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Particle fluxes during austral spring and summer in the southern Ross Sea, Antarctica

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Abstract. The flux of particles from the euphotic zone through 200 m was investigated on the Ross Sea continental shelf during two cruises, the first in November-December 1994 and the second in December 1995 and January 1996. An assessment of surface layer phytoplankton biomass and productivity was made simultaneously. Particle flux was measured using floating sediment traps whose collection efficiency was assessed rigorously. Phytoplankton biomass and productivity increased rapidly in November-December, and biomass was maximal in mid-December. Thereafter productivity appeared to decline substantially. Biomass declined as well, but not as rapidly as productivity. Vertical flux rates were low early in the bloom period, averaging 457 mg m\(^{-2}\) d\(^{-1}\), but increased markedly in late December and January (mean = 1160 mg m\(^{-2}\) d\(^{-1}\)). Daily losses due to vertical flux represented only 2.3% of the surface layer particulate organic carbon standing stock. Measured particle fluxes were greater than those observed previously, and this is attributed to the period and depths sampled as well as to the care taken to ensure accuracy of sample collection. As in other regions, vertical flux of biogenic material is coupled with surface layer production and biomass. In our study area, however, a distinct temporal lag is introduced between surface production and flux at depth as a result of the temporal characteristics of the dominant mechanism generating large particles (aggregation) as well as the characteristic species of the region (*Phaeocystis antarctica*).

1. Introduction

The continental shelf of the Ross Sea is characterized by extensive, annual phytoplankton blooms [e.g., Comiso et al., 1993; Arrigo and McClain, 1994]. These blooms generally are spatially distinct [Smith et al., 1996], with the coastal region being dominated by diatoms [Smith and Nelson, 1985] and the south central region being dominated by the haptophyte *Phaeocystis antarctica* [Smith and Gordon, 1997]. The latter bloom is characterized by its early development (being initiated in early to mid-October) [Arrigo et al., 1998], high levels of productivity [Smith and Gordon, 1997], and unusual community structure. The bloom reaches maximum biomass in mid-December (particulate carbon concentrations of 53.9 \(\mu\)mol L\(^{-1}\) at the surface [Smith and Gordon, 1997]), but decreases to much lower levels through January and February [Smith et al., 1996], despite seemingly favorable conditions for phytoplankton growth in summer.

It is uncertain what processes cause the decrease in phytoplankton biomass during the summer. Time series sediment trap studies have shown that mesozooplankton grazing and fecal pellet production/flux contribute to diatom removal and export of organic matter [Dunbar et al., 1998], and microzooplankton also consumes and regenerates a fraction of the surface layer's particulate matter [Gowing et al., 1995; DiTullio and Smith, 1996]. It has also been suggested that aggregate formation and the subsequent enhanced vertical flux of the larger particles also contribute significantly to the "biological pump" [Longhurst, 1991] of the Ross Sea [Hill, 1992; Smith et al., 1996]. Samples from moored, deep sediment trap studies in the southern Ross Sea [Dunbar et al., 1998] and the temporal phasing of surface production and vertical flux [Smith and Dunbar, 1998] both suggest that the contribution of aggregates to vertical flux is substantial [Smith and Dunbar, 1998]. However, given the differences in the sinking rates of aggregates and fecal
material, it is uncertain how much material is remineralized during transit to the seafloor, and it remains unclear which of the mechanisms that regulate the termination of the bloom is quantitatively most significant.

Sediment traps have been widely used throughout the ocean to characterize the quality and quantity of particulate fluxes to depth [e.g., Knauer et al., 1979; Honjo, 1990; Asper et al., 1992a]. Many of the long-term, bottom-moored deployments are able to collect discrete samples through time and therefore better resolve the temporal nature of vertical flux. Surface-moored, floating sediment traps have also been used [e.g., Rivkin et al., 1996; Murray et al., 1996], but their collection efficiency has been questioned. In addition, studies using the particle-reactive isotope $^{234}$Th suggest that surface-moored traps may in certain environments seriously under- or oversample particle flux [Buesseler, 1991]. To date, there has been no adequate resolution to the question of quantifying vertical flux, although Murray et al. [1997] suggest that all methods, when treated in a rigorous manner, yield similar estimates.

In order to better understand the controls of surface layer production and distribution in the Ross Sea and the coupling of vertical flux to surface processes in both space and time, two cruises were completed. We hypothesized that vertical flux was dominated by rapidly sinking aggregates (rather than fecal pellets), and we strived to understand their formation, distribution, and relationship to surface processes (such as primary and new production). Surface-moored, floating traps were deployed to quantify vertical flux, and extreme care was taken to minimize hydrodynamic biases. The results suggest that these precautions largely minimized collection uncertainties and that the flux production relationship was primarily a function of the stage of the phytoplankton bloom and its taxonomic composition.

2. Materials and methods

2.1. Cruise Location

Two cruises were conducted within the Ross Sea polynya in the southern Ross Sea (Antarctica) on the R.V.I.B. Nathanial B. Palmer. The first was conducted from November 12 to December 5, 1994, and the second from December 8, 1995 to January 8, 1996. Ice concentrations during both studies were variable. During the 1994 study the region initially was completely covered by thin ice (approximately 30 cm), with thicker ice east of 175°W and west of 170°E. The ice disappeared in the central portion of the study area by the end of the cruise. In 1995-1996 the polynya was largely open, with thick ice remaining near the Victoria Land coast. Many stations were occupied along 76°30’S, perpendicular to the direction of ice retreat. Deployments of floating sediment traps were also concentrated along this transect (Figure 1).
2.2. Array Design

The sediment trap array incorporated a "flexible spar buoy" arrangement (Figure 2), which consisted of a series of small floats on a portion of the surface line. Below this point the array was configured to be neutrally buoyant. As a surface wave passes, the vertical stress on the down line is proportional to the amount of floats submerged by the wave and their individual buoyancy. For this reason the floats are as small as possible (< 3 kg of buoyancy each), so that even a large wave will exert a force that is small compared to the mass and friction of the array. A large frame was also attached to the array at 175 m. This frame held a special sediment trap with attached cameras for determining the flux and sinking speed of large aggregates and provided a substantial amount of drag at that depth. This effectively positioned the array at that depth by reducing its slippage relative to the surrounding water and hence minimized the flow of water relative to the trap openings. In addition, the array also incorporated an elastic connector between the spar buoy and the subsurface flotation to further isolate the traps and instrumentation from vertical motion.

Instruments were also deployed on the array to assess its performance. A Woods Hole Instrument Systems electromagnetic current meter was installed on the frame at 175 m to monitor the seawater flow relative to the frame. This instrument also had tilt, pressure and temperature sensors to evaluate the physical orientation and depth.
displacements of the array. At several (from 5-10) depths, Richard Brancker thermographs, which record temperature to 0.1°C and depth to 0.1 m, were installed. This information is useful in examining the tilt or movement of the array, particularly if it is transported significantly by wind and/or ice.

On the top of the buoy a vertical mast extended 3 m above the water, on which were installed dual radio transmitters. Inside the buoy two Telonics ST-5 Argos transmitters and their lithium battery packs were installed. The buoy allowed the signal to reach the satellite with no external antennae. These signals were relayed to the Argos system office, where positions were calculated and then transmitted daily to the ship. Tracking of the array was critical to compare the array trajectory with in situ flow readings. If the array were to move rapidly but the current meter registers minimal flow, this would suggest that the entire water mass was in motion and carrying the array with it. However, if the array moved more rapidly than the water mass, it is likely that the array was dragged by the surface flotation package in response to wind and surface water/ice flow.

2.3. Sediment Traps

The sediment traps used were the MULTITRAP design [Knauer et al., 1979]. The traps are cylindrical, with a mouth opening of 0.0039 m² and an aspect ratio of 10:1. The cylinder is equipped with a base that holds a 90-mm Poretics polycarbonate membrane filter (pore size 0.4 μm). A PVC drain valve is mounted under the base of the filter holder. At the surface of the cylinder a plastic baffle consisting of circular openings 1.2 cm in diameter provided turbulence reduction at the trap opening. Twelve of these individual traps were placed at each of five depths using a cruciform support. In all cases, any preservative solution was filled only to a height of 10 cm and the remaining volume was filled with filtered seawater. This assured that the interface between the pretreatment solution and overlying seawater was in the lowest portion of the trap where it would be unaffected by any eddies within the trap. If the traps had been filled completely with solution, these eddies could remove the solution from the trap, resulting in a constantly changing solution volume and potentially affecting the accuracy of the traps [Gardner and Zhang, 1997]. For mass and carbon/nitrogen samples, the traps were filled with a preservative/brine solution intended to minimize diffusion and mixing with the trap. This solution was prepared by adding 1 L formalin and 2.5 kg NaCl to 50 L of seawater, yielding a 2% formalin and 50 g L⁻¹ NaCl solution. After mixing, the solution was gravity filtered through a 0.5 μm cartridge membrane filter (Milipore). Deployment times ranged from 0.8 to 2.6 days, except for deployment 94-5, which was lost under the sea ice for over a week (Table 1).

Care was taken to deploy the traps under conditions that would minimize hydrodynamic biases (such as within thin ice). When this was difficult, the array was deployed in open water, but the short fetch and our proximity to the Ross Ice Shelf prevented the generation of substantial surface waves. If the flow of water past the trap opening is excessive, it can induce currents within the interior of the trap, resulting in compromised trapping efficiency. Some flow within the trap is normal, and it has been inferred that accurate samples are obtained by the lateral transfer of material into the trap and its subsequent removal by settling, once the particles are below the level of turbulence. The specific characteristics of this flow and particle transfer are affected by the magnitude of the flow, the aspect ratio and shape of the trap, the trap's tilt, and the composition and volume of the trap solution used. In addition to lateral motion, if the trap is suspended from a surface flotation package, vertical oscillations induced by wave motion can

<table>
<thead>
<tr>
<th>Deployment</th>
<th>Date</th>
<th>Site Location</th>
<th>Recovery Location</th>
<th>Drift Distance, km</th>
<th>Deployment Duration, days</th>
<th>Drift Direction, °T</th>
<th>Mean Velocity, cm s⁻¹</th>
<th>Average Flow, cm s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>94-1</td>
<td>Nov. 13, 1994</td>
<td>76.8°S, 180.0°W</td>
<td>76.4°S, 179.4°W</td>
<td>17</td>
<td>0.9</td>
<td>311</td>
<td>25</td>
<td>17.8</td>
</tr>
<tr>
<td>92-2</td>
<td>Nov. 17, 1994</td>
<td>76.5°S, 168.5°E</td>
<td>76.5°S168.5°E</td>
<td>2.1</td>
<td>0.9</td>
<td>162</td>
<td>4</td>
<td>3.37</td>
</tr>
<tr>
<td>94-3</td>
<td>Nov. 18, 1997</td>
<td>76.5°S, 72.9°E</td>
<td>76.3°S171.8°E</td>
<td>40</td>
<td>1.1</td>
<td>310</td>
<td>42</td>
<td>24.2</td>
</tr>
<tr>
<td>94-4</td>
<td>Nov. 23, 1997</td>
<td>77.1°S, 173.1°E</td>
<td>77.2°S, 174.4°E</td>
<td>36</td>
<td>1.7</td>
<td>100</td>
<td>34</td>
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</tr>
<tr>
<td>94-5</td>
<td>Nov. 27, 1997</td>
<td>75.0°S, 173.0°E</td>
<td>73.6°S, 172.6°E</td>
<td>170</td>
<td>9.1</td>
<td>356</td>
<td>24</td>
<td>11.9</td>
</tr>
<tr>
<td>94-6</td>
<td>Dec. 6, 1994</td>
<td>76.6°S, 173.0°E</td>
<td>76.5°S, 173.2°E</td>
<td>7.1</td>
<td>0.7</td>
<td>40</td>
<td>11</td>
<td>NI</td>
</tr>
<tr>
<td>95-1</td>
<td>Dec. 24, 1995</td>
<td>76.5°S, 171.8°E</td>
<td>76.3°S, 177.7°E</td>
<td>11</td>
<td>1.8</td>
<td>345</td>
<td>19</td>
<td>6.97</td>
</tr>
<tr>
<td>95-2</td>
<td>Dec. 27, 1995</td>
<td>76.5°S, 170.8°E</td>
<td>76.5°S, 171.5°E</td>
<td>9.6</td>
<td>2.6</td>
<td>94</td>
<td>3.6</td>
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<td>95-3</td>
<td>Jan. 2, 1996</td>
<td>76.5°S, 165.0°E</td>
<td>76.5°S, 165.0°E</td>
<td>5.8</td>
<td>1.7</td>
<td>344</td>
<td>8</td>
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<tr>
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<td>Jan. 7, 1996</td>
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<td>76.4°S, 177.4°W</td>
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<td>36</td>
<td>20</td>
<td>6.91</td>
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<tr>
<td>95-5</td>
<td>Jan. 12, 1996</td>
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<td>76.4°S, 165.0°E</td>
<td>6.6</td>
<td>1.6</td>
<td>312</td>
<td>12</td>
<td>6.90</td>
</tr>
</tbody>
</table>

ND is no data; NI is not installed.
be transferred down the vertical array member, causing the trap to experience rapid vertical accelerations, with the potential of influencing the trapping efficiency.

Upon recovery the traps are covered with polyethylene gloves and brought into the ship’s laboratory for processing. The seawater at the top of the trap is siphoned off to just above the level of the visible density interface using acid-rinsed (0.6N HCl) Teflon tubing. For mass flux samples the density gradient solution is drained through the bottom of the trap and discarded. The Poretics filter is removed, returned to its petri dish, sealed with Parafilm, labeled, and stored under refrigeration until analyzed. The “swimmers” (recognizable zooplankton) are removed using forceps under a dissecting microscope (12-25 power magnification). The material on the filter is then scraped into a bolus at the center of the filter with a scalpel and desalted by rinsing with Milli-Q water adjusted to pH 9 with ammonium hydroxide. The filter with the sample bolus is oven dried (65°C) and placed in a dessicator until its weight becomes constant.

Carbon and nitrogen analyses are performed using a Carlo Erba EA-1108 elemental analyzer calibrated with acetanilide. The bolus is scraped off the filter with a scalpel and ground in an agate mortar. The whole sample (50-300 mg) is transferred to a silver boat and weighed on a CAHN Electrobalance (model 4400). The silver boats are fumed with concentrated HCl for 36 hours to volatilize inorganic carbon, desiccated overnight, and then analyzed. The results were expressed as percentages of carbon and nitrogen.

2.4. Water Samples
Seawater samples were collected using twenty-four 10-L Niskin bottles mounted on a rosette to which a Seabird 911 conductivity-temperature-depth (CTD) profiler was attached. Subsamples were collected for chlorophyll via fluorometry (Turner Designs model 10 fluorometer) and particulate carbon and nitrogen using high-temperature pyrolysis (Carlo Erba model EA-1108 elemental analyzer). Samples were also collected for the determination of primary productivity using 14C uptake and simulated in situ incubations [Smith and Nelson, 1990]. New production estimates were also conducted using 15N stable isotope techniques (i.e., using simulated in situ incubations to assess the uptake of isotopically labeled ammonium and nitrate; Smith and Nelson, 1990). All incubations lasted approximately 24 hours.

3. Results
3.1. Trap Performance and Drift
During the first cruise, circulation was stronger, the arrays drifted farther, and the traps experienced more relative flow (Figure 1 and Table 1) than during the second cruise, when conditions were less rigorous and when some of the deployments remained in essentially the same location as deployed, indicating minimal flow. Although conditions were generally more difficult during the first cruise, on occasion it was possible to examine it using a remote operated vehicle (ROV). The video showed the traps and the array hanging vertically in the water column with minimal flow relative to the trap opening.

Records from the current meter attached to the array confirm the same flow pattern as the array trajectories, which indicates that most of the array drift was due to the effect of the wind on the surface components of the array. Figures 3a and 3b show the most extreme and typical records of the movement of the array (deployments 94-3 and 95-1, respectively), as determined by the distance moved, as well as the flow measured by the current meter at 175 m. Of the nine deployments for which both sets of data exist, deployments 94-1 and 94-3 had the highest mean flows (17.8 and 24.2 cm s⁻¹, respectively). Peak flows during all deployments were experienced during deployment and recovery and were not included in the reported mean values. Occasional velocity spikes of 20 cm s⁻¹ were observed, probably corresponding to instances where the surface floatation was dragged by drifting ice floes. Overall, the flows detected during all deployments except 94-1 and 94-3 were within the range of minimal hydrodynamic bias predicted by numerous flume and in situ studies [Butman, 1986; Gardner, 1980; Gust et al., 1992, 1994].

Records from the thermographs indicate that vertical excursions and tilt were, in most cases, minimal (Figure 4). The thermographs recorded both parameters every 3-10 s during the deployment, providing sufficient temporal resolution to detect wave-induced motion. High-frequency variation in the signal was minimal throughout the deployment. The absolute depths recorded and depth interval between the thermographs, both of which indicate tilt of the array, changed very little during the deployment (except for deployment 94-3). These observations suggest that the arrays performed well and that the design provided a platform for the traps that was sufficiently free of vertical and lateral displacements relative to the surrounding water.

Deployment 94-3 was unique among the deployments, in that the drift trajectory (Figure 1) from which its average drift rate was calculated (Table 1) is anomalously large, indicating unusually high wind stress during this period. Winds measured by the ship’s meteorological sensors exceeded 30 knots (15.6 m s⁻¹) during the deployment; furthermore, the entire array appeared to have become ensnared by an ice floe and dragged through the water, causing the tilt of the array to increase. The shallow traps experienced lateral displacement with little vertical change, but the deep traps were lifted disproportionately by the stress on the surface floatation package. Because of this tilt, the changing sampling depths and the high flows induced on the array, the results from this deployment should be viewed with extreme caution.

3.2. Particle Fluxes
The total particulate flux was low during austral spring 1994, with mass fluxes at 100 m ranging from 256 to 1210 mg m⁻² d⁻¹ (Figure 5a). Fluxes for all traps averaged 457 mg m⁻² d⁻¹ and generally did not decrease with depth. The highest fluxes were observed during the extended
Figure 3. Current meter records for the deployments during both cruises showing (a) extreme, high current conditions and (b) more typical low flow conditions. The depth indicates the degree to which the bottom of the array remained at a constant depth.
Figure 4. Thermographs (temperature and depth recorders) deployed at several positions along the array, indicating both the vertical motion (absolute change in depth over time) and tilt (changing relative values) of the array, under (a) high flow conditions where the shallow sensors are pulled laterally by strong flows while the deep sensors are lifted, and (b) more typical conditions with all sensors remain at constant depths.
deployment (94-5) in the northern Ross Sea, where a maximum flux of 1290 mg m\(^{-2}\) d\(^{-1}\) was observed at 75 m (Table 2). On average, 29% of the total mass flux was organic carbon, and particulate organic matter (POM) and particulate organic carbon (POC) were linearly correlated \((n = 29, R^2 = 0.69, p < 0.001)\), where \(n\) is the number of samples, \(R^2\) is correlation coefficient, and \(p\) is the probability that the correlation is due to random chance). For the 1994 samples analyzed, nearly all (>97%) of the material collected in the traps was organic. When all data were pooled, the POC:PON ratio equaled 14.9 \((n = 9, \text{standard deviation} = 9.1)\); however, there appeared to be an increase with depth in the relative proportion of carbon, as the mean POC:PON ratio increased from 8.7 at 50 m \((n = 16, \text{standard deviation} = 1.0)\) to 25.5 at 200 m \((n = 1)\), suggesting that the material being exported was undergoing substantial biological modification during transit [e.g., Banse, 1990; Eppley et al., 1983].

It should be pointed out that because of the initially short deployment periods and low flux rates, many of the samples did not have enough material to analyze for all variables and that the confidence in the absolute flux rates (and therefore elemental ratios) is less than for the 1995/1996 samples. No relationship between the carbon:nitrogen ratio of the material collected in the sediment traps and that in the water was observed in 1994. At the locations of the trap deployments, primary productivity in 1994 ranged from 0.13 to 2.65 g C m\(^{-2}\) d\(^{-1}\) (mean = 1.36 g C m\(^{-2}\) d\(^{-1}\); see Table 3). The \(f\) ratios, as determined via \(^{15}\)N tracer incubations, were high and ranged from 0.44 to 0.89 at five locations. New production (the product of the \(f\) ratio and productivity) \([\text{Rivkin et al., 1996}]\) ranged from 0.05 to 0.90 g C m\(^{-2}\) d\(^{-1}\). Nearly all stations along 76\(^\circ\)30'S were dominated by the colonial haptophyte *Phaeocystis antarctica*. Euphotic zone standing stocks of POC averaged 6.58 g C m\(^{-2}\), whereas stocks of POC integrated through 150 m averaged 11.8 g C m\(^{-2}\) (Table 3). The flux through 150 m relative to the euphotic zone standing stock of POC and the daily productivity were quite low, ranging from 0.8 to 2.3% and 2.8 to 21.5%, respectively.

During the 1995/1996 cruise the fluxes were substantially higher, ranging from 262 to 2610 mg m\(^{-2}\) d\(^{-1}\) (Figure 5b and Table 4). Mean fluxes for the 1995/1996 cruise were 1160 mg m\(^{-2}\) d\(^{-1}\) or 2.5 times greater than in 1994. The fluxes from 1995/1996 also exhibited an exponential decrease in flux with depth, unlike the results from 1994 \((F_z = F_{50} e^{-kz},\) where \(k\) is the remineralization constant in units of m\(^{-1}\) and \(F_{50}\) and \(F_z\) are the fluxes at 50 and \(z\) m, respectively; \(k = 106.4, n = 5, p < 0.05\)). Particulate carbon was overwhelmingly organic (>98%), and the mean POC:PON ratio (as determined via linear regression) was 5.87. Carbon:nitrogen ratios of material collected in the traps increased slightly but consistently from 7.2 at 50 m \((n = 14, \text{standard deviation} = 0.59)\) to 7.94 at 200 m \((n = 13, \text{standard deviation} = 0.60)\).

Primary productivity at the 1995/1996 deployments averaged 1.26 g C m\(^{-2}\) d\(^{-1}\) (range 0.59 - 2.47 g C m\(^{-2}\) d\(^{-1}\); see Table 4), nearly the same as the trap deployment stations in 1994. The \(f\) ratios and new production were determined at only two of the deployments, but both remained high (0.64 and 0.89 for \(f\) ratios and 0.96 and 1.58 g C m\(^{-2}\) d\(^{-1}\) for new production). Although *Phaeocystis antarctica* was present and dominated at certain stations, diatoms were also present.

![Figure 5a](image1.png) Total dry weight mass fluxes (mg m\(^{-2}\) d\(^{-1}\)) during the deployments in 1994.

![Figure 5b](image2.png) Same as Figure 5a, but for 1995/1996.
Table 2. Fluxes of Total Mass, Total Carbon C\textsubscript{T}, Organic Carbon C\textsubscript{O}, and Organic Nitrogen as Measured by Traps Suspended From a Floating Array at Five Depths in 1994

| Depth, m | Mass | C\textsubscript{T} | C\textsubscript{O} | N | Mass | C\textsubscript{T} | C\textsubscript{O} | N | Mass | C\textsubscript{T} | C\textsubscript{O} | N | Mass | C\textsubscript{T} | C\textsubscript{O} | N | Mass | C\textsubscript{T} | C\textsubscript{O} | N |
|---------|------|-----------------|-----------------|---|------|-----------------|-----------------|---|------|-----------------|-----------------|---|------|-----------------|-----------------|---|------|-----------------|-----------------|---|------|-----------------|-----------------|---|------|-----------------|-----------------|---|
| 50      | 261  | 79.3           | -               | 7.7| 161  | 37.4           | -               | 2.8| 233  | 84.5           | -               | 10.1| 272  | 89.9           | 84.7           | 9.2| 917  | 249           | 243           | 36.2| 527  | 165           | 160           | 27.9|
| 75      | 320  | 83.6           | -               | 6.7| 193  | 42.8           | -               | 2.8| 580  | 210           | -               | 16.6| 358  | 136           | 136           | 11.6| 1290 | 228           | 226           | 31.7| 202  | 65.2           | 63.7           | 10.0|
| 100     | 475  | 153            | -               | 9.0| 426  | 120           | -               | 3.9| 257  | 66.1           | -               | 7.4| 519  | 192           | 183           | 6.1| 1210 | 231           | 227           | 30.1| 369  | 121           | 119           | 17.8|
| 150     | 464  | 167            | -               | 18.0| 135  | 25.7           | -               | 0.7| 708  | 229           | -               | 14.9| 220  | L             | 75.2           | 4.6| 849  | 157           | 155           | 21.2| 272  | 78.9           | 70.4           | 9.2|
| 200     | 539  | 205            | -               | 4.1| 296  | 5.1           | -               | 0.0| 396  | L             | -               | 0.0| 268  | 95.4           | 96.3           | 4.4| 714  | 120           | 114           | 15.7| 231  | 54.5           | -               | 6.1|

All variables are in mg m\textsuperscript{-2} d\textsuperscript{-1}. L denotes sample lost; hyphens indicate no data.

Table 3. Integrated Euphotic Zone Primary Production, Particulate Organic Carbon Integrated Through the Euphotic Zone (POC\textsubscript{122}) and 150 m (POC\textsubscript{150}), New Production, f Ratios, and Percentages of Primary Productivity and Standing Stock Removed Daily by Measured Vertical Flux

<table>
<thead>
<tr>
<th>Station Number</th>
<th>Primary Productivity, g C m\textsuperscript{-2} d\textsuperscript{-1}</th>
<th>Rate of New Production, g C m\textsuperscript{-2} d\textsuperscript{-1}</th>
<th>f Ratio</th>
<th>POC\textsubscript{122}, g C m\textsuperscript{-2}</th>
<th>POC\textsubscript{150}, g C m\textsuperscript{-2}</th>
<th>POC Flux at 150 m, mg C m\textsuperscript{-2} d\textsuperscript{-1}</th>
<th>Daily Productivity Removal, %</th>
<th>Daily Standing Stock Removal, %</th>
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</thead>
<tbody>
<tr>
<td>94-1*</td>
<td>0.94</td>
<td>0.84</td>
<td>0.89</td>
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<td>11.7</td>
<td>167</td>
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ND is no data.

*Data were collected at the time of trap retrieval.
and often represented a large proportion of the phytoplankton carbon. Mean-integrated POC concentrations through the euphotic zone and 150 m averaged 10.7 and 31.9 g C m⁻², respectively (Table 3). The flux through 150 m relative to the euphotic zone standing stock of POC and the daily productivity were quite low, ranging from 0.8 to 1.6% and 4.9 to 18.1%, respectively, again similar to the results in 1994.

4. Discussion

Although these data were obtained during cruises from 2 consecutive years, we have emphasized the temporal progression of the phytoplankton bloom and the relationship of vertical flux to conditions in the surface layer. Arrigo et al. [1998] have found that ice concentrations, winds, and air temperatures interact to create interannual variability in the timing of the bloom’s onset and maximum in the Ross Sea. However, they concluded that the peak biomass (as determined by coastal zone color scanner (CZCS) images) varied by no more than 3 weeks. The maximum biomass we found in the 1994 cruise occurred during the second week of December, and in 1995/1996 the maximum biomass observed was in the third week of December. In 1979 (based on CZCS images) the maximum biomass occurred during the second week of December [Arrigo and McClain, 1994]. On the basis of all available satellite and observational data, we believe the bloom in the southern Ross Sea to be relatively predictable in terms of both onset and duration (+2 weeks). It is recognized that each bloom is unique; however, we suggest that our results reflect the processes of the seasonal progression of the bloom in the Ross Sea. We further suggest that the relationships found between surface layer processes and vertical flux are characteristic of this seasonal bloom during other years.

4.1. Accuracy of Sediment Trap Collections

As with any investigation involving sediment traps, it is important to evaluate the potential hydrodynamic biases. With any trap, errors will be minimal in low flow regimes and nonexistent in still waters. Therefore the main criterion to meet in order to insure accurate performance is the water flow relative to the trap opening and the degree to which the traps are affected by wave-induced vertical oscillations. Our results (the low flow relative to the array, the lack of vertical motion or array tilt, and the direct observations of the array by the ROV) all indicate that the hydrodynamic bias was minimal during most of our deployments. We therefore believe that (with the exception of deployment 94-3) the material collected represents an accurate quantitative estimate of the vertical flux of particles, as predicted by investigations of hydrodynamic bias on similar traps [Butman, 1986; Gardner, 1980; Gust et al., 1992, 1994].

Another potential source of error in trap sample is the introduction of “swimmers” (mesozooplankton that are collected by the trap through vertical migration or other natural behavior [Karl and Knauer, 1989]). This problem...
is particularly acute in cases where precharge solutions include poisons, where the flow is sufficient to create eddies within the trap interior that bring zooplankton into contact with the poison, and when deployment times are long. The swimmer problem will be reduced if the abundance of zooplankton is low and the relative flow and number of associated eddies are low. We feel that the impact of migratory organisms in our samples was minor because the flow was sufficiently low to have induced eddies only within the upper reaches of the trap and not to its bottom, where the poison was placed, and we observed very few zooplankton in the water column or trap samples. Hence we concluded that swimmers were not a significant bias in our estimates of vertical flux.

In contrast to mesozooplankton, microzooplankton were common and in a few cases represented a substantial percentage of the mass in the sample (M. M. Gowing, personal communication, 1998). Caron et al. [1982] have reported that these organisms are often closely associated with marine snow aggregates and, in fact, may be specialized to exist and feed only on these large collections of organic debris. If this is the case, their presence in the trap sample is expected as they remain attached to the sinking particles and are carried to the sea floor.

4.2. Spatial and Temporal Patterns in Flux

Vertical flux increased through time, with the 1994 rates averaging 440 mg m\(^{-2}\) d\(^{-1}\) at 150 m and the 1995/1996 rates averaging 840 mg m\(^{-2}\) d\(^{-1}\) at the same depth. There was little variation within 1994, even when all deployments are considered. In 1995 there was greater variability, and some of it appears to be related to the nature of the phytoplankton assemblage. That is, the two deployments with the highest mass fluxes at 150 m (1520 mg m\(^{-2}\) d\(^{-1}\) at 95-3 and 1120 mg m\(^{-2}\) d\(^{-1}\) at 95-5) were situated in the western portion of the Ross Sea. This portion of the Ross Sea is characterized by high silica accumulation rates [DeMaster et al., 1996], a surface diatom assemblage that often reaches extreme concentrations of biogenic opal [Nelson and Smith, 1986; Smith et al., 1996], and large fecal pellet generation rates [Dunbar et al., 1998]. Furthermore, microzooplankton grazing rates in this region have been hypothesized to be high based on pheopigment distributions [DiTullio and Smith, 1996]. Although we do not have direct evidence for significant export by fecal pellets in the western portion of the Ross Sea, such a result would not be unexpected.

The other three sites sampled in 1995/1996, located in the central Ross Sea where *Phaeocystis antarctica* is dominant, had a mean mass flux at 150 m of 524 mg m\(^{-2}\) d\(^{-1}\). This flux was much closer to that measured in 1994, when all sites were dominated by this species. Also, it is similar to the flux found in a floating sediment trap deployed in late January at 50 m (545 mg m\(^{-2}\) d\(^{-1}\) (R. Dunbar, unpublished data, 1992) deployed in an area of *P. antarctica* dominance. The material collected in our traps was largely aggregates and colonies of *P. antarctica*, and there was little evidence for significant fecal pellet generation and flux. A similar conclusion was reached by Dunbar et al. [1998], although they did find a larger contribution of fecal material in their long-term deployments than we did. *Phaeocystis* generally is thought to be avoided by mesozooplankton, particularly its colonial form [Verity and Smyda, 1989; Bautista et al., 1992], although in some sites, active grazing has been demonstrated [e.g., Bathmann et al., 1991] and hence the generation of large, rapidly sinking fecal pellets within *Phaeocystis* blooms is unlikely. Microzooplankton grazing has been observed, but its contribution to vertical flux is probably small both because the activity was low and because the pellets produced are small and sink slowly. Indeed, microzooplankton grazing may reduce vertical flux by disrupting larger colonies and aggregates and creating smaller particles, which then sink more slowly. On the basis of the activity during our study, we believe that grazing by this group probably did not influence vertical flux markedly.

4.3. Coupling of Productivity With Rate of Export

It is clear that the fluxes measured by the traps are related to primary production (since there is no other source of organic carbon in the region), but the temporal relationship between surface production, surface biomass, and vertical flux is uncertain. Production at the trap deployment sites in 1994 averaged 1.36 g C m\(^{-2}\) d\(^{-1}\), and in 1995/1996 the average was 1.26 g C m\(^{-2}\) d\(^{-1}\). However, the productivity values measured at the stations where sediment traps were deployed are not necessarily reflective of the productivity of the entire southern Ross Sea. For example, Smith and Gordon [1997] reported the mean productivity along the 76°30'S transect in mid-November to be 0.52 g C m\(^{-2}\) d\(^{-1}\), and by December 2 it had increased to 3.13 g C m\(^{-2}\) d\(^{-1}\). Similarly, the mean productivity along 76°30'S in mid-January was 0.70 g C m\(^{-2}\) d\(^{-1}\) (W. O. Smith et al., unpublished data, 1996). Wassmann [1998] discussed the factors which exert control over the timing and efficiency of particle export in pelagic systems and concluded that both are controlled in part by the structure of the grazing community. A compilation of our mean productivity, particulate matter standing stocks, and flux data from these 2 years (Figure 6) supports this model. These results suggest that the temporal variations in productivity in the Ross Sea are substantial, with a distinct maximum and rapid changes, but the changes in biomass and flux rates do not appear to be as abrupt. Furthermore, increased productivity (as in 1994) is not necessarily reflected in a rapid increase in flux from the surface layer. The early (growth) phase of the bloom appears to be dominated by active phytoplankton growth and accumulation in the surface layer with relatively little flux of particulate matter to depth (Figure 6) and little dissolved organic carbon (DOC) release and accumulation [Carlson et al., 1998]. Conversely, the relatively increased fluxes observed in 1995/1996 occurred during periods of reduced productivity, and the diminished production is not adequately represented by the productivity data from the five trap stations.

Few data on short-term particle fluxes are available from the Ross Sea. Dunbar et al. [1998] reported that organic carbon flux as determined from time series sediment trap
deployments ranged from 0 to 160 mg C m$^{-2}$ d$^{-1}$ in the central Ross Sea. Smith and Dunbar [1998] found that organic carbon flux during mid- and late January ranged from 1.8 to 92.7 mg C m$^{-2}$ d$^{-1}$ (corresponding to a mass flux range of 16 to 545 mg m$^{-2}$ d$^{-1}$) as measured by floating sediment traps. Flux rates from the western Ross Sea were within this range as well. Our average flux rates in 1995/1996 were substantially greater than any previously found, and we suggest that this was due to the collection of particles just below the euphotic zone (and not at the bottom of the water column, which collects material that is resistant to degradation and sinks extremely rapidly) as well as the timing of the trap deployments, which was close to the period of biomass and productivity maxima. Other areas of the ocean demonstrate a close temporal coupling of vertical flux with surface production [e.g., Asper et al., 1992b], and although the mechanisms may differ within systems, the coupling in the Ross Sea also exists, albeit with a short time lag.

New production during the spring-summer bloom period can be approximated from either nitrate removal during periods of strong stratification or from crude integrations of particulate pools and rates of production [Smith and Gordon, 1997]. During just the period over which flux was measured (approximately 60 days, from mid-November through mid-January), new production was approximately 50 g C m$^{-2}$. Standing stocks of particulate organic carbon were approximately 8.5 g C m$^{-2}$, and flux from this layer was approximately 7 g C m$^{-2}$. Dissolved organic carbon concentrations increased slightly (1.4 g C m$^{-2}$) [Carlson et al., 1998]; therefore a substantial amount of the production cannot be accounted for in the budget. We suggest that this material was remineralized by the active bacterial population in the water column. This suggestion is supported by the exponential decrease of organic matter found in traps placed from 50 to 200 m. Material could have been laterally advected, but satellite images of pigments suggest that the region is one of uniform, high biomass [Arrigo and McClain, 1994]. Furthermore, our current velocities did not suggest large transports of water during the December-January period, and in fact, the flows were quite low. Although we cannot completely discount advective losses, we feel that they were minor loss terms in the carbon budget, particularly during the latter portion of the study. If this is true, then the substantial losses of carbon must be a result of heterotrophic regeneration of particulate organic carbon within the water column, which in turn has broad implications for the lability of the organic
matter and the structure of pelagic-benthic coupling processes.

It is possible by using a crude one-dimensional carbon budget to assess the relative roles of export and regeneration using the data we have collected. Means of all station data where traps were deployed are used in this analysis, and because DOC increases were minor [Carlson et al., 1998], no DOC accumulations are included in this estimate. The surface 150 m can be divided into two regions, the euphotic zone and from the base of the euphotic zone through 150 m. In the spring study the mean euphotic zone POC concentration was 6.58 g C m$^{-2}$ (Table 3), whereas the POC from the base of the euphotic zone to 150 m was 5.23 g C m$^{-2}$. Similarly, for the summer the means were 10.7 and 21.2 g C m$^{-2}$. New production (mean of 1994 data = 0.94 g C m$^{-2}$ d$^{-1}$; see Table 3) and a time period of 60 days were used to estimate a euphotic zone production of 56.4 g C m$^{-2}$. Given that vertical flux equaled 7.2 g C m$^{-2}$, approximately 29.2 g C m$^{-2}$ of the carbon is "missing" between the two periods (sum of POC from surface to 150 m in first period, 11.8 g C m$^{-2}$ plus production, minus sum of POC from 0 - 150 m and vertical flux). This material must have been regenerated within the water column prior to vertical flux and is approximately 50% of the total production. Such a regeneration rate clearly represents a significant carbon removal term.

We cannot differentiate among the possible mechanisms of regeneration (microzooplankton grazing, mesozooplankton grazing, bacterial degradation). Carlson et al. [1998] measured the bacterial production at the same time (4.3 mmol C m$^{-2}$ d$^{-1}$, equivalent to 20.6 g C m$^{-2}$) if growth efficiency is 15%, which is near that estimated using in situ DOC (H. C. Ducklow et al., Bacterial growth in experimental plankton assemblages and seawater cultures from the Phaeocystis antarctica bloom in the Ross Sea, Antarctica, submitted to Aquatic Microbial Ecology, 1998). As such, we believe that most of the heterotrophic remineralization to be bacterial. Furthermore, ammonium concentrations that bacteria were the largest contributors to this process. If nitrogen were released in a 6.6 ratio to carbon, then less than 0.4 $\mu$M would accumulate in the zone between the euphotic zone and 150 m. Given that NH$_4$ concentrations of greater than 3.0 $\mu$M are often observed in summer [Smith, 1991] over depth ranges of 50 m and more, such a regeneration rate is certainly feasible.

The material that is present in the subeuphotic depths at the end of the summer is still available for export through 150 m, meaning that material that had been produced during this period was not represented in the sediment trap collections. This delay between production and flux [Smith and Dunbar, 1998] appears to be a consistent feature of the Ross Sea. As such, it is important to consider the fluxes we report as instantaneous measurements rather than integrated estimates of flux, and care must be taken when estimating seasonal export from the euphotic zone.

In addition to the seasonal pattern in particle export, distinct differences in flux were characteristic of the different regions within the Ross Sea. The central polynya area is dominated by blooms of the haptophyte Phaeocystis antarctica [Smith and Gordon, 1997]. This alga passes through several life stages, beginning with a motile cell which develops into large (> 1 mm) colonies. Associated with these aggregations of cells is a sticky mucoid sheath that is optically clear and highly viscous. Some investigators have proposed that colonies undergo senescence, coalesce, and settle from the euphotic zone, where individual cells exit from colonies/aggregates in the form of motile cells or where aggregates are degraded by bacterial and protozoan activity [Wassmann, 1994]. Sinking speed measurements of aggregates during this study ranged from 4 to >>200 m d$^{-1}$ and suggest that these aggregates provide a significant contribution to vertical export [Asper et al., 1997]. In addition, aggregated abundance is extremely high relative to other areas of the ocean [Asper et al., 1997]. It is unclear why the Ross Sea has higher aggregate abundances; furthermore, it is not clear why material derived from Phaeocystis colonies form aggregates, as laboratory studies using a different species suggest that stickiness of Phaeocystis colonies is in fact lower than diatoms [Passow and Wassmann, 1994]. We can only conclude that laboratory derived stickiness estimates are either inappropriate for extrapolation to the Ross Sea, or that P. antarctica has markedly different intrinsic characteristics than other members of the genus. The substantial range in the settling velocities, however, suggests that this contribution may not be predictable from either the abundance of aggregates in the water or from the total POC present.

Grazing on Phaeocystis colonies is a complex function of physiological activity, microbial colonization and size, but it is generally believed that when colonies are present, grazing and fecal pellet formation contribute little to vertical flux [Bautista et al., 1992], especially in the Ross Sea [Dunbar et al., 1998]. Both fecal pellet production and aggregate formation result in the production of particles with sinking rates from 6 to > 400 m d$^{-1}$ [Dunbar et al., 1998; Smith and Dunbar, 1998], and hence exported material will likely be rich in organic matter that is relatively undegraded and a high quality substrate for heterotrophic organisms.

In summary, our results are consistent with the hypothesis that flux of material from the euphotic zone is coupled with biomass and production in the surface layer. Flux is low during the early phases of the phytoplankton bloom in the Ross Sea, but as the bloom's biomass reaches its maximum and growth begins to decrease, large aggregates are formed which in turn exhibit increased sinking rates and settle from the euphotic zone. The aggregation process appears to be intimately linked with the bloom and demise of Phaeocystis in the Ross Sea and appears to be modified by cellular and colonial abundance, particle stickiness, and in situ turbulence [Wassmann, 1994]. Much of the material is remineralized in the upper 150 m by bacterial activity. As with any high-latitude region, the flux of biogenic material is highly episodic and this in turn greatly influences food web structure, water
column remineralization, benthic faunal strategies, and regional biogeochemical patterns. Understanding the quantitative relationship between surface processes and vertical flux within a seasonal cycle on all timescales will likely greatly elucidate the carbon dynamics of continental shelf regions throughout the Antarctic.

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