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Regional variation of spring N-uptake and new production in the Southern Ocean

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[1] Nitrate, ammonium and urea uptake were examined in the Southern Ocean (Australian sector) during the 2001 austral spring. On the basis of N-uptake conditions, three regions were distinguished: (1) the Sub-Antarctic Zone and the Sub-Antarctic Front, (2) the Polar and Inter-Polar Frontal Zones, and (3) the Antarctic Zone-South and the Seasonal Ice Zone. N-uptake was highest in region 3 and dominated by new production. Region 1 had the lowest N-uptake, and switched from regenerated to new production between two visits approximately 1 month apart. Region 2 displayed intermediate N-uptake and the lowest new production. This contrasts with previous study at 170°W where new production was high around the Polar Front and indicates that this area is not highly productive nor particle-exporting at all longitudes. Overall, N-uptake and new production were low all along the latitudinal transect compared to other areas of the Southern Ocean under spring conditions. *INDEX TERMS:* 4805 Oceanography: Biological and Chemical: Biogeochemical cycles (1615); 1615 Global Change: Biogeochemical processes (4805); 4207 Oceanography: General: Arctic and Antarctic oceanography; 4855 Oceanography: Biological and Chemical: Plankton; *KEYWORDS:* N-uptake, *f*-ratio, new production, Southern Ocean. **Citation:** Savoye, N., F. Dehairs, M. Elskens, D. Cardinal, E. E. Kopczyńska, T. W. Trull, S. Wright, W. Baeyens, and F. B. Griffiths (2004), Regional variation of spring N-uptake and new production in the Southern Ocean, *Geophys. Res. Lett.*, *31*, L03301, doi:10.1029/2003GL018946.

1. Introduction

[2] The Southern Ocean plays a key role in the global climate acting as a net sink for atmospheric CO_2. Especially the area south of 50°S accounts for *ca* 20% of the global ocean CO_2 uptake due to temperature and biological effects, the latter generally dominating [*Takahashi et al.*, 2002]. However, the validity of current estimates of phytoplankton production in the surface ocean based on remote sensing and of export to the deep ocean remains in debate. In the Southern Ocean, this may be due to the presence of sub-surface chlorophyll maxima—not detected by remote sensing [*Schlitzer*, 2002]—and/or to chlorophyll *a* algorithms which cannot be extrapolated there [*Reynolds et al.*, 2001].

[3] In this context, the study of nitrogen cycling in the surface ocean provides helpful information to better understand the primary production and its export flux. Indeed, the determination of nitrogen uptake enables the separation of new from regenerated production—i.e., of primary production sustained by nitrate and N_2 from that sustained by regenerated N-nutrients [*Dugdale and Goering*, 1967]—and the estimation of "export" production via the use of *f*-ratio [*Eppley and Peterson*, 1979]. Although the concept of new production as a proxy of export production has been questioned and revised [*Bronk et al.*, 1994], new production and *f*-ratio remain useful tools to characterize ecosystem functioning. Yet, new production should be considered as "exportable production" rather than "export production" [e.g., *Sambrotto and Mace*, 2000].

[4] The present paper reports nitrate, ammonium and urea uptake rates and new production estimates for surface waters of the Southern Ocean during the austral spring 2001. Latitudinal (49°S to 65°S) and temporal (one to four weeks) variability leads to identifying three separate functional regions. The transect at 140–144°E is then compared to other areas of the Southern Ocean.

2. Experimental and Analyses

[5] Nitrate, ammonium and urea uptake rates as well as new production were studied during the CLIVAR SR3 cruise (October 30–December 14, 2001; 140–144°E) from 48.8 to 64.9°S (Figure 1). Seven stations were visited when cruising southward; stations at 63.9°, 60.9° and 51.0°S were re-visited during the return transect after a delay of 11, 17 and 31 days, respectively. Seawater was sampled using Niskin bottles at four depths from 5 down to 70 or 100 m.

[6] Uptake rates were estimated from incubations using ^{15}N and ^{13}C as tracers. Three 1 L-aliquots of seawater were poured in polycarbonate bottles. Each aliquot was spiked with 0.1, 0.05 or 0.05 μM of ^{15}N-labeled nitrate, ammonium or urea, respectively, along with 10 or 20 μM of ^{13}C-labeled HCO_3^-. Bottles were placed for 12 h in a cabinet where temperature was set at the surface mixed layer temperature and saturating irradiance ($7\ 10^{15}$ quanta $cm^{-2}\ s^{-1}$) of cool white light was supplied by fluorescence tubes. Samples from 5 m and 10 m depths received 100% of this flux; seawater from 25 m (or 30 m), 50 m, and 70 m (or deeper) received 70%, 45% and 15% of it, respectively, by using appropriate neutral density screens. After incubation, the seawater was filtered on a pre-combusted glass fiber filter. For each incubation, aliquots were taken to measure initial and final ammonium, nitrate or urea concentrations.

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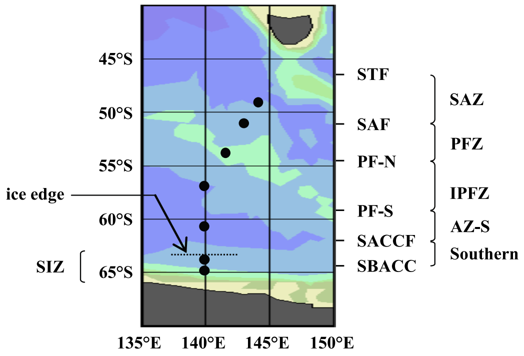

Figure 1. Location of the stations in the study area. STF: Sub-Tropical Front; SAF: Sub-Antarctic Front; PF-N and PF-S: northern and southern branches of the Polar Front, respectively; SACCF: Southern Antarctic Circumpolar Current Front; SBACC; Southern Boundary of the Antarctic Circumpolar Current; SAZ: Sub-Antarctic Zone; PFZ: Polar Front Zone; IPFZ: Inter-Polar Front Zone; AZ-S: southern Antarctic Zone; SIZ: seasonal Ice Zone. See *Trull et al.* [2001a] and references therein for definition of fronts and zones.

[7] Ammonium and urea were analyzed using methods referenced in *Elskens et al.* [2002] and nitrate using methods referenced in *Lourey and Trull* [2001]. Phytoplankton was sampled, preserved, determined and counted as in *Kopczyńska et al.* [2001]. PN and POC concentrations along with their ^{15}N and ^{13}C abundances were analyzed according to *Lorrain et al.* [2003]. Replicate incubations gave relative standard deviation of <2% for ^{15}N and ^{13}C abundances. ^{13}C and ^{15}N uptake rates were calculated according to *Dugdale and Goering* [1967] and *Elskens et al.* [2002], respectively. *f*-ratio and new production were calculated as follows:

$$f-\text{ratio} = \text{nitrate uptake}/\text{N}-\text{uptake} \tag{1}$$

where N-uptake is the sum of nitrate, ammonium and urea uptake rates.

$$\text{New production}\left(\text{mmol C}/\text{m}^2/\text{d}\right) = \text{carbon uptake} \times f-\text{ratio} \tag{2}$$

[8] Hourly uptake rates and new production were converted into daily flux by multiplying them by the day length (from 14.5 to 24 hours). Fronts and zones of the Southern Ocean and their acronyms are indicated on Figure 1.

3. Results

[9] The physical and nutrient conditions encountered during the cruise were rather typical of the area and season [*Trull et al.*, 2001a]. Sea surface temperature decreased southward from 9.5°C to −1.4°C whereas surface nitrate concentration increased from 11 μM to 30 μM (see auxiliary material[1]). In the upper 70 m—mean depth of the mixed layer—ammonium concentrations ranged between 0.06 and 0.56 μM whereas urea concentrations were below the detection limit (0.1 μM) except in the AZ-S during the second visit (up to 0.15 μM at 25 m).

[10] Nitrate, ammonium, urea and total nitrogen uptake rates, new production, chlorophyll *a* and phytoplankton abundance were integrated over the upper 70 m of the water column (Figure 2). On the southbound transect, nitrate uptake rate increased with latitude (from 1.4 mmol/m^2/d at 48.8°S to 8.8 mmol/m^2/d at 64.9°S) whereas ammonium and urea uptake rates were nearly constant (2.3 ± 0.5 and 0.5 ± 0.1 mmol/m^2/d, respectively) except at 60.9 and 64.9°S where peak values of 1.5 and 2.0 mmol/m^2/d were observed for urea uptake. Thus, the overall N-uptake rate was moderate north of 57°S (4.9 ± 0.7 mmol/m^2/d) and high in the south (9.6 ± 2.2 mmol/m^2/d). Between the two visits nitrate uptake rate decreased in the AZ-S and SIZ (from *ca* 6.1 to *ca* 4.4 mmol/m^2/d) but increased in the SAF (from 2.0 to 3.6 mmol/m^2/d); ammonium uptake rates diminished by *ca* 1.3 mmol/m^2/d; urea uptake rate increased of 0.5 mmol/m^2/d

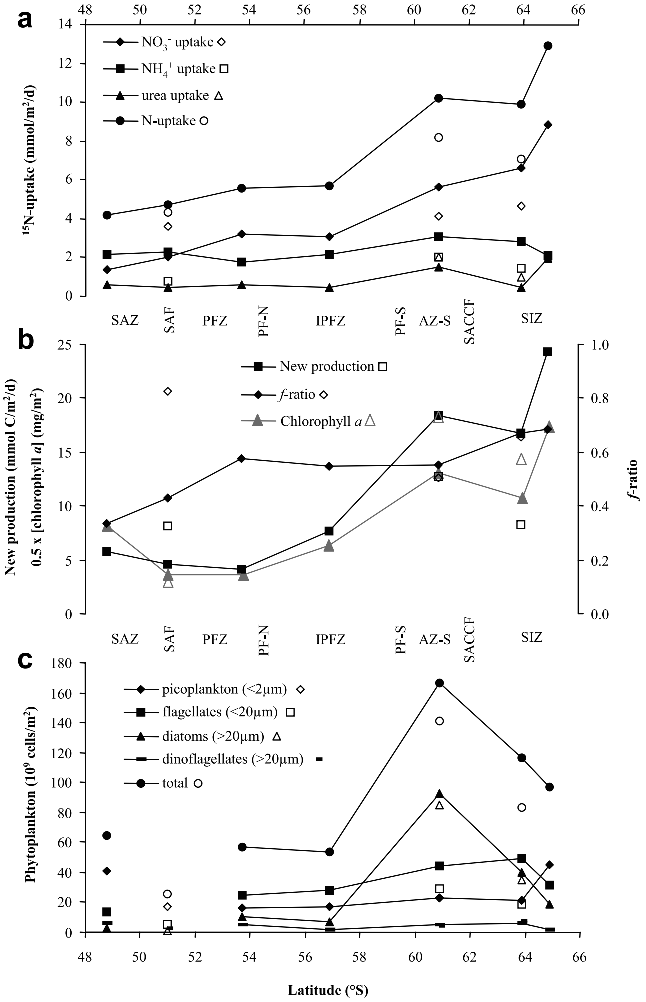

Figure 2. (a) integrated nitrogen, nitrate, ammonium and urea uptake rates; (b) *f*-ratio, integrated chlorophyll *a* and new production; (c) integrated phytoplankton abundance. Closed and open symbols correspond to first and second visits, respectively. SAZ, SAF, PFZ, PF-N, IPFZ, PF-S, AZ-S, SACCF and SIZ: see Figure 1.

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[1] Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2003GL018946.

Table 1. Comparison of Present and Literature Data for the Southern Ocean During Spring (1–7) and for the SR3 Transect During Summer (8)

Area	Longitude	Latitude	N-uptake (mmol/m^2/d)	*f*-ratio	New production (mmol C/m^2/d)	
SAZ, SAF	143–144°E	49–51°S	4.4 ± 0.3	0.53 ± 0.26	6.2 ± 1.8[c]	1
PFZ, IPFZ	140–142°E	54–57°S	5.6 ± 0.1	0.56 ± 0.02	5.9 ± 2.5[c]	1
AZ-S, SIZ	140°E	61–65°S	9.6 ± 2.2	0.61 ± 0.08	16.1 ± 6.0[c]	1
Weddell Sea	37–41°W	58–61°S		0.52 ± 0.09	21.2[c]	2
SWC	47–49°W	57–62°S	3.6 ± 2.7	0.56 ± 0.17		3
Bransfield Strait	59–65°W	62.5–65°S	10.8–33.1	0.31–0.64		4
Bellingshausen Sea	88°W	56.5°S	27	0.10	17.5[d]	5
Bellingshausen Sea	79–86°W	63–69°S	42 ± 10[a]	0.44 ± 0.12[a]	128 ± 65[a,d]	5
Bellingshausen Sea	67–88°W	63–69°S	16 ± 6[b]	0.21 ± 0.10[b]	23 ± 15[b,d]	5
Bellingshausen Sea	85°W	67–68°S	3.3–7.4	0.41–0.86	24–39[c]	6
SAZ, SAF, PFZ	170°W	55–59°S		0.08	16.7[d]	7
IPFZ	170°W	59–61.5°S		0.20–0.25	45.8[d]	7
AZ-S, SIZ	170°W	61.5–65°S		0.21–0.25	49.2[d]	7
SAZ	142°E	47–51°S	4.3 ± 1.3	0.31 ± 0.11	4.1 ± 1.5[c]	8
PFZ, IPFZ	142°E	53–55°S	2.3 ± 1.3	0.37 +0.05	3.3 ± 0.2[c]	8

SAZ, SAF, PFZ, IPFZ, AZ-S, SIZ: see Figure 1; SWC: Scotia-Weddell Confluence. N-uptake rate, *f*-ratio and new production: average ± standard deviation or minimal-maximal values, when available.

[a] bloom conditions. [b] post-bloom conditions. [c] calculated using equation (2). [d] calculated by multiplying the nitrate uptake rate by the C:N Redfield ratio.

1: this study; 2: *Smith and Nelson* [1990]; 3: *Goeyens et al.* [1991]; 4: *Bode et al.* [2002]; 5: *Waldron et al.* [1995]; 6: *Bury et al.* [1995]; 7: *Sambrotto and Mace* [2000]; 8: calculated from *Elskens et al.* [2002].

in the AZ-S and SIZ; N-uptake rate was constant in the SAF but decreased by *ca* 25% in the AZ-S and SIZ.

[11] *f*-ratio increased southward (from 0.33 to 0.69). On the north-bound transect, *f*-ratio slightly decreased in the AZ-S and SIZ, but strongly increased up to 0.82 in the SAF. Since there was no urea experiment during the second visit of SAF, the value of 0.82 was calculated neglecting urea uptake. Using a mean urea uptake of 0.5 mmol/m^2/d (see above), the *f*-ratio would then be of 0.73. New production slightly decreased from SAZ to PFZ (from 5.7 to 4.1 mmol C/m^2/d), then increased southward to reach a maximum of 24.3 mmol C/m^2/d at 64.9°S where sea ice was just melted. Between the first and the second sampling it decreased by 30% in the AZ-S and 50% in the SIZ, but increased by 77% (56% if using the *f*-ratio of 0.73; see above) in the SAF. Chlorophyll *a* ranged between 5.9 and 36.6 mg/m^2 with highest values in the south—where an increase was observed between the two visits.

[12] Phytoplankton abundance varied from 26 × 10^6 to 166 × 10^6 cells/m^2. Picoplankton and flagellates numerically dominated the phytoplankton assemblage from 48.8 to 56.9°S. Diatoms were more abundant in the AZ-S and SIZ and dominant at 60.9°S (both visits) where a bloom have taken place, and at 63.9°S (second visit).

4. Discussion

[13] On the basis of N-uptake conditions and new production, three regions are distinguished:

[14] (1) SAZ and SAF, in the north of the study area (48.8–51.0°S), are characterized by low N-uptake rate (4.4 ± 0.3 mmol/m^2/d), low new production (6.2 ± 1.8 mmol C/m^2/d) and by dominance of small phytoplankton cells (<20 μm) over a time scale of one month. The N-uptake conditions of this region are versatile since there was a shift from a system dominated by regenerated production (*f*-ratio = 0.38 ± 0.05) to a system dominated by new production (*f*-ratio = 0.82) within one month. During the second visit of the SAF, surface water was more influenced by northern water (higher water temperature and salinity). SAZ waters were higher in iron concentration [*Sedwick et al.*, 2002] and perhaps this may explain the observed increase in *f*-ratio [*cf Armstrong*, 1999], although the lack of iron measurements during the second visit preclude a clear examination of this possibility.

[15] (2) PFZ and IPFZ, in the central part of the study area (53.7–56.9°S), are characterized by slightly higher N-uptake rates (5.6 ± 0.1 mmol/m^2/d), low new production (5.9 ± 2.5 mmol C/m^2/d) and dominance of small phytoplankton. N-uptake is slightly dominated by nitrate uptake (*f*-ratio = 0.56 ± 0.01). However, as this area was not re-visitedbecause of bad weather, temporal variability of the production conditions could not be assessed.

[16] (3) AZ-S and SIZ (60.9–64.9°S) are characterized by high *f*-ratio (0.61 ± 0.08). Large phytoplankton (>20 μm) dominated the community. N-uptake and new production are the highest of the transect but appear variable at relatively short time scale since the N-uptake decreased from 11.0 ± 1.7 to 7.6 ± 0.8 mmol/m^2/d and the new production from 19.8 ± 3.9 to 10.5 ± 3.2 mmol C/m^2/d within *ca* two weeks.

[17] The latitudinal pattern of N-uptake conditions during spring fits with the nitrogen regime in nitrate excess (in the North) and silicate excess (in the South) areas as reported by *Goeyens et al.* [1998]: low new production in the North and pulsed system in the South. The latitudinal trend of new production is similar to the ^{234}Th flux results obtained during the same cruise [*Savoye et al.*, 2003] and is in agreement with C fluxes from sediment trap record of the productive period 1997–1998 between SAZ and PFZ [*Trull et al.*, 2001b]. It appears that AZ-S and SIZ constitute the region of highest exportable production and PFZ the region with the lowest one. This is consistent with previous results of *Trull et al.* [2001b] and *Elskens et al.* [2002] along the northern part of the same transect, and of *Sambrotto and Mace* [2000] along 170°W. However, there is a strong contrast between the 140°E [present study] and 170°W [*Sambrotto and Mace*, 2000] lines in the Inter-Polar Frontal Zone. New production at 140°E is low and close to values of northern waters whereas at 170°W it is high and close to values of southern waters. This may be due to the physics:

the Polar Front at 140°E divides into two branches 4–5° apart from each other whereas the Polar Front at 170°W is much narrower (1.5°).

[18] The present N-uptake and new production results are in the lower range of the literature data for spring—as much as one order of magnitude lower than in the Bellingshausen Sea under bloom conditions—and are only slightly higher than summer values reported for the same line (Table 1). Thus the bloom recorded in the AZ-S (Figure 2c) was small compared to other areas and consequently exportable production was low throughout this study.

[19] If excluding an outlier (SAF, second visit, see above), *f*-ratio was strongly correlated to sea surface temperature ($R^2 = 0.83$, $p < 0.01$) and to integrated nitrate concentration ($R^2 = 0.80$, $p < 0.01$). Also temperature and integrated nitrate concentration were strongly correlated ($R^2 = 0.95$, $p < 0.01$; all data). Such a relationship between *f*-ratio and temperature has been previously proposed by *Laws et al.* [2000] on the basis of a simple ecosystem model emphasizing differential responses of autotrophs and heterotrophs to temperature. However there are many other possible reasons for its occurrence, including variations in phytoplankton community responses alone, correlations of mixed layer depths and thus light levels with temperature, etc. Further study of the variation of *f*-ratios is required before a preferred model can be clearly identified.

[20] The present paper brings information on nitrogen uptake rates and exportable production for the Australian sector. It allows further comparison of these data with particulate organic carbon export (estimated from ^{234}Th flux; *N. Savoye et al.*, *K. Buesseler et al.*, manuscripts in preparation, 2004), mineralization of organic carbon in the mesopelagic zone (estimated from particulate Ba [*Cardinal et al.*, Particulate Ba distributions and fluxes suggest latitudinal variations of carbon mineralization in the Southern Ocean, submitted to *Deep-Sea Res. I*]) and fluxes in the deep ocean (estimated from the sediment traps). These different approaches were used during the CLIVAR SR3 cruise to better understand and describe the POC fluxes from surface to deep ocean.

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