600 m depth, noticeably higher than for the previous stations (Fig. 4). Salinity, 34.69 psu, and temperature, 0.47°C, at 600 m depth were more uniform than those measured in closer proximity to C-18a.

Strong trends in size and abundance of clearly identifiable mineral grains were found between the four LST deployments. The largest and most abundant mineral grains were observed at the first station (43), with the largest grain exceeding 50 μm in two dimensions. The large grains were course and broken, showing no sign of rounding. The average grain sizes (as the product of two dimensions) at Sta. 43 were twice those observed in the following three LST deployments (Stas. 95, 96, 142). The lowest number of mineral grains were observed in the control sample from Sta 142, suggesting decreasing abundance with distance from the iceberg. Overall, the size and abundance of mineral grains are consistent with the concept that the iceberg is providing a local source of terrestrial material to the surrounding waters.

3.2. Estimates of microbial abundance and activity

Microbial abundance and activity were significantly higher in the LST samples than concurrently measured at a depth of 500 m in the same area (Table 2). The variance in values between the four LST station samples was high, but they provide a range from which to estimate the relative remineralization potential associated with sinking particulate matter in the NW Weddell Sea. Bacterioplankton cell abundance was 5 to 12 times higher in the LST samples than in seawater samples collected by a CTD/rosette at 500 m. In comparison, leucine incorporation rates were one to three orders of magnitude higher in the LST samples than in the surrounding water (Table 2). Biomass production rates were between 8 and 475 times the rates determined in 500 m water samples with generation times as short as 0.42 days at LST Sta. 95.

Algal cell abundance was two to three orders of magnitude higher in the LST samples than in the seawater samples collected at 500 m depth (Table 2). Cell abundance in the LST samples was...
Table 1
Identification of the particulate matter collected in the four deployments of the LSTs around iceberg C-18a. Presence of each taxon or category in each of the four LST deployments marked with an X.

<table>
<thead>
<tr>
<th>Particulate Matter</th>
<th>Sta. 43</th>
<th>Sta. 95</th>
<th>Sta. 96</th>
<th>Sta. 142</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diatoms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actinocyclus achinoculus</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Chaetoceros chiropilus</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Chaetoceros dichaeta</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Chaetoceros sp.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corethron penumatum</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Coscinodiscus sp.</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Fragilaripis curta</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fragilaripis nana</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Fragilaripis obliquecostata</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Fragilaripis pseudonana</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Fragilaripis rhombica</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fragilaripis ritscheri</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td>Haslea sp.</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leptocylindrus mediterraneus</td>
<td>x</td>
<td></td>
<td></td>
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<tr>
<td>Porosira sp.</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Probosic inermis</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pseudonitzchia sp.</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Thalassiosira gracilis</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Small centric diatoms</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(unidentified)</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicoflagellate</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dictyocea sp.</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Phydodetrus</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Radiolarian</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Euphausiidae exuviae (fragments, molts)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Fecal material</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euphausiidae string pellets (cylindrical)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Minipellets (spherical, &lt; 50 μm)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Small crustacean pellets (cylindrical, ovoid)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Salp fecal material (tabular)</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larvacean fecal material (ellipsoid)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Fish feces (orange)</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Fecal fluff (amorphous)</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Mineral grains</td>
<td>x</td>
<td>x</td>
<td></td>
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</tr>
</tbody>
</table>

highest at the control station (Sta. 142), 2.45 × 10⁵ cells ml⁻¹, and lowest at the iceberg station (Sta. 95), 1.12 × 10⁴ cells ml⁻¹. Sinking phytoplankton particle size followed the same distribution pattern of suspended cells in the surface waters (Vernet et al., this issue), with higher sedimentation of small particles (≤ 3 μm) and lower numbers of larger cells (> 20 μm). The exception was control station (Sta. 142) where intermediate size phytoplankton cells (3-10 μm) were most abundant (Table 2).

3.3. Flux of particulate matter:

The three stations associated with iceberg C-18a had the highest particulate fluxes, however, they exhibited the most variability in the nine subsample collections compared to the three subsamples from the control deployment (Fig. 5). We treated each flux measurement as a subsample for each of the three deployments, calculating a mean value. A collective mean flux and standard error were then determined for the particulate flux measurements from collections within 30 km of C-18a (Fig. 5). The mean mass flux (124.0 ± 55.8 mg m⁻² d⁻¹) and organic carbon flux (5.6 ± 3.1 mg m⁻² d⁻¹) were 2.7 and 2.2 times higher, respectively, than the mean subsample mass flux (45.8 mg m⁻² d⁻¹) and organic carbon flux (2.5 mg m⁻² d⁻¹) at the control site (Fig. 5A, C). However, due to the high variability, there was no significant difference (p > 0.05) between the iceberg-associated mass and organic carbon fluxes and those for the control site. Similarly, the total nitrogen flux associated with C-18a (0.87 ± 0.38 mg m⁻² d⁻¹) was 2.3 times higher than the nitrogen flux (0.37 mg m⁻² d⁻¹) at the control site. The difference between the iceberg associated and control stations were less apparent for total carbon, 3.9 ± 1.3 mg m⁻² d⁻¹ and 2.2 mg m⁻² d⁻¹, respectively (Fig. 5B).

The organic C/C²⁳⁴Th activity ranged from a low of 1.6 μmoles Corg per DPM of C²³⁴Th at Sta. 142 to a high of 4.2 μmoles Corg per DPM of C²³⁴Th at Sta. 96. The trend in organic Corg/C²³⁴Th activity followed that of organic carbon export which is consistent with higher or more efficient organic carbon export associated with larger biogenic particles (see Shaw et al., this issue a; Buesseler et al., 2006).

4. Discussion

A compelling argument can be made that the mean mass and organic carbon fluxes within a radius of 30 km around iceberg C-18a (Stas. 43, 95, 96) are higher than the fluxes measured at the control site 74 km away (Sta. 142), albeit with considerable variability (Fig. 5A, C). Does the influence of C-18a extend such an extensive distance or do the collections, made over three to four days, reflect a proportionately larger sampling in closer proximity to the iceberg with lower contributions at greater distances? Previous studies have shown that free-drifting icebergs have a surrounding enrichment of chlorophyll, krill and seabirds out to a radial distance of ~3.7 km (Smith et al., 2007). It is reasonable to assume that this pelagic community enrichment contributes to particulate export fluxes that can radiate out tens of kilometers at a depth of 600 m. Neutrally buoyant sediment traps, similar to the LST, have an estimated collection range of tens of kilometers at comparable depths (Siegel et al., 2008). The surface meltwater from C-18a is detectable up to 19 km away from the iceberg and can persist for at least 10 days (Helly et al., this issue).

Assuming a collection radius of 30 km around iceberg C-18a, the influenced area would be 2826 km² with an estimated mass flux of 350.4 tons d⁻¹ and an organic carbon export of 15.8 tons d⁻¹.
(Fig. 6A). Decreasing the area of influence to 1256 km² (20 km radius) and 314 km² (10 km radius), the particulate organic carbon export estimates are 7.0 tons d⁻¹ and 1.7 tons d⁻¹, respectively. Since the icebergs and the LSTs are drifting targets, representing the collection area as a circle seems reasonable and the distances from C-18a compatible with those in Fig. 5. Extrapolation of the mass and organic carbon export fluxes around C-18a to a broader regional perspective is possible with

Fig. 3. Photomicrographs of particulate matter collected in the sample cups of the Lagrangian sediment traps deployed at four stations (Stas. 43, 95, 96, 142) around iceberg C-18a. A) Sta. 43; Corethron pennatum. B) Phytodetrinitus with diatom frustules of Corethron pennatum, Actinocyclus achtinochilus, Chaetoceros sp, and the silicoflagellate Dictyocha speculum. C) Fragment of a euphausiid (Euphausia sp.). D) Fecal material from euphausiids (brown cylindrical shape) and fish (large reddish pellet). E) Sta. 95; Phytodetrinitus with C. pennatum frustules and a euphausiid molt. F) Crustacean fecal pellet containing lipid globules and phytodetrinitus. G) degraded salp fecal material and euphausiid exoskeletal fragments. H) fecal fluff and large salp fecal pellet. I) Sta. 96; C. pennatum frustules with phytodetrinitus. J) ruptured fecal pellet with phytodetrinitus. K) Cylindrical euphausiid fecal pellets and phytodetrinitus. L) Radiolarian “balls”, amorphous phytodetrinitus patches and euphausiid fecal pellets. M) Sta. 142; Euphausiid molt surrounded by phytodetrinitus dominated by C. pennatum frustules. N) Phytodetrinitus with C. pennatum frustule fragments. O) Dense orange fecal pellet with diatom frustules. P) Euphausiid fecal pellets immersed in fecal fluff and phytodetrinitus.
population estimates of similar-sized icebergs from satellite images taken over the same period of time in the Weddell Sea. Between March and April 2009, there were five icebergs of comparable size to C-18a identified in satellite images (D. Long, pers. comm.) covering an area of approximately 47,636 km² of the northwestern Weddell Sea (Fig. 1). The combined area of the five icebergs was 907 km² or 2% of the designated surface area along "Iceberg Alley". Using the estimated area of each iceberg and assuming it was circular, we calculated the area of influence with a 10, 20 and 30 km radius. Expanding the area of each iceberg by 10 km radius increased the combined area to 4752 km² and with a 30 km radius expanded to 21,859 km² or 46% of the iceberg alley area. The estimated mass flux over this extended 30-km radius area for the five icebergs was 2710.5 tons d⁻¹ and the organic carbon export was 122.4 tons d⁻¹ (Fig. 6B). This estimate only includes the 5 icebergs of comparable size to C-18a and not the multitude of smaller icebergs routinely

Fig. 3. (Continued)
The estimated production in the NW Weddell Sea. The primary production was 6002 tons C d\(^{-1}\) (Vernet et al., this issue). Using the primary production of 126 mg C m\(^{-2}\) C\(0\)\(d\) for the 30 km radius around the five icebergs is 122.4 tons d\(^{-1}\) organic carbon export for the 30 km radius around the five icebergs (47,636 km\(^2\)), the estimated flux is expected to be greater (Bienfang 1984). In the LST samples, observed in the study area during the cruise. Given the increased surface area to volume ratio of smaller icebergs, their impact has been estimated to be very substantial (Smith et al., 2007).

Another important comparison is with the estimated primary production in the NW Weddell Sea. The primary production measured in the ice-edge zone in March 1986 was 126 mg C m\(^{-2}\) d\(^{-1}\) (Smith and Nelson, 1990). During our cruise in March/April 2009, primary production varied from 106.4 to 368.9 mg C m\(^{-2}\) C\(0\)\(d\) from 1.2-10 \(\mu\)m. In the LST samples, Fragilariopsis nana and other small diatoms of the same genus also dominated numerically; their sinking could be attributed to small particle aggregation (Burd and Jackson 2009). Due to the larger size of C. pennatum, their contribution to the carbon flux is expected to be greater (Bienfang 1984). In the LST samples, observed in surface waters (0-100 m; Cefarelli et al., this issue). The sinking flux of particulate matter associated with free-drifting iceberg C-18a consisted of diatoms and heterotrophically generated fecal material. The diatom diversity was similar to that observed in surface waters (0-100 m; Cefarelli et al., this issue). Corethron pennatum and several species of Chaetoceros dominated the larger fraction of phytoplankton (> 20 \(\mu\)m). In the LST samples, Fragilariopsis nana and other small diatoms of the same genus also dominated numerically; their sinking could be attributed to small particle aggregation (Burd and Jackson 2009). Due to the larger size of C. pennatum, their contribution to the carbon flux is expected to be greater (Bienfang 1984). In the LST samples,

Table 2

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sta 43</th>
<th>Sta 95</th>
<th>Sta 96</th>
<th>Sta 142</th>
<th>500 m Plankton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bacteria cell abundance (cells (\times) mL(^{-1}))</td>
<td>nd</td>
<td>2.97 (\times) 10(^5)</td>
<td>3.85 (\times) 10(^5)</td>
<td>7.60 (\times) 10(^5)</td>
<td>6.51 (\pm) 1.31 (\times) 10(^6)</td>
</tr>
<tr>
<td>Leucine incorporation rate (pM (\times) hr(^{-1}))</td>
<td>36.32</td>
<td>167.32</td>
<td>2.83</td>
<td>42.64</td>
<td>0.35 (\pm) 0.20</td>
</tr>
<tr>
<td>Bacterial biomass production (mgC (\times) L(^{-1}) day(^{-1}))</td>
<td>1.31 (\times) 10(^{-3})</td>
<td>6.02 (\times) 10(^{-3})</td>
<td>0.10 (\times) 10(^{-3})</td>
<td>1.53 (\times) 10(^{-3})</td>
<td>1.27 (\pm) 0.73 (\times) 10(^{-5})</td>
</tr>
<tr>
<td>Generation time (day)</td>
<td>nd</td>
<td>0.42</td>
<td>32.52</td>
<td>4.25</td>
<td>55.82 (\pm) 27.08</td>
</tr>
<tr>
<td>Phytoplankton cell abundance (cells (\times) mL(^{-1}))</td>
<td>2.29 (\times) 10(^4)</td>
<td>1.12 (\times) 10(^4)</td>
<td>2.13 (\times) 10(^4)</td>
<td>2.45 (\times) 10(^5)</td>
<td>0.25 (\times) 0.15 (\times) 10(^2)</td>
</tr>
<tr>
<td>Phytoplankton &gt; 10 (\mu)m (cells (\times) mL(^{-1}))</td>
<td>0.37 (\times) 10(^3)</td>
<td>0.66 (\times) 10(^3)</td>
<td>0.15 (\times) 10(^3)</td>
<td>4.75 (\times) 10(^3)</td>
<td>1.5 (\times) 1.7</td>
</tr>
<tr>
<td>Phytoplankton 3-10 (\mu)m (cells (\times) mL(^{-1}))</td>
<td>1.75 (\times) 10(^3)</td>
<td>2.27 (\times) 10(^3)</td>
<td>8.31 (\times) 10(^3)</td>
<td>3.04 (\times) 10(^4)</td>
<td>0.13 (\times) 0.1 (\times) 10(^4)</td>
</tr>
<tr>
<td>Phytoplankton &lt; 3 (\mu)m (cells (\times) mL(^{-1}))</td>
<td>5.04 (\times) 10(^3)</td>
<td>8.26 (\times) 10(^3)</td>
<td>1.29 (\times) 10(^4)</td>
<td>2.1 (\times) 10(^5)</td>
<td>0.1 (\times) 0.07 (\times) 10(^5)</td>
</tr>
</tbody>
</table>

Please cite this article as: Smith, K.L. Jr., et al., Carbon export associated with free-drifting icebergs in the Southern Ocean. Deep-Sea Research II (2011), doi:10.1016/j.dsr2.2010.11.027

Fig. 4. Depth profiles of temperature (A), salinity (B) and percent light transmission (C) from the surface to a maximum depth of 1000 m in the vicinity and during the same time as the four LST deployments; Sta. 43 [14 casts (red)], Stas. 95 and 96 [10 casts (blue)], and Sta. 142 [5 casts (yellow)].
most diatoms were identified from frustules and were representative of the NW Weddell Sea assemblages. These same taxa are abundant in sediments in the region (Buffen et al., 2007).

Fecal material collected in a similar area of the NW Weddell Sea between November and January 1989 was dominated by krill cylindrical strings and oval pellets in the upper 50 m, decreasing exponentially in number and dry weight with depth to 1000 m (Gonzalez, 1992). The highest abundance of fecal material was found in the Weddell-Scotia Confluence or associated with the seasonal ice edge. In areas of natural iron fertilization associated with the Kerguelen Plateau, a similar condition prevailed with zooplankton grazing and the production of copepod fecal material being a primary constituent of the export flux either singly or in the abundant aggregates (Ebersbach and Trull, 2008). The export flux measured at ≤100 m depth in association with the iron enriched phytoplankton community around the Crozet Plateau to the northeast of the Kerguelen site was primarily diatom species with few fecal pellets (Salter et al., 2007). At these more northerly sites, the influence of krill diminishes markedly compared with areas south of the Antarctic Polar Front (Atkinson et al., 2009).

The presence of mineral grains in the LST samples validates chemical tracer evidence of significant terrestrial material delivery during iceberg transit (Smith et al., 2007; Shaw et al., this issue a). The presence of large mineral grains in LST collections in close proximity to the iceberg also indicates delivery of abundant finer grain (down to nanoscale) material to the water column. Size distribution information on ice collected during this study suggest that a minimum of 25% of the ice-borne material is less than 63 μm in size with much of that being rock flour (Shaw et al., this issue b). Similar work on glacial material suggests a significant input of nanoscale iron rich material associated with icebergs (Raiswell et al., 2006; Raiswell, this issue). Overall, these observations confirm a source for observed iron enrichments in proximity to free drifting icebergs (de Baar et al., 1995; Lin et al., this issue).

The sinking fluxes of particulate matter associated with icebergs can be compared with flux measurements made with moored and drifting sediment traps in other regions of the Southern Ocean. The most comparable particle flux measurements were conducted in the abyssal northern Weddell Sea to the east of our site (Table 3; Fig. 1). A sediment trap was moored at a depth of 863 m with 11 days each during March 1985 (Fischer et al., 1988), a period not covered by seasonal pack ice and most comparable to our LST collection period. Particulate mass fluxes ranged from a high of 9.20 mg m⁻² d⁻¹ in mid-March to a low of 0.37 mg m⁻² d⁻¹ in early April, which are 1–3 orders of magnitude lower than the fluxes measured in the LST deployments (Table 3). Mass fluxes measured at 494 m depth with moored sediment traps in Bransfield Strait (Fig. 1) in March 1984 were considerably lower but the organic carbon fluxes were comparable to those measured at 600 m depth with the LSTs (Table 3).

Drifting sediment traps were deployed to measure the flux of particulate matter associated with areas of natural iron enrichment from topographic features in the S. Indian Ocean (Fig. 1). Over the Kerguelen Plateau, where local upwelling sustains higher productivity, the organic carbon fluxes measured with drifting sediment traps at 430 m depth were 3 times higher than those measured in association with iceberg C-18a (Table 3). Similarly, on the Crozet Plateau, drifting sediment traps deployed for 600 days at depths of 87 and 100 m depth yielded comparable mass fluxes but order of magnitude higher organic carbon fluxes than those measured with the LSTs (Table 3). The order of magnitude difference is consistent with ²³⁴Th based fluxes from

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Fig. 5. Plots of mass flux (A), total carbon flux (B), organic carbon flux (C), total nitrogen flux and molar Corg:Ntot (D) with distance from iceberg C-18a. Fluxes are estimated from each subsample, collection cup, on the three deployments of the LST in the vicinity of iceberg C-18a and at the control site 74 km away. Sta. 43 (red triangle – 4 subsamples); Sta. 95 (blue diamond – 2 subsamples); Sta. 96 (green square – 3 subsamples); and Sta. 142 (yellow circle – 3 subsamples). Mean fluxes ± standard error (black crosses with whisker bars) for the three deployments in proximity to iceberg C-18a and for the one control deployment 74 km away are plotted at the mean distance from the iceberg.
the upper 100 meters at C-18a (Shaw et al., this issue a, this issue b). The benthic enrichment of nutrients combined with higher ambient light one to two months earlier and at lower latitude could easily account for the difference in carbon flux between the Indian Ocean sites and the C-18a site (Fig. 1).

The role of bacterial remineralization in carbon export is debated and its importance may vary from coastal to open ocean and with latitude (Baltar et al., 2009), and in anoxic basins (Taylor et al., 2009). However, it is clear that due to high microbial biomass on sinking particles (Simon et al., 2002) local remineralization rates can also be high. The proportional differences between production and export remain to be quantified for most of the ocean. Bacterioplankton abundance and biomass production based on protein synthesis rates varied significantly though are likely underestimates due to challenges in counting cells on particles (the samples were not sonicated as per Taylor et al., 2009). Additionally, low leucine incorporation rates in LST samples from Sta.96 may have been due to the lower particulate matter concentration in comparison to the other LST samples (based on visual inspection of DAPI-stained preparation) resulting in an underestimate of biomass production. POC was not determined on the same sample cup that the microbial samples were taken.

In theory, it seems plausible to measure the export of organic carbon from free-drifting icebergs of a wide range in size at different times of the year using the LSTs. However, in reality it is difficult to achieve such measurements given the logistical constraints of shiptime combined with natural constraints of Southern Ocean weather and seasonal pack ice. We feel a complementary strategy is needed in the future to measure the organic carbon export flux using moored sediment trap arrays positioned across the most frequently traveled iceberg route, “Iceberg Alley”. Placing moored sediment traps across a hypothesized gradient from high iceberg concentrations in the northwest to lower concentrations in the central Weddell Sea at comparable depths over an entire year would provide a mechanism to estimate the export flux and sequestration of organic carbon from icebergs compared to “control” situations influenced by seasonal pack ice alone. These long-term studies would be done in conjunction with short-term LST deployments around a size range of icebergs. Particulate fluxes associated with individual icebergs would then

![Fig. 6.](image-url)
be used in combination with shipboard and satellite population estimates for comparison with concurrent broader scale export flux and sequestration measurements across “Iceberg Alley”.

Our results thus far strongly suggest the importance of free-drifting icebergs on enriching the pelagic ecosystem and ultimately enhancing the export and sequestration of organic carbon in the deep Southern Ocean.

Acknowledgments

This research was funded by National Science Foundation grants (ANT-0636813 to K. Smith; ANT-0636319 to T. Shaw; ANT-0636543 to A. Murray; ANT-0636730 to M. Vernet) and by the David and Lucile Packard Foundation. We thank B. Hobson and P. McGill who were instrumental in the development of the LSTs. Shipboard support was provided by B. Hobson, P. McGill, J. Ellena, and C. Hexel. Captain Watson and the crew on RVIB N.B. Palmer accompanied by the Raytheon Polar Services support group made the LST deployments and recoveries a success. J. Ellena conducted the chemical analyses and S. Wilson identified the fecal material. We thank K. Stuart and D. Long for providing the satellite data on icebergs in the vicinity of C-18A during our study and two reviewers for critical comments which greatly improved this paper.

References


