

9-1-2000

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## A balanced nitrogen budget of the surface layer of the southern Ross Sea, Antarctica

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**Abstract.** To understand marine biogeochemical cycles, it is critical to quantitatively balance organic matter transformations within the euphotic zone. Such an assessment for nitrogen is difficult because of lateral advection, uncertainties in individual measurements, the complexity of elemental transformations (including nitrification and denitrification), and the difficulty of collecting data on appropriate space and time scales. Two cruises were conducted to the southern Ross Sea, Antarctica, to understand the time-varying fluxes of nitrogen into its various pools. From these data a balanced inventory was constructed. Nitrate removal in the upper 200 m was balanced by particulate and dissolved organic nitrogen production, ammonification, and vertical flux. In austral spring nearly all (92%) of the new production remained as particulate nitrogen, but this percentage decreased markedly (52%) by mid-summer, when nitrogen regeneration, PN flux, and DON production were 23, 13 and 12% of net production, respectively. The organic matter budget in this coastal Antarctic site is dominated by particle transformations.

### 1. Introduction

The Ross Sea is one of the most productive regions in the entire Antarctic, with production approaching 200 g C m<sup>-2</sup> for the growing season (from late October through early March; Smith and Gordon, 1997; Arrigo et al., 1998). Indeed, the seasonality of the production cycle is a major feature of Antarctic waters [Nelson et al., 1996]. Although the onset of rapid growth in spring is somewhat variable (Arrigo et al., 1998), the patterns of biomass distribution and production are relatively invariant. Large deposits of diatomaceous oozes occur in the sediments [DeMaster et al., 1996], and seasonal and annual vertical flux rates are substantial [Dunbar et al., 1998]. The southern Ross Sea is dominated by two taxa: diatoms and the haptophyte *Phaeocystis antarctica* [Arrigo et al., 1999]. The spatial distribution of the two groups is largely distinct, but each has markedly different impacts on local biogeochemistry and nitrogen transformations. Two cruises were conducted to the

southern Ross Sea in 1994 and 1995/96 in order to understand the conversions of organic matter within the surface layer. Such transformations are strongly influenced by phytoplankton removal of nitrate and production of particulate and dissolved organic nitrogen (PN and DON, respectively), as well as by heterotrophic (bacterial and planktonic) use of this material and subsequent release of inorganic (as ammonium) nitrogen and DON. Phytoplankton production often is temporally uncoupled from heterotrophic utilization in polar systems (e.g., Smith and Sakshaug, 1990), and so any analysis of the various transformations must sample over the appropriate time scales and include periods of positive growth, relatively rapid nitrogen removal, and active remineralization.

Because processes such as nitrification and denitrification are quantitatively negligible during summer in waters of the Southern Ocean [Karl et al., 1996], nitrogen budgets are simplified relative to other oceanic regimes. The changes in the various pools of nitrogen (NO<sub>3</sub><sup>-</sup>, NO<sub>2</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>, DON, PN and F<sub>PN</sub>, the vertical flux of PN) can be related by the following:

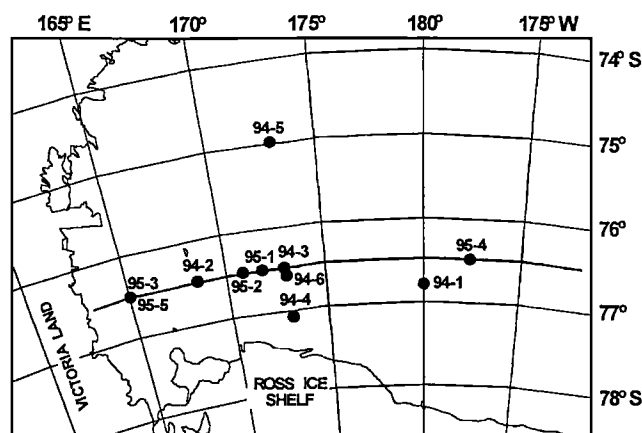
$$\Delta \text{NO}_3^- = \Delta \text{PN} + \Delta \text{NO}_2^- + \Delta \text{NH}_4^+ + \Delta \text{DON} + F_{\text{PN}} \quad (1)$$

Because growth in austral spring begins from winter conditions [Smith and Gordon, 1997] and these conditions are quantitatively similar to deep-water values (due to winter convective overturn), it is possible to accurately identify the initial, pre-growth concentrations of each pool. Nitrite concentrations were exceedingly small under all circumstances (mean = 0.037 ± 0.025 μM; n = 1407) and were not included in this analysis. A series of stations was sampled repeatedly (from 13 - 22 stations, depending on ice concentrations) along 76°30'S (between 167°E and 176°W; Fig. 1), and the pools of nitrogen quantified (Table 1). The sampling spanned two seasons, and the data represent a seasonal composite. Although interannual variability could obscure the seasonal pattern, interannual variations appear to be small relative to those imposed by seasonal growth (Smith et al., 2000). This likely results because phytoplankton growth is limited by irradiance in spring, which in turn is largely a function of ice concentration (Arrigo et al., 1998).

Initial nitrate and PN concentrations were taken as being equal to the mean [NO<sub>3</sub><sup>-</sup>] and [PN] at 150 m from 15 stations sampled in early spring. Nitrate concentrations at 150 m during this first transect varied by ±1.2%, which is a measure of the error associated with the integrated nitrate pools (and hence new

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Paper number 1999GL011034.  
0094-8276/00/1999GL011034\$05.00



**Figure 1.** Region where nitrogen pool data and fluxes in the Ross Sea were collected. Solid circles (●) indicate the location of the deployment of floating sediment traps (Asper and Smith, 1999).

production estimates). Pre-bloom ammonium concentrations were negligible, and vertical flux rates were assumed to be zero. Vertical flux rates were determined from drifting sediment traps deployed for short periods (days) at 200 m during the same periods that the N pools were assessed [Asper and Smith, 1999]. Phytoplankton nitrate removal through 150 m at each station was computed by integrating nitrate concentrations from 12 depths between the surface and 150 m, and subtracting those from the pre-bloom integrated concentration. Because the vertical gradients in all variables were small and consistent between 100 m and 500 m, the distributions were extrapolated to 200 m using the values observed at 150 m. Concentrations of all variables were integrated both from 0 - 150 m as well as from 0 - 200 m. PN stocks were integrated by the same procedure except that PN concentrations were used from the same 12 depths.

## 2. Results and Discussion

Phytoplankton nitrate uptake increased rapidly as the spring bloom developed and continued to increase through early January (Fig. 2). Particulate nitrogen accumulation also increased in parallel with  $\text{NO}_3^-$  removal in early spring, but PN concentrations began to decline in mid-December (Fig. 2). Nearly all (> 90%) of the nitrate removed was converted to

particulate nitrogen during austral spring, but this percentage steadily decreased as the bloom progressed (Fig. 3). The early (mid-bloom) decline in PN suggests that either losses from the upper 150 m via vertical flux or remineralization of organic N had become substantial. However, the vertical flux at 200 m was not observed to increase, and ammonium (the end product of oxidative consumption of organic nitrogen) concentrations rose sharply (Table 1). Hence, heterotrophic remineralization of particles was the likely cause for the decrease in integrated PN concentrations.

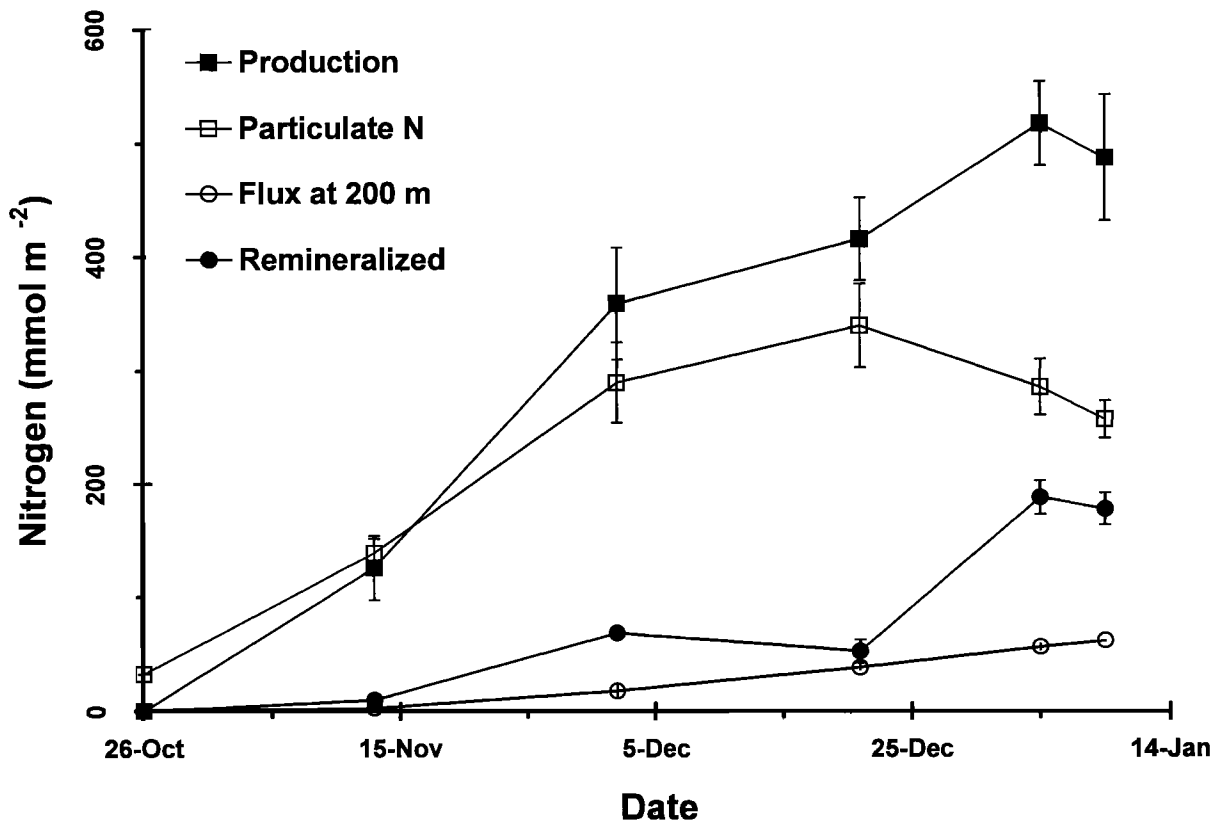
Equation 1 can be solved directly for the change in DON concentrations using the measured fluxes. When the initial (pre-bloom) and mid-January data are used, DON production in the upper 200 m is  $67.3 \text{ mmol m}^{-2}$ . If this increase were confined to the upper 100 m, this would correspond to a net DON increase of  $0.67 \text{ } \mu\text{M}$  over 75 days, or an increase of  $< 0.01 \text{ } \mu\text{mol l}^{-1} \text{ d}^{-1}$ . Such DON production rates, while being net rates and not directly comparable to short-term,  $^{15}\text{N}$ - isotopic estimates, are modest and similar to those derived by isotopic studies [Bronk et al., 1994]. It strongly suggests that the role of DON production in the nitrogen budget of the Ross Sea is minor. This conclusion is also supported by the net changes in dissolved organic carbon concentrations [Carlson et al., 1998]. Integrated DOC levels increased by  $220 \text{ mmol m}^{-2}$  over the same period (from 6,490 to 6,750  $\text{mmol m}^{-2}$ ), and if the DOM had a C:N molar ratio of 6.6, this increase would represent a DON increase of  $0.33 \text{ } \mu\text{M}$  in the upper 100 m, which is similar to that found by our analysis. Thus DON (or at least that portion which can be considered semi-labile; Carlson and Ducklow, 1992) represents a small pool of nitrogen in Antarctic waters.

The one-dimensional nitrogen inventory was remarkably consistent, especially in comparison to other areas of the ocean, where such analyses are poorly constrained [Quay, 1996; Emerson et al., 1997]. For example, in the equatorial Pacific production estimates have fairly large uncertainties [Bender et al., 1999], and estimates of fluxes from the surface layer using different techniques also have yielded orders of magnitude variations [Murray et al., 1996; Bacon et al., 1996]. Similarly, the variations in nutrient supply rates from depth are difficult to measure in oligotrophic (low nutrient) regions (such as the US JGOFS time series sites off Hawaii and Bermuda), and hence a quantitative balance between production, regeneration and flux has been impossible to obtain [Ducklow et al., 1995]. Because waters of the Southern Ocean are exceptionally seasonal in their production cycle and production is initiated from the same baseline each year, seasonal growth estimates can be more easily derived [Karl et al., 1991]. Similarly, transformations

**Table 1.** The concentrations of nitrogen pools along  $76^{\circ}30'\text{S}$  at various times of the growing season. All concentrations and vertical fluxes ( $F$ ) integrated and measured through 200 m. The time interval represents the mean sampling date within each transect.  $\Delta\text{NO}_3^-$  is calculated from Year Day 300, and flux data were collected within each transect. N = number of stations in each transect.

Year Day	N	$[\text{NO}_3^-]$ ( $\text{mmol m}^{-2}$ )	$\Delta\text{NO}_3^-$ ( $\text{mmol m}^{-2}$ )	$[\text{NH}_4^+]$ ( $\text{mmol m}^{-2}$ )	[PN] ( $\text{mmol m}^{-2}$ )	$F_{200 \text{ m}}$ ( $\text{mmol m}^{-2} \text{ d}^{-1}$ )
300	-	4687	0	0*	32.1	0*
318	14	4562	126	9.2	139	0.146
337	15	4328	359	24.6	290	0.779
356	24	4271	416	55.9	340	1.08
370	15	4169	518	86.8	286	1.29
375	22	4200	487	92.8	257	1.14

\*: Assumed value

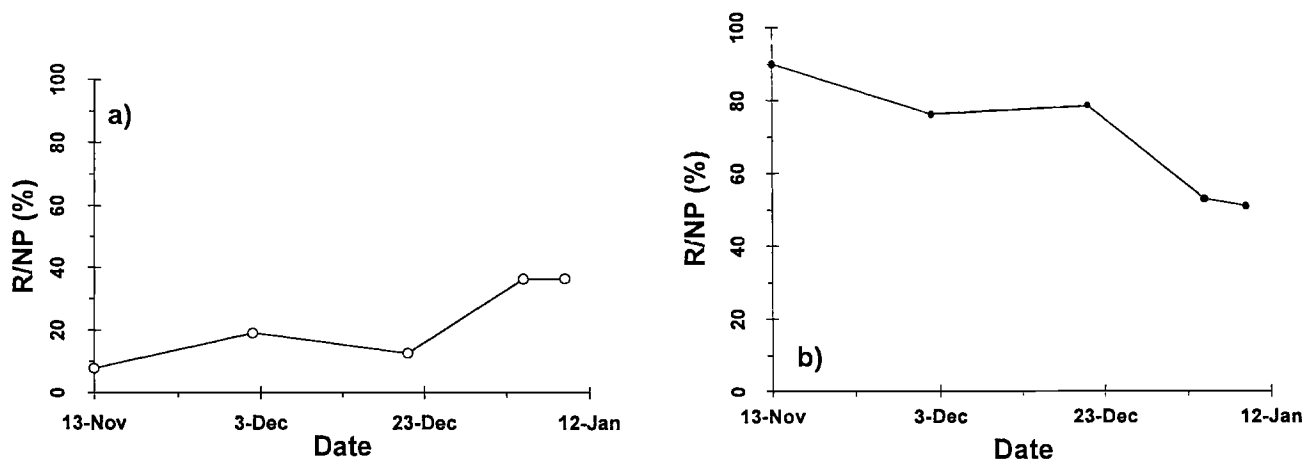


**Figure 2.** The temporal changes in various pools of nitrogen (and their standard errors) within the upper 200 m of the Ross Sea. Production calculated from nitrate disappearance (relative to pre-bloom conditions), and remineralization estimated by the increase in  $\text{NH}_4$  concentrations. Flux data represent the cumulative PN determined from drifting sediment traps<sup>12</sup>.

within the surface layer can be determined if all N pools are assessed. Our results constrain the flux estimates and give us confidence that the flux at 200 m was reliably measured. Similarly, the build-up of ammonium is similar to the estimated remineralization rates, which again give us confidence that the one-dimensional approach is producing reliable insights into the nitrogen transformation rates in the surface layer of the Ross Sea.

It has been argued that in some areas of the ocean respiration exceeds photosynthesis [del Giorgio et al., 1997], but Williams

[1998] argued that the upper 100 m of the ocean are largely in balance with regard to photosynthesis and respiration. The mean respiration rate as a percentage of gross production from the Southern Ocean (based on oxygen profiles largely collected during austral summer; Williams, 1998) was 39%. Our data, while being derived in an entirely different manner, suggest that in mid-summer there is a quantitatively similar relationship between nitrogen remineralization and new production, with strong temporal control on regeneration (Fig. 3). Early in the



**Figure 3.** The temporal variations of a) the percentage of material remineralized relative to new production (NP), and b) the percentage of nitrogen which is contained in the particulate nitrogen pool.

bloom respiration accounts for only a small (ca. 7%) percentage of new production (or nitrate removal), whereas during the austral summer the percentage increases to nearly 37% (quite similar to oxygen based estimates for the Southern Ocean). The early season values likely reflect the temporal uncoupling of autotrophic production and heterotrophic consumption (by bacteria and/or herbivores).

The Ross Sea is known to have spatially restricted phytoplankton distribution [Arrigo et al., 1999], with diatoms dominating the western region and the haptophyte *Phaeocystis antarctica* dominating in the central region. No evidence was found that the nitrogen inventories were quantitatively influenced by species composition, despite the fact that regions dominated by either diatoms or *P. antarctica* may have different rates of production and vertical flux [Smith and Dunbar, 1998]. It is likely that by using means for the entire transect and completing the analysis over seasonal time scales that these species effects became quantitatively less important. The presence of mesoscale eddies also was not detected, which would increase the nitrate concentrations within a transect and alter the distribution of biomass [McGillicuddy et al., 1998]. We conclude that either the frequency or intensity of such eddies in the Ross Sea during this study was small, or that our sampling pattern was too coarse to include their effects.

Our analysis shows that in coastal Antarctic waters an internally consistent N budget can be derived. The nitrogen budget for the southern Ross Sea shows that it is highly productive, that most of the production is partitioned into particles, and that community respiration of organic matter increases through the season and is decoupled from new production during austral spring. The inventory also confirms that drifting sediment traps can accurately determine particulate flux from the surface layer under some circumstances, and that these fluxes were quantitatively similar to DON production during this period. Such elemental analyses should be of great use when extended to other polar regions that undergo seasonal progressions of nitrogen transformations, and should help in the elucidation of the temporal evolution of the various organic pools within the water column.

**Acknowledgments.** We thank L.I. Gordon for nutrient analyses and the Captain and crew of the *R.V.I.B. Nathaniel B. Palmer* for their assistance at sea. This work was supported by NSF grants OPP-9317587 to WOS and OPP-9317598 to VLA.

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(Received September 20, 1999; revised February 20, 2000; accepted July 16, 2000.)