Variations in the distribution of chlorophyll $a$ and inorganic nutrients around South Georgia, South Atlantic

M.J. WHITEHOUSE, C. SYMON and J. PRIDDLE

British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK

Abstract: Data collected on four large-scale surveys around the subantarctic island of South Georgia provide information on the variability in the distribution of chlorophyll and inorganic nutrients during the austral summer and winter. During three summer surveys, surface water chlorophyll and nutrient concentrations were highly patchy over scales ranging from a few to hundreds of kilometres. The highest measurement of chlorophyll $a$ was $8 \text{ mg m}^{-3}$ and a wide range of nutrient concentrations were found; $5-32 \text{ mmol m}^{-3} \text{NO}_3$-$N$, $1.1-2.2 \text{ mmol m}^{-3} \text{PO}_4$-$P$ and $8-60 \text{ mmol m}^{-3} \text{Si(OH)}_4$-$Si$. In winter, chlorophyll and nutrient levels were far more uniform, with chlorophyll concentrations lower and nutrient concentrations generally higher than in summer. The spatial variability in nutrient concentrations was due to a variety of factors acting over a range of scales, however biological processes appeared most important in creating the mesoscale patchiness around the island. Although phytoplankton abundance and nutrient concentrations were not directly correlated, the scales of variability were clearly similar.

Key words: Southern Ocean, South Georgia, chlorophyll, nitrogen, phosphorus, silicon, variability

Introduction

The Southern Ocean contains high concentrations of inorganic nitrogen, phosphorus and silicon, all nutrients essential to phytoplankton growth. However, productivity is paradoxically low in these seas, and nutrient concentrations are rarely reduced to the low summer levels found in many other ocean areas (Le Jehan & Tréguer 1985, Jones et al. 1990, Smith & Sakshaug 1990, Tréguer & Jacques 1992). Substantial nutrient depletion has only been recorded during localized phytoplankton blooms in areas such as the ice edge (Jennings et al. 1984, Nelson & Smith 1986), under pack-ice (Smetacek et al. 1992) and inshore coastal sites (Clarke et al. 1988, Holm-Hansen et al. 1989).

Although levels of macronutrients in the Southern Ocean are generally high, this may not reflect their availability, and various features of the nutrient supply have been implicated in the control of phytoplankton growth rates. Nutrient preference, for instance ammonium versus nitrate, may be important (Olson 1980, Glibert et al. 1982, Smith & Nelson 1990, Smith & Harrison 1991, Jacques 1991, Owens et al. 1991).

Silicate limitation of diatom growth has been proposed on the basis of inefficient uptake kinetics (Jacques 1983), and the temperature-dependent ionization equilibrium of silicic acid (Priddle et al. 1986a). However, the role of silicon as a limiting nutrient in open-ocean areas of the Southern Ocean is ambiguous (Nelson & Tréguer 1992, Tréguer & Jacques 1992).

Despite the current interest in this subject, data for the Southern Ocean are sparse and biased, both spatially and temporally (Tréguer & Jacques 1992). Quantitative measurements of phytoplankton and nutrient dynamics, made during the summer and winter and over a period of years, are rare for remote Antarctic areas. As yet, such surveys are the only means by which we can monitor long-term trends and are an important component in understanding upper-ocean carbon cycling (Priddle et al. 1992, Tréguer & Jacques 1992). The British Antarctic Survey has undertaken oceanographic cruises...
around South Georgia since 1978, and this paper documents the variation found in the distribution of chlorophyll a and inorganic nutrients, measured during four of the cruises.

Study site

South Georgia is an elongated mid-oceanic island, centred at 54°20’S, 36°40’W and forming part of the Scotia Arc which links the South American Andes to the mountains of the Antarctic Peninsula (Fig. 1). It is c. 180 km long and up to 30 km wide and is surrounded by a deep continental shelf approximately eight times as extensive as the island itself.

South Georgia is sited in the Antarctic Circumpolar Current (ACC), the main path of which flows into the Scotia Sea through the Drake Passage and is then deflected north across the North Scotia Ridge, before turning east to flow to the north of South Georgia. The surface waters of the ACC comprise Subantarctic Surface Water (SASW) and Antarctic Surface Water (ASW), separated by a thin band of Antarctic Intermediate Water (AIW). The major surface water in the vicinity of South Georgia is ASW. This is c. 200 m deep and is underlain by a thick layer of Circumpolar Deep Water (CDW). The ASW is delimited to the north by the Polar Front (PF) (which separates the ASW from the SASW) and to the south by the Weddell-Scotia Confluence (WSC) (which separates the Scotia Sea ASW from water of Weddell Sea origin). As the positions of the PF and the WSC are not fixed (Deacon 1937), the composition of the water flowing around South Georgia varies in both space and time. Thus the island lies in a hydrographically complex area, and the surrounding ASW is influenced intermittently by SASW to the north and west, and Weddell Sea water to the south and east.

Nutrient concentrations are generally low in the SASW, with concentrations increasing southwards across the Polar Frontal Zone (PFZ) towards the relatively high levels of the ASW (Sievers & Nowlin 1988). Superimposed on this general trend may be some local enhancement at the Subantarctic Front (SAF) and the PF (Jones et al. 1990). Circumpolar Deep Water (CDW), underlying the ASW, is relatively higher in nutrients.
and resupplies the ASW during the winter when the seasonal mixed layer breaks down and there is deep turbulent mixing (Sievers & Nowlin 1988). Silicate, an essential nutrient for diatom growth, is found at very high levels in the surface waters of the Weddell Sea (Stein 1979).

**Methods**

**Summary of cruises**

The data discussed in this paper were collected during four surveys from RRS John Biscoe. Three took place during the austral summer: JB02 (27 March–6 April 1980), JB03 (24 November–19 December 1981) and JB08 (16 January–5 February 1988), and one during winter; JB04 (31 July–20 August 1983). The surveys took up to 25 days to complete and were situated in an area termed the ‘South Georgia Zone’ (SGZ, between 52°–57°S and 32°–41°W). The cruise tracks and station positions for each of the four surveys are shown in Fig. 2. JB02 comprised a stellate circumnavigation of South Georgia, similar to those undertaken during the Discovery Investigations (1925–39; Clowes 1938). Nineteen water bottle casts were made, c. 50 km apart, in 13 days. JB03 consisted of a large scale grid survey around the island during which 63 water bottle casts were made, 30 nautical miles (56 km) apart and covering an area of 1.4 x 10^5 km^2 in 25 days. JB04 was intended to replicate the JB03 survey during the austral winter. However, only 42 stations were completed successfully, covering an area of 0.9 x 10^5 km^2 in 24 days. JB08 comprised a rapid mapping survey of surface conditions along a series of transects running NW–SE across the stations worked during the JB03 and JB04 cruises and covering an area of 0.9 x 10^5 km^2 in seven days. Surface measurements made during the JB08 transects were used to select three sites (A, B and C, Fig. 2) for an investigation of vertical structure.

**Sample collection and analytical methods**

Vertical profiles of temperature, salinity, chlorophyll a and inorganic nutrients were measured at each site shown in Fig. 2 for JB02, JB03, JB04 and at 15 sites in three discrete locations during JB08 (A, B and C). Vertical temperature and salinity data were collected with a Plessey or Neil Brown CTD and twelve 2.5 litre Niskin bottles. Surface nitrate and silicate were measured continuously during the JB08 survey whilst the ship was underway. These horizontal profiles were obtained by analysing seawater pumped to the laboratory from an intake port in the ship’s hull, c. 3 m below the sea surface. Continuous horizontal nutrient profiles were sub-sampled to give one value per nautical mile travelled by the ship.

Water bottle samples were analysed routinely for particulate chlorophyll a, nitrate+nitrite-N (nitrate), orthophosphate-P and silicate. Ammonium-N and nitrite-N were measured during the later cruises only. Nutrient analyses were performed on a

| Table I. Chlorophyll a (mg m^(-2)) and nutrient (mmol m^(-3)) mean concentrations in surface waters (0–30 m) during the austral summer and winter. |
|----------------|----------------|----------------|----------------|
| Cruise | No | Min | Max | Med | Mean | SD |
| **Ch a** | | | | | | |
| summer JB02 | 54 | 0.03 | 1.00 | 0.28 | 0.39 | 0.25 |
| JB03 | 235 | 0.13 | 4.54 | 0.36 | 0.75 | 0.84 |
| JB08 | 28 | 0.17 | 8.06 | 0.40 | 1.67 | 2.32 |
| winter JB04 | 153 | 0.11 | 0.38 | 0.23 | 0.23 | 0.05 |
| **NO_3-N** | | | | | | |
| summer JB02 | 18.2 | 28.3 | 21.7 | 21.9 | 2.64 |
| JB03 | 777 | 5.9 | 31.2 | 20.4 | 19.8 | 6.13 |
| JB08 | 153 | 17.4 | 26.8 | 23.4 | 23.5 | 2.20 |
| winter JB04 | 23 | 0.14 | 0.24 | 0.19 | 0.19 | 0.03 |
| **NO_2-N** | | | | | | |
| summer JB02 | 0.07 | 1.34 | 0.46 | 0.47 | 0.10 |
| JB03 | 207 | 1.17 | 1.78 | 1.75 | 0.19 |
| JB08 | 6 | 1.57 | 1.61 | 1.60 | 0.02 |
| winter JB04 | 150 | 1.99 | 2.18 | 2.17 | 0.07 |
| **PO_4-P** | | | | | | |
| summer JB02 | 14.1 | 33.6 | 23.2 | 22.4 | 4.54 |
| JB03 | 227 | 12.4 | 54.8 | 29.0 | 30.1 | 7.96 |
| JB08 | 882 | 8.8 | 59.6 | 28.1 | 29.3 | 8.24 |
| winter JB04 | 153 | 19.7 | 57.1 | 29.7 | 32.4 | 8.96 |

Segmented Flow Analyser, no more than one or two hours after collection for discrete water bottle samples and within a minute for horizontal profiles (Whitehouse & Woodley 1987). Chlorophyll a was measured fluorometrically on particulate samples extracted in acetone (UNESCO 1980, Friddle et al. 1986b).

The surface depth ranges used to describe the data are ~3 m for the horizontal profiles and 0–30 m for the vertical profiles (thus representing water from the seasonal surface mixed layer which is usually 30–50 m depth). Nutrient concentrations in discrete surface samples taken from the ship’s 3 m intake at the JB02, JB03 and JB04 CTD stations, showed good correlation with the corresponding water-bottle values integrated to 30 m; coefficients of correlation for nitrate and silicate were respectively 0.985 and 0.959 for JB03 (63 stations) and 0.995 and 0.999 for JB04 (42 stations). Therefore, the horizontal profiles measured during JB08 were considered reliable representations of concentrations in the upper 30 m of the water column.

**Results**

**Chlorophyll a**

The coastal waters surrounding South Georgia support sporadic phytoplankton blooms during the austral summer. These blooms are usually dominated by diatoms and may achieve a
Fig. 3. Contour plots showing spatial variation in surface (0–30 m) chlorophyll a (mg m⁻³) and nutrient (mmol m⁻³) mean concentrations during the austral summer (JB03) and winter (JB04); a. summer and b. winter chlorophyll; c. summer and d. winter nitrate.

biomass of >20 mg m⁻³ chlorophyll (Whitehouse et al., unpublished). The maximum concentration measured during the surveys reported here was 8.06 mg m⁻³ during JB08 at site B (Fig. 2d). Chlorophyll distribution varied widely around South Georgia during the summer with median surface concentrations of 0.28, 0.36 and 0.40 mg m⁻³ for JB02, JB03 and JB08 respectively (Table I). Median and mean summer chlorophyll levels differed strongly due to the skewed distribution of chlorophyll concentrations. The winter median and mean values were identical. Highest chlorophyll concentrations were mainly found during the summer to the north and west of the island (Fig. 3a), although the distribution was highly patchy. Winter concentrations were generally lower and more-or-less uniform throughout the region (Fig. 3b).

There was no evidence of deep chlorophyll maxima in any of the vertical profiles measured during the summer cruises. High biomass stations had consistently more chlorophyll in shallow water (Fig. 4a). Vertical profiles measured during winter (JB04) were more or less uniform to a depth of 100 m (Fig. 4b), below which little chlorophyll was found. Chlorophyll and nutrients were not directly correlated. For example, during the JB03 survey, the coefficient of variation of chlorophyll with nitrate was -0.263 (n = 218), with phosphate -0.386 (n = 214) and with silicate -0.219 (n = 224).
Nitrogen

Surface nitrate levels varied widely during all the cruises (Table I). Median concentrations during JB03 and JB08 were similar at 21.7 and 20.4 mmol m\(^{-3}\) respectively, although the range of values measured during JB03 was smaller. During summer, the highest surface values (>31 mmol m\(^{-3}\) during JB08) were found beyond the shelf-break to the north of the island (Fig. 5a), with the lowest levels (<6 mmol m\(^{-3}\) during JB08) to the south. However, isolated low concentrations were found throughout the region. During the winter, surface nitrate concentrations were slightly higher than during summer and little spatial variability was evident (Fig. 3d).

Vertical nitrate profiles show more variable surface concentrations during the summer (JB03) than the winter (JB04) (Fig. 4c & d). In both datasets concentrations increase linearly with depth below the surface mixed layer (about 30 m in summer and 100 m in winter), consistent with the resupply of nutrients to the ASW from the underlying CDW.

Nitrite was measured during one summer cruise (JB08) and during the winter (JB04). In contrast to nitrate, the winter nitrite distribution was relatively patchy and concentrations below 100 m decreased, rather than increased, with depth (Fig. 6a & b). As with nitrate, highest concentrations were found along the shelf-break to the north of the island (>0.6 mmol m\(^{-3}\)) while the
Fig. 4. Scatter plots showing the vertical distribution of chlorophyll $a$ (mg m$^{-3}$) and nutrient (mmol m$^{-3}$) concentrations during the austral summer (JB03) and winter (JB04); a. summer and b. winter chlorophyll; c. summer and d. winter nitrate; e. summer and f. winter phosphate; g. summer and h. winter silicate.

lowest concentrations were to the south (<0.3 mmol m$^{-3}$) (Table 1). A lower and narrower range of nitrite concentrations was measured during JB08 than JB04, although, this may have been due in part to the smaller number of samples and the limited area which was sampled.

Ammonium was measured at sites A, B & C during JB08 and surface water concentrations were generally low (0.07–1.34 mmol m$^{-3}$). The highest levels were measured at site C, which also had the highest nitrate and silicon concentrations.

**Phosphorus**

As with nitrate, phosphate distribution showed considerable patchiness during the summer (JB03), with surface concentrations generally higher to the north of South Georgia (> 2.0 mmol m$^{-3}$) and lower to the south (1.20 mmol m$^{-3}$) (Fig. 3e). Little variation in concentration was evident during the winter except for two bands of slightly higher phosphate levels running east-west through the centre of the region and to the south of the island (Fig. 3f). Elsewhere, surface concentrations during the winter were relatively uniform and higher than during summer.

The vertical phosphate profiles show a distinct contrast between summer (JB03) and winter (JB04). Surface phosphate concentrations are very variable in the summer relative to the winter, and as with nitrate, both profiles increase linearly with depth below about 30 m in the summer and 100 m in the winter (Fig. 4e & f).

**Silicon**

Silicate was measured during all four cruises. For two of the summer surveys (JB03 and JB08), median surface concentrations and the range in concentrations measured were similar (Table 1), while lower concentrations with a smaller range, were measured during JB02. However, all three summer surveys showed similar spatial patterns. Surface concentrations during JB02 were relatively uniform, although concentrations tended to be lower on the shelf. During JB03 and JB08 low concentrations were again found on and near the shelf (Figs 3g & 5f), with bands of higher concentration along the two offshore edges of the survey grid during JB03, especially to the north-east. An analysis of variance showed significantly higher concentrations of silicate ($P < 0.001$) in offshore surface waters compared with on-shelf and shelf-slope areas during JB03. The JB08 horizontal profiles showed high surface silicate in the north-east sector of the SGZ, associated with an incursion of cold Weddell Sea water. In winter, the spatial distribution of silicate was markedly different. The highest concentrations were found to the south (Fig. 3h), again attributable to an incursion of Weddell Sea surface water, and no shelf-related distribution patterns were evident.

The vertical silicate distribution was similar to that of nitrate and phosphate, i.e. little, if any, increment in concentration to about 30 m in summer, and 100 m in winter (Fig. 4g & h), with concentrations below these layers increasing with depth.

**Discussion**

There are few contemporary studies which provide data comparable with that of the present study. The one major exception is that of Chlapowski & Grelowski (1978) who report a 34-station survey around the island, concentrated on the northern shelf. Their data, for the period February–March 1976
are of a similar magnitude to those given here. Over the top
100 m they report the following range in concentrations;
nitrate 15–33 mmol m\(^{-3}\), nitrite 0.3 mmol m\(^{-3}\) max., phosphate
1.2–2.3 mmol m\(^{-3}\) and silicate 4–51 mmol m\(^{-3}\). Other than the
Chlapowski and Grelowski study the only comparable surveys
are those of the Discovery Investigations. However, as these
pre-date contemporary marine chemistry methods, it would be
inappropriate to attempt a direct comparison of the Discovery
data with the present dataset. Nevertheless, qualitative
observations support the data presented here, including the
patchy nature of phytoplankton distribution and the large-scale
water mass distributions (Hardy & Gunther 1936, Clowes
1938).

The four surveys reported here provide an indication of the
spatial and temporal variability of phytoplankton and nutrient distributions in the waters around South Georgia during summer and winter. This variability is clearly due to a number of factors acting over a range of scales. There are likely to be three major causes of variability in the distribution of macronutrients around South Georgia. Firstly, large-scale variations due to the presence of different water masses and fronts. Secondly, mesoscale variation associated with shelf-break processes such as upwelling. Finally, small-scale variability due to variation in phytoplankton biomass and production resulting in differential nutrient utilization.

Large-scale variability

We have noted that the hydrography of the South Georgia Zone is not uniform and that the influence of different water types may present an identifiable pattern in nutrient distribution (Stein 1979, Michie 1984). Atkinson et al. (1990) report warm water areas around South Georgia during JB03, which they conclude were of subantarctic origin as opposed to upwellings of CDW (Priddle et al. 1986b). The nutrient concentrations measured during this cruise support neither of these arguments as they are neither particularly low (as in SASW) or high (as in CDW). Indeed, examination of nutrient data from all four cruises suggests that the majority of the sampling occurred in ASW (i.e. water from south of the PF). However, data from two of the cruises indicate a clear ingress of Weddell Sea water to the south (JB04) and east (JB08) of the study area, as shown by high silicate concentrations and low temperatures (unpublished data). Unlike silicate, surface nitrate and phosphate values show no systematic variability which can be attributed to gross hydrographic change (Figs 3 & 5).

Mesoscale variability

Mesoscale variability, resulting from local influences, might be identified by comparing nutrient distributions in the four surveys for similarities. Priddle et al. (1986b) noted the presence of 'shelf water' around South Georgia during JB03, but failed to demonstrate any linear relationship between nutrient concentrations and distance from shore. An analysis of variance between nutrient values measured at shelf, shelf-break and offshore stations during JB03 and JB04 provided no statistically significant differences for nitrate or phosphate levels. However, offshore silicate concentrations were consistently higher than on-shelf areas during all the summer surveys. Our nutrient plots would suggest higher surface nitrate and phosphate levels to the north of the island during the summer surveys, especially evident for nitrate in the shelf-break region during the high resolution sampling of JB08 (Fig. 5). Since the ACC is eastward-flowing, the north-eastern side of South Georgia is in the lee of the island relative to the predominant wind and water movements, and this is likely to result in features, such as upwelling, which would affect surface nutrient levels.

Fig. 6. Variation in nitrite concentrations (mmol m⁻³) measured during winter (JB04); a. Contour plot of surface (0–30 m) mean concentrations; b. scatter plot showing vertical distribution.
Small-scale variability

The most obvious feature to emerge from this study is the strong contrast between the highly patchy nature of distributions in summer, and the relatively uniform distributions in winter. For those summer cruises which used station grids (JB02 & JB03), it is clear that the range of scales of spatial variability extended to the same order of magnitude as the station spacing. The continuous profiles undertaken during JB08 reinforced this, and they also showed even smaller scales of variability (Fig. 5).

Chlorophyll biomass was the most patchy variable of the summer surveys and, for the grid surveys (JB02 & JB03), high biomass regions appeared as isolated stations rather than as extensive blooms. This is consistent with the documented behaviour of phytoplankton in the turbulent waters of the Southern Ocean, where the predicted patch size is small, owing to growth dynamics and the small scale of physical variability (Okubo 1978, Weber et al. 1986).

Although the patchiness of phytoplankton biomass implies a similar variability in macronutrient concentrations, this relationship cannot be revealed by simple statistical correlation. Priddle et al. (1986b) interpret biogeographic patterns in microplankton in terms of water types, with small-scale variability resulting from nutrient interactions and grazing pressure, but fail to show any significant correlation between chlorophyll and nutrients. For a more diverse and wide-ranging series of surveys, Priddle et al. (1993) also failed to demonstrate any correlation between chlorophyll biomass and macronutrient concentrations in the Antarctic Peninsula region. The reasons for this are clear. Within both study areas, phytoplankton blooms would appear to be both small and transient features (Owens et al. 1991). In contrast, the macronutrient pool retains a 'memory' of utilization, which may not necessarily correspond to contemporary phytoplankton biomass (Jennings et al. 1984, Priddle et al. 1993). The relationship may also be confused by the resupply of nutrients to the surface mixed layer from the underlying nutrient uptake (Heywood & Priddle 1987, Murphy et al. unpublished, Whitehouse et al. unpublished).

Acknowledgements

We thank Terry Whitaker and Vince Woodley for their assistance with data collection and Andy Wood and Alistair Murray for their guidance with data management and statistical analysis.

We are grateful to Osmund Holm-Hansen, Marcus Baumann and an anonymous referee for their valuable comments.

References


Olson, R.J. 1908. Nitrate and ammonium uptake in Antarctic waters. Limnology and Oceanography, 12, 149-162.


