Observations on the nutrients, chlorophyll and primary production of the Southern Ocean south of Africa

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Chl a *has been measured on two cruise tracks between South Africa and Antarctica in an attempt to determine its relationship to phytoplankton stocks and available nutrients in frontal systems in the Southern Ocean. A strong correlation between potential primary production (PPP) and Chl* a *at the sea surface was obtained. Both PPP and Chl* a *were negatively correlated with $PO_4(P)$. $NO_3(N)$, Si and pH exhibited weak correlation with production components implying that $NO_3(N)$ and Si were not limiting while $PO_4(P)$ may become so at fronts and in certain regions of Antarctic Surface Water. The geographic positions of peaks in measured Chl* a *corresponded well with the positions of physical fronts, particularly with the Antarctic Polar Front.*

Chl a *se voorkoms is tydens twee vaarte tussen Suid-Afrika en Antarktika gemeet in 'n poging om enige verband tussen die konsentrasie daarvan en die voorkoms van fitoplankton en van die beskikbare voedingstowwe in frontstelsels in die Suidelike Oseaan vas te stel. Daar is 'n hoë korrelasie tussen die potensiële primêre vorming (PPP) en Chl* a *aan die see-oppervlak gevind. PPP en Chl* a *is albei negatief teenoor $PO_4(P)$ gekorreleer. $NO_3(N)$, Si en pH het swak korrelasie met vormingskomponente vertoon, wat inhou dat $NO_3(N)$ en Si nie beperkend was nie, terwyl $PO_4(P)$ by fronte en in sekere dele van die Antarktiese Oppervlakwater wel beperkend kan wees. Die geografiese posisie van gemete Chl* a*-pieke stem goed ooreen met die posisie van fisiese fronte - veral met die Antarktiese Poolfront.*

Introduction

The relief voyage (Voyage 17) of the research and supply vessel *S.A. Agulhas* to South Africa's Antarctic base (Sanae) in January 1981 provided an opportunity to make an extended series of observations on productivity-related variables in a part of the Southern Ocean in which few such measurements have as yet been made. During the voyage, vertical attenuation profiles of photosynthetically-active radiation (PAR) were measured, and the concentrations of essential plant nutrients (N, P, Si), chlorophyll concentration and potential primary productivity were determined in surface waters along the ship's track.

These measurements by members of the Institute for Freshwater Studies were complemented by those made simultaneously as part of a physical oceanology research programme of the National Research Institute for Oceanology. A comparison of the two data sets affords an opportunity to study the potential relationship between the physical and biological regimes.

Methods

The hydrographic stations occupied during the cruise are shown in Fig. 1, and the co-ordinates of the underway sampling sites for chemical and biological parameters are given in Table 1. Samples were collected underway by means of a shipboard pump (Iwaki Magnet Pump), fabricated from polyvinylidene fluoride and ceramic materials. It drew water from the sea at a level of 3 m above the keel and supplied it to the laboratory through PVC piping. During the voyage the pump ran continuously at slightly less than maximum capacity of 100 *l*/min., stopping for short periods when the ship passed through heavy pack ice. Samples along the southbound track were taken at 06h00 and 12h00 local time for chlorophyll *a* (Chl *a*), reactive nitrate ($NO_3(N)$), soluble reactive phosphorus ($PO_4(P)$), reactive silica (Si) and pH, and potential primary productivity (PPP). The frequency of sampling was increased where rapid changes in surface temperature were observed. Along the northbound track, sampling frequency for Chl *a* was increased to two h, $NO_3(N)$, $PO_4(P)$, Si and pH to four h, while PPP was determined on samples collected at local noon, with consideration again being given to changes in surface temperature so as to resolve greater detail of oceanic frontal systems.

At each southbound noon CTD station, measurements of PAR attenuation were made, and over the side samples of sea water, using simple "Challenger" bottles painted black, were taken from 5 m below the surface. These samples were used to provide a direct comparison with samples taken from the ship's scientific sea water supply just prior to occupation of the station.

PAR was measured with a 'Quantum' sensor and meter (Li-Cor Lincoln, Nebraska). The analytical methods for pH, total and carbonate alkalinity $NO_3(N)$ and Si were those given in Strickland and Parsons (1968). For $PO_4(P)$, sea water filtered through 0,45 μm Sartorius membrane filters (type SMN 11106), was treated as described by Mackereth, Heron and Talling (1978) and modified by Allanson (MS); Chl *a* determination followed the SCOR-UNESCO method as given in Strickland and Parsons (1968) using either 1,5 *l*, 5 *l* or 10 *l* of sea water, filtered through GF/C filters.

In all analytical methods, particular care was taken to measure the precision of our estimate as the per cent coefficient of variation (Sutcliffe 1979). $NO_3(N)$ as μg at l^{-1} was 3,0 per cent ($n = 10$) and $PO_4(P)$ as μg at l^{-1} measured on two separate series of replicates was 1,8 and 3,5 per cent ($n = 6$).

Primary productivity was determined by the ^{14}C incubator method of Gargas *et al.* (1976). Aliquots of 25 m*l* of sea water

Table 1

Latitude and longitude coordinates for each shipboard scientific supply sampling on each track of the January 1981 cruise of the *SA Agulhas*.

Southbound Track		Northbound Track		49°57′S	06°01′E
36°55′S	21°06′E	70°00′S	02°40′E	49°36′S	05°22′E
39°55′S	24°14′E	69°33′S	02°25′E	49°13′S	06°43′E
41°56′S	23°47′E	69°08′S	02°10′E	48°48′S	07°06′E
44°16′S	22°32′E	68°43′S	01°53′E	48°25′S	07°26′E
45°47′S	21°57′E	68°19′S	01°33′E	48°01′S	07°44′E
46°33′S	21°36′E	67°54′S	01°12′E	47°37′S	08°05′E
48°40′S	20°74′E	67°30′S	00°54′E	47°25′S	08°16′E
50°06′S	19°41′E	67°03′S	00°34′E	47°14′S	08°25′E
50°29′S	19°21′E	66°38′S	00°16′E	46°51′S	08°44′E
51°29′S	18°59′E	66°13′S	00°01′E	46°39′S	08°54′E
52°20′S	17°49′E	65°48′S	00°20′E	46°16′S	09°13′E
53°34′S	17°40′E	65°23′S	00°40′E	45°54′S	09°33′E
54°48′S	17°18′E	64°57′S	00°58′E	45°32′S	09°32′E
55°31′S	16°40′E	64°32′S	01°16′E	45°10′S	10°10′E
58°03′S	14°37′E	64°06′S	01°35′E	44°45′S	10°28′E
58°50′S	14°05′E	63°17′S	02°11′E	44°22′S	10°48′E
59°13′S	13°48′E	62°51′S	02°29′E	43°59′S	11°10′E
59°38′S	13°21′E	62°26′S	02°47′E	43°36′S	11°30′E
60°05′S	12°45′E	62°00′S	03°06′E	43°14′S	11°50′E
60°39′S	12°03′E	61°32′S	03°08′E	43°04′S	11°59′E
62°17′S	10°26′E	61°06′S	03°10′E	42°51′S	12°13′E
62°41′S	10°01′E	60°39′S	03°11′E	42°41′S	12°21′E
63°02′S	09°37′E	60°12′S	03°13′E	42°27′S	12°33′E
63°25′S	09°12′E	58°01′S	03°26′E	42°16′S	12°41′E
63°51′S	08°40′E	57°35′S	03°26′E	42°05′S	12°51′E
64°19′S	07°56′E	57°11′S	03°28′E	41°54′S	13°00′E
64°56′S	07°09′E	56°45′S	03°31′E	41°42′S	13°15′E
66°29′S	04°50′E	56°20′S	03°34′E	41°31′S	13°23′E
67°01′S	03°37′E	55°54′S	03°35′E	41°21′S	13°34′E
67°33′S	03°11′E	55°28′S	03°38′E	41°10′S	13°41′E
70°14′S	02°48′E	55°02′S	03°40′E	40°58′S	13°58′E
		54°38′S	03°31′E	40°57′S	13°55′E
		54°26′S	03°27′E	40°35′S	14°02′E
Eastbound Track		54°20′S	03°27′E	40°23′S	14°11′E
		53°54′S	03°29′E	40°12′S	14°19′E
69°31′S	01°21′E	53°27′S	03°32′E	39°50′S	14°50′E
69°33′S	01°34′E	53°02′S	03°33′E	39°35′S	14°41′E
69°49′S	02°04′E	52°34′S	03°30′E	39°28′S	14°48′E
69°41′S	09°01′E	52°16′S	03°43′E	39°07′S	15°06′E
69°49′S	01°17′E	51°52′S	04°05′E	38°39′S	15°18′E
70°05′S	01°29′E	52°46′S	03°34′E	38°15′S	15°35′E
		51°27′S	04°27′E	37°53′S	15°51′E
		51°04′S	04°51′E	37°33′S	16°16′E
		50°53′S	05°05′E	37°09′S	16°28′E
		50°42′S	05°17′E	36°31′S	16°46′E
		50°21′S	05°38′E	36°00′S	16°55′E
		50°05′S	05°54′E	35°33′S	17°07′E
				35°11′S	17°33′E

were taken from the scientific supply or from the "Challenger" bottles and transferred to a paired array of 30 m*l* Pyrex glass-stoppered bottles to which $NaH^{14}CO_3$ (from the ^{14}C Agency, Denmark) was added to a specific activity equivalent of 4 μCi/100 m*l*. At no time were the samples exposed to full incident radiation so that light shock was reduced to a minimum. Formaldehyde "blanks" were used to correct for self-adsorption. Dark ^{14}C fixation was determined in incubation bottles wrapped in aluminium foil and mounted on the reverse (shaded) side of the rotating disc of the incubator. A series of neutral density filters reduced light flux to 50, 25, 15, 10 or 5 per cent of the incubator output and permitted a simulation of vertical light attenuation effects. Aluminium foil backing increased the light flux to 160 per cent for one pair of bottles. Bottles were incubated for four to six hours close to the temperature of the sea from which the samples were taken. By maintaining a constant light flux output of 385 μ Einsteins $m^{-2}\,s^{-1}$ and near-ambient temperatures, the ^{14}C fixation estimates provided by the incubator allowed comparison of the productivity of sequential samples. While no claim is made that this particular incubator method simulates light conditions exactly, the energy flux obtained was found to be equivalent to that at *c.*5 or *c.*10 m depth on a cloudy and bright day respectively, as shown in Fig. 2.

After incubation the aliquots were filtered through Sartorius 0,45 μm filters under a 1/3 atm., and the damp filters were fumed over concentrated hydrochloric acid and transferred to 10 m*l* "Redisolve" (Beckman) cocktail. Samples were radio-

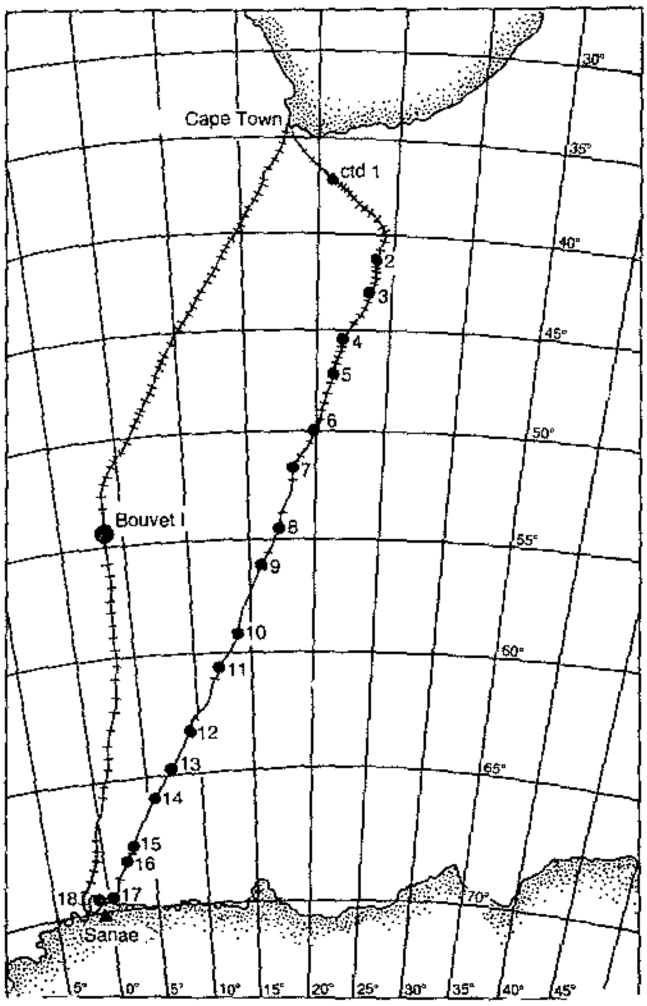


Fig. 1. Expendable bathythermograph stations (bar lines) and conductivity temperature-depth stations (numbered dots) occupied during the January 1981 cruise of *S.A. Agulhas*.

assayed on board, using a Beckman LS 133 spectrometer. From these data the response of a light adapted algal community to decreasing irradiance was measured, which provided a measure of ΣP, the primary productivity integral. This integral is at the irradiance extinction available in the incubator, and is therefore viewed as potential or relative productivity (PPP), allowing direction comparison between water masses independently of variation in natural radiance. In this regard it has considerable comparative value.

The physical measurements consisted of two hourly expendable bathythermograph (XBT) dips, calibrated by sea surface temperatures measured with the aid of a Crawford bucket (Crawford 1965). XBT traces were inspected for faults according to Kroner and Blumenthal (1977) and a small number rejected. On the southbound track 18 conductivity-temperature-depth (CTD) measurements were undertaken to a depth of at least 1 000 m (Fig. 1). A Neil Brown CTD-probe was used.

Results

Representativeness of the scientific sea water supply

It was of prime importance to the validity of the data to establish whether the supply from the ship's scientific sea water supply was a reasonable sample of the sea water at $\simeq$ 5 m depth. In Table 2, comparisons are given between this supply and samples taken over the side for NO_3(N), PO_4(P) and PPP determinations.

The differences between the scientific supply and overboard samples drawn from 5 m at each noonday station as regards NO_3(N), PO_4(P) and PPP were not significant. It was not possible to collect sufficiently large water samples for Chl *a* measurements from over the side, due to inadequate equipment. As a result, no comparative data are available.

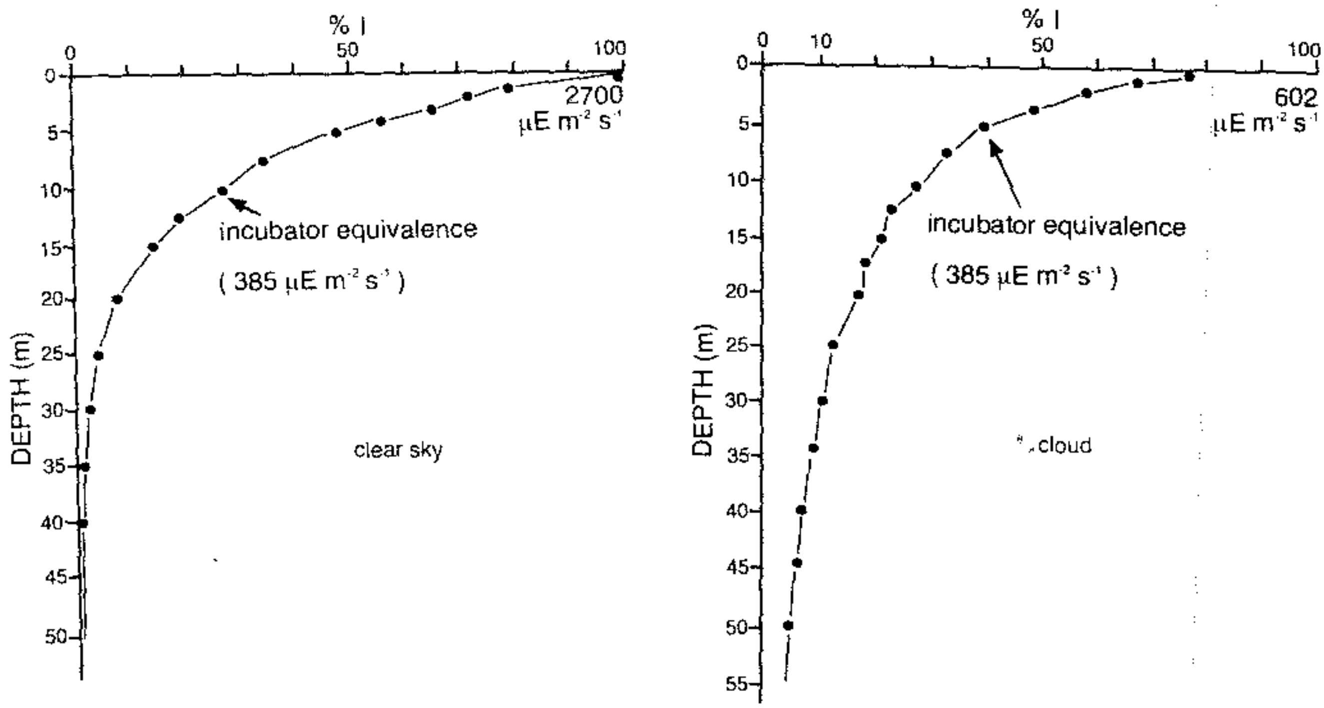


Table 2

Comparison of nutrient concentrations (PO_4(P) and NO_3(N)) and potential primary productivity (PPP) in samples collected from the pumped scientific sea water supply (S.C.) and from over the side using "Challenger" bottle sampling (C.B.). Wilcoxon's matched-pairs signed-ranks tests (Siegel 1956) showed no significant differences at $p = 0{,}05$. N is the number of ranked pairs and T is the sum of ranks with the less frequent sign.

NO_3(N) μg at l^{-1}		PO_4(P) μg at l^{-1}		PPP mg.C. $m^{-3}.h^{-1}$	
C.B.	S.C.	C.B.	S.C.	C.B.	S.C.
17,0	21,6	0,85	0,92	3,52	2,09
23,4	23,1	0,73	1,05	2,41	1,31
29,7	28,4	0,84	0,83	2,17	3,19
28,4	21,8	0,78	1,02	0,35	0,28
20,0	22,0	0,92	1,11	0,41	0,18
21,4	19,8	0,70	0,85	1,29	1,89
17,3	21,2	0,96	0,92	1,69	1,76
24,9	21,5	0,95	0,95	0,34	0,33
22,8	25,6	0,73	0,71	9,08	10,07
25,0	24,5	0,73	0,70	11,98	10,34
		0,75	0,70		
		0,78	0,75		
		0,81	0,78		
$N=10$	$T=28$	$N=14$	$T=56$	$N=10$	$T=17$

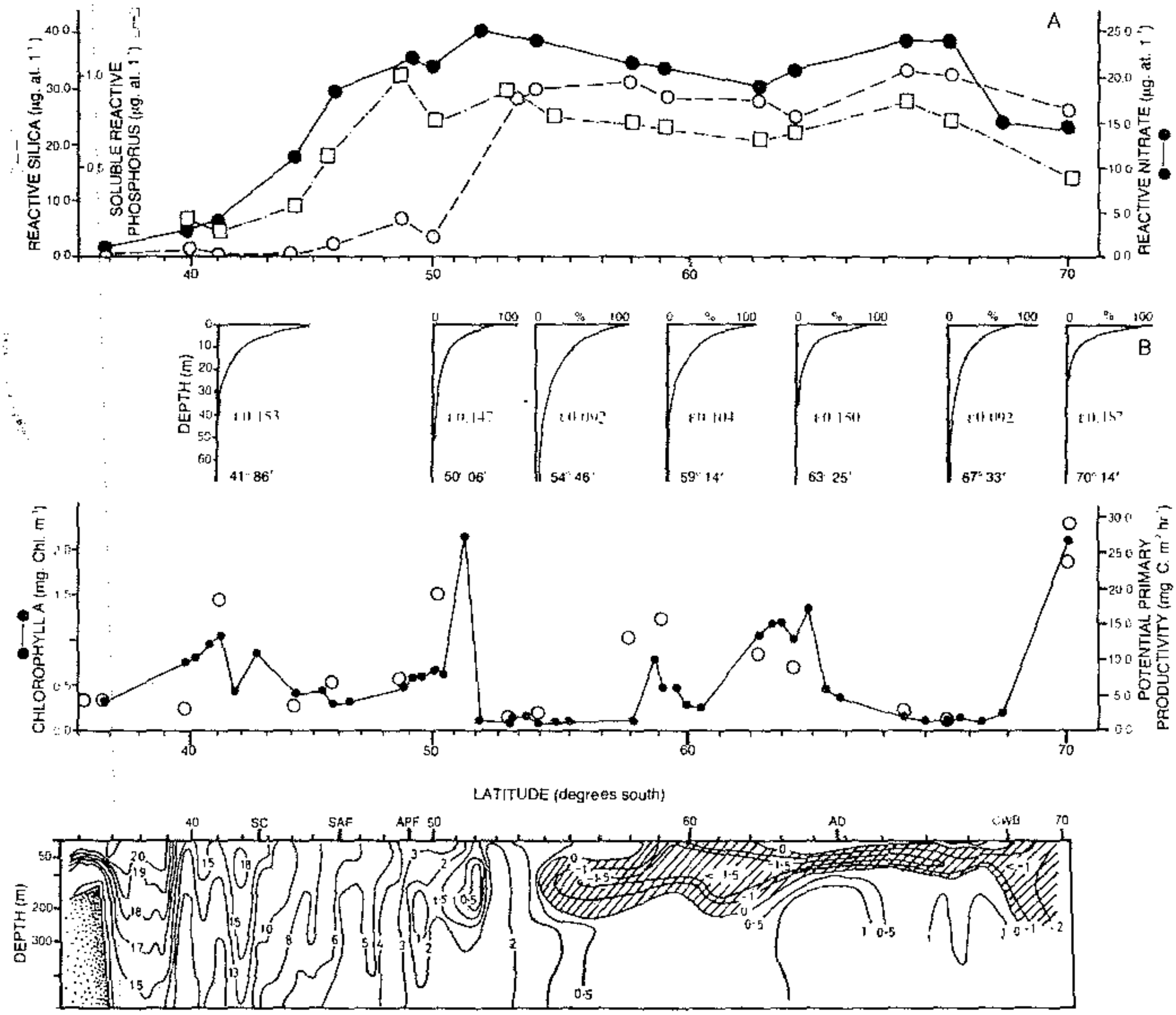
However, in view of the similarity between the PPP values of samples from these two sources, it seems reasonable to expect Chl *a* concentrations to follow suit.

Silica (Si), Nitrate (N) and Phosphate (P)

The variations in concentration of the three nutrients measured are portrayed in parts *A* of Figs. 3 and 4. Along the southbound cruise track, station spacing was rather wide (Fig. 3a); on the northbound track (Fig. 4a) sampling frequency was increased so that some finer detail of the variations could be resolved.

In both instances low concentrations of silica ($< 2{,}0\ \mu g\ l^{-1}$), nitrate ($< 5{,}0\ \mu g$ at l^{-1}) and phosphate ($< 2{,}0\ \mu g$ at l^{-1}) were

Fig. 3. Latitudinal variation in surface chlorophyll concentrations, and relative primary production (PPP) in relation to temperature, PAR attenuation and plant nutrients along the southbound track.
A. Changes in NO_3(N), PO_4(P) and Si μg at l^{-1}.
B. PAR [1]attenuation curves, ϵ = [2]attenuation coefficient.
C. Chlorophyll *a* mg m^{-3}; PPP, large open circles.
D. Temperature (°C) isolines derived from XBT & CTD recordings.
SC Subtropical convergence.
SAF Sub-Antarctic front.
APF Antarctic polar front.
AD Antarctic divergence.
CWB Continental water boundary.



measured north of 42°S; that is, north of the Subtropical Convergence (see Figs. 3d, 4d). At higher latitudes there was a marked increase in nitrate and phosphate, reaching a maximum between 47° and 48°S. Concentrations of nitrate rose from between 1 and 4 to between 17 and 22 μg at l^{-1} over 6° of latitude, the higher values in both cases being on the northbound track. Only a small increase in silica concentrations was measured at these latitudes. A marked increase in the silica concentrations was, however, measured between 50½°S and 52½°S on the northbound track near the Antarctic Polar Front (Fig. 4a), an increase only vaguely mirrored in the nitrate and phosphate concentrations. A similar increase in silica concentrations was observed on the southbound track but, because of the wider station spacing, can only be said to lie somewhere between 50° and 54°S. Generally only smaller fluctuations in the concentrations of the nutrients were measured south of 54°S, an exception being the nitrate minimum/silica maximum found at 65½°S on the northward track (Fig. 4a).

These concentration values and distributions may be compared to previous work of a similar nature in the region. The pioneer work by Clowes (1939) indicates marked horizontal gradients at 42°S and 50°S for phosphate and at 50°S for silicate. His measurements indicate that surface values are representative of at least the upper 300 m of water.

Further measurements in the region have been undertaken by Soviet investigators (Treshnikov *et al.* 1970, Grigorev and Kornilov 1971, Shamontyev 1977) who have, however, concentrated their attention on physical parameters, while Japanese scientists (Ishino *et al.* 1958, Torii 1959, Fukase 1962, Kuga & Watanuki 1963, Ishino *et al.* 1963, Hori 1966, Shiozake 1966) have carried out many chemical measurements during the numerous Japanese Antarctic Research Expeditions (JARE). The most recent measurements were made from the *R.D. Conrad* during 1974 (Jacobs & Georgi 1977).

A comparison between the concentrations we measured across the two main oceanic fronts along the cruise track and those measured by others is given in Tables 3a and b. These comparisons are coarse at best, since cruise tracks were in many cases widely spaced zonally and in time. In a number of cases station spacing was very wide, so that the precise range of concentration values across fronts was not resolved.

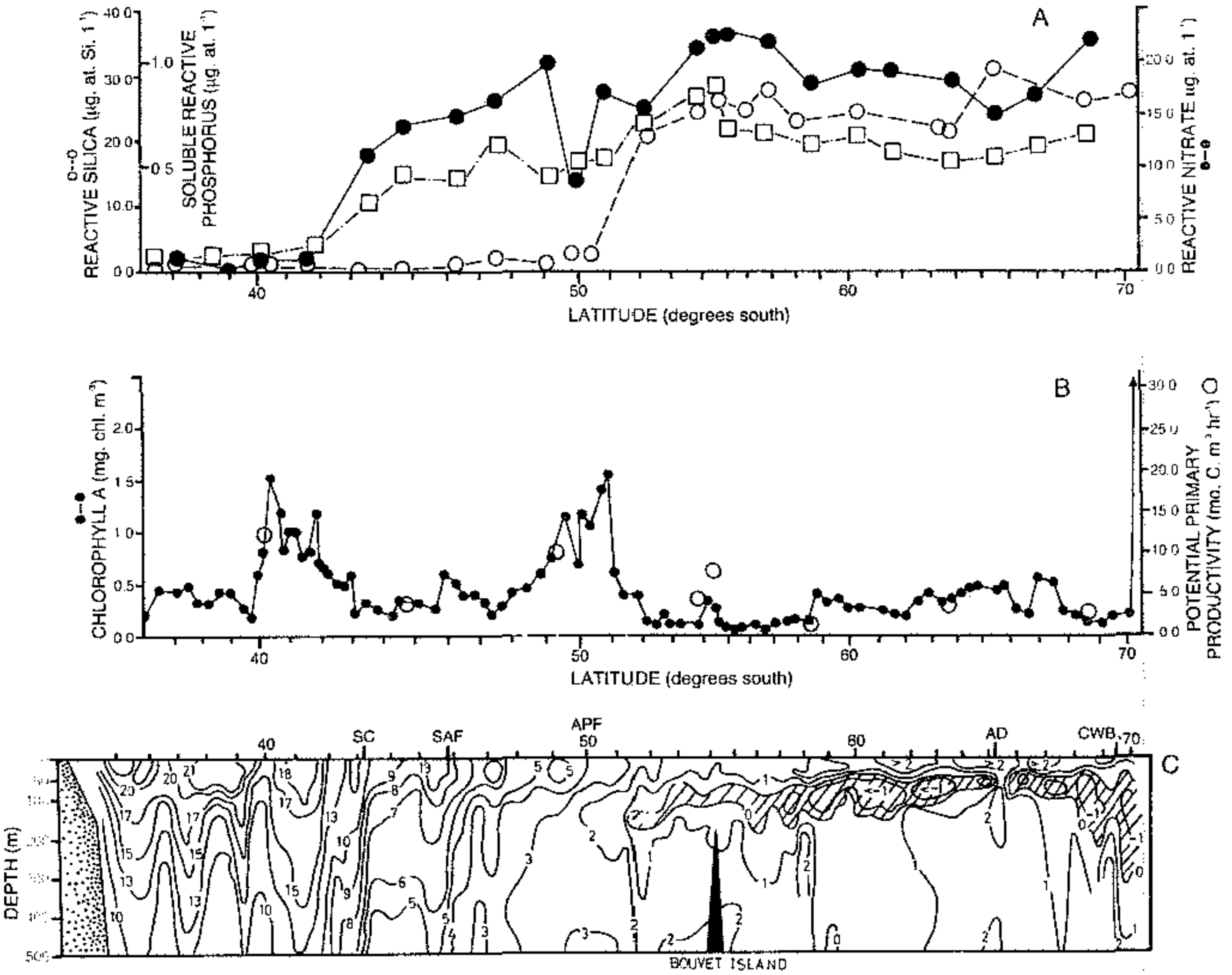


Fig. 4. Latitudinal variations in surface chlorophyll concentrations, and relative primary production (PPP) in relation to temperature and plant nutrients along northbound track.

A. NO_3(N), PO_4(P) & Si, μg at l^{-1}.
B. Chlorophyll *a*, mg m^{-3}; PPP, large open circles.
C. Temperature (°C) isolines derived from XBT records. The bars mark position of convergences referred to in text. See Fig. 3 for abbreviations.

Table 3a

Changes in temperature and nutrients across the Subtropical Convergence south of Africa derived from various sources. *Centre* denotes the mean of the horizontal gradient measured; *drop* the decrease in values going southward.

Author	Date	Temp (°C)		PO_4-P (μg at l^{-1})		NO_3-N (μg at l^{-1})		Si (μg at l^{-1})	
		Centre	Drop	Centre	Drop	Centre	Drop	Centre	Drop
Ishino *et al.* (1958)	Mar 1957	15	2,5	—	—	—	—	—	—
Fukase (1962)	Dec 1957	12,1	7,1	0,7	−0,6	—	—	—	—
Fukase (1962)	Mar 1958	11,7	8,3	0,9	−0,4	—	—	6	−2
Fukase (1962)	Dec 1958	12,5	3,2	0,9	−0,2	—		—	—
Fukase (1962)	Feb 1959	13,2	13,2	—	—	—	—	3	−4
Fukase (1962)	Dec 1959	14,0	7,2	0,7	−0,6	-	—	0,5	−1
Fukase (1962)	Mar 1960	17,3	13,7	0,6	−1,2	—	—	1	0
Kuga *et al.* (1963)	Dec 1961	9,0	4,0	1,2	−0,8	—	—	18	−9
Kuga *et al.* (1963)	Feb 1962	8,0	4,0	—	—	—	—	11	−4
Shiozaki (1966)	Feb 1966	—	—	0,6	−1,2	9	−9	1	−1
Jacobs *et al.* (1980)	Mar 1974	8,0	5,0	1,1	−0,8	—	—	2	−3
Allanson *et al.* (1981)	Jan 1980 (S)	13,6	7,4	0,2	−0,1	7	−7	0,2	−0,1
Allanson *et al.* (1981)	Jan 1980 (N)	11,5	3,4	0,2	−0,1	6	−10	0,5	−0,3

Table 3b

Changes in temperature and nutrients across the Antarctic Polar Front south of Africa derived from various sources. *Centre* denotes the mean of the horizontal gradient measured; *drop* the decrease in values going southward.

Author	Date	Temp (°C)		PO_4-P (μg at l^{-1})		NO_3-N (μg at l^{-1})		Si (μg at l^{-1})	
		Centre	Drop	Centre	Drop	Centre	Drop	Centre	Drop
Fukase (1962)	Dec 1956	3,5	3,2	—	—	—	—	—	—
Ishino *et al.* (1958)	Mar 1957	3,8	2,0	—	—	—	—	20,2	−20
Torii *et al.* (1959)	Dec 1957	3,7	3,0	1,1	0,4	—	—	18	−21
Torii *et al.* 1959	Mar 1958	3,6	1,5	1,4	0,0	—	—	21	−34
Torii *et al.* (1959)	Dec 1958	3,9	3,6	0,8	0,8	—	—	—	—
Torii *et al.* (1959)	Feb 1959	3,9	2,8	—	—	—	—	20	−30
Fukase (1962)	Dec 1959	3,0	3,9	2,1	0,3	—	—	17	−26
Fukase (1962)	Feb 1960	3,0	2,7	2,0	0,2	—	—	19	−22
Kuga *et al.* (1963)	Dec 1961	3,0	2,0	2,2	−1,0	—	—	22	−20
Kuga *et al.* (1963)	Feb 1962	3,0	2,0	—	—	—	—	28	−7
Shiozaki (1966)	Feb 1966	—	—	1,7	−0,2	22	−4	22	−40
Jacobs *et al.* (1980)	Mar 1974	2,5	2,0	1,4	−0,1	—	—	19,0	−32
Allanson *et al.* (1981)	Jan 1980 (S)	4,0	2,0	0,8	0,2	23	−4	16	−26
Allanson *et al.* (1981)	Jan 1980 (N)	2,2	2,6	1,3	−0,2	16	2	12	−10

In such cases the measurements of the two stations spanning the front were used, however far apart geographically. Temperature values for some cruises were extracted from publications of other authors; the authors mentioned in the first column of the table in all cases refer to the publication from which nutrient concentrations were derived. Columns denoted *centre* indicate the mean of the temperature or concentration gradients; *drop* denotes the range from north to south.

Our nutrient concentrations measured at the Subtropical Convergence (Table 3a) generally seem on the low side compared to those found by others, which may be a function of the coarser station spacing during most other cruises. Silica values measured in December 1959 (Fukase 1962), when closer station spacing was employed, compares better with values we found. Most of the Japanese measurements included nitrite-nitrogen, only one value of nitrate-nitrogen (Shiozake 1966) can be used for comparison. For this table the latitude of the Subtropical Convergence was selected mainly on the basis of gradients in nutrient concentrations while temperature and salinity data were used in a support role where the nutrient fronts were complicated or unclear.

A comparison of values determined across the Antarctic Polar Front (Table 3b) shows that our phosphate-phosphorus values fall well within the range of historical measurements, while silicate is rather low and exhibits a smaller increase across the front than that usually observed. The Antarctic Polar Front was here defined as the centre of the strongest horizontal silicate gradient. The latitude of the front determined in this way does not always agree in detail with that derived from thermal information. These differences are discussed in greater detail in the next section.

Differences in concentration values across the two frontal systems during the southbound and northbound tracks of our cruise, may, in part, be due to the decrease in station spacing. Nitrate-nitrogen was, however, significantly higher on the whole of the southbound track, as was phosphate-phosphorus and, to a lesser extent, silica. The N:P ratio as measured along the ship's tracks and given in Fig. 5 was high, 29:1. This

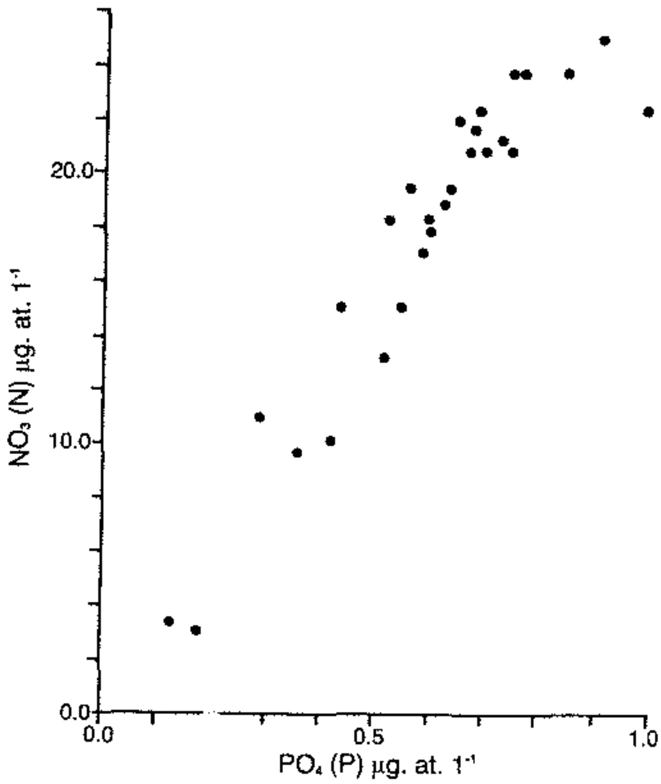


Fig. 5. N:P ratios as measured along the southbound, eastern and northbound tracks of the *S.A. Agulhas* cruise, January 1981.

differs markedly from the 16:1 ratio normally found in phytoplankton cells. It is generally recognised (Raymont 1980) that very wide variations in the N:P ratio of the euphotic zone do occur, so this high value for the N:P ratio may reflect a lowering of phosphorus as a result of phytoplankton activity during the southern summer.

Light, chlorophyll and primary production

Photosynthetically active radiation profiles were observed at each noonday station. The attenuation coefficients recorded in Fig. 3b are inversely correlated with chlorophyll concentration. The difference was most striking at 49°S-51°S, in the vicinity of 63° and over the Antarctic shelf where a high attenuation value of ϵ = 0,187 was obtained. While the majority of Chl *a* concentrations fell within the range (0,06-2,89 mg m^{-3}) reported by Tanimura (1981), along the Antarctic continent two stations (69°49'S, 0,01°17'W and 70°14'S, 02°48'W) gave 3,52 and 4,28 mg m^{-3} for samples taken from 5 m depths close to the Antarctic ice shelf.

With the gear available it was not possible to sample the euphotic depths either underway or at the daily CTD station. The overside and scientific supply samples drawn from $\simeq$ 5 m below the surface were therefore used in the Gargas Lϕnholdt incubator with its array of neutral density filters to assess the effect of light attenuation upon photosynthetic rate. If the individual rates from the neutral density array are expressed as a per cent of the maximum and plotted against variation in simulated downwelling irradiance (I) as per cent,

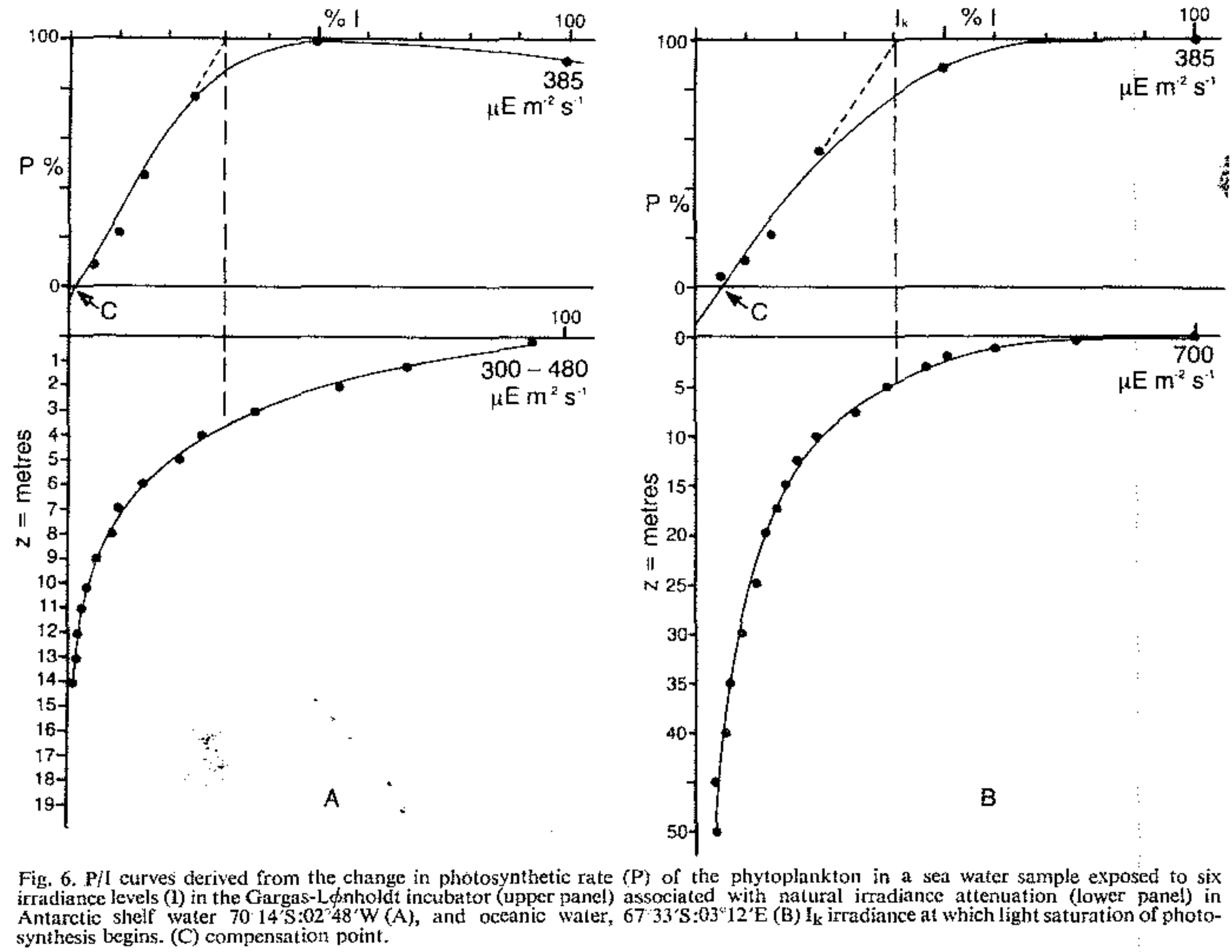


Fig. 6. P/I curves derived from the change in photosynthetic rate (P) of the phytoplankton in a sea water sample exposed to six irradiance levels (I) in the Gargas-Lϕnholdt incubator (upper panel) associated with natural irradiance attenuation (lower panel) in Antarctic shelf water 70°14'S:02°48'W (A), and oceanic water, 67°33'S:03°12'E (B) I_k irradiance at which light saturation of photosynthesis begins. (C) compensation point.

a characteristic P/I curve is obtained. When this curve is linked to the known pattern of light attenuation for the water column from which the incubator sample was taken, as shown in Fig. 6, the positions of the compensation depth, and the depths of onset of light saturated photosynthesis (I_k) and of maximum photosynthetic activity (P_{max}) can be inferred.

The close similarity of the P/I curve obtained from the incubated samples to the standard photosynthetic profile for unproductive or productive, salt or freshwater (Fogg 1981) provides the means whereby this incubator method can be used to obtain effective estimates of both P_{max} and a potential productivity integral, PPP. Rodhe (1965) has shown that ΣP (of which PPP is an estimate) is related to P_{max} in the equation

$$\Sigma P = z_{0.1\,mpc} \cdot P_{max} \qquad (1)$$

by the depth at which most penetrating component (MPC) of the light, usually green (or in this instance PAR) has been reduced to 10 per cent of its surface value.

Such an analysis of the changing pattern of phytoplankton photosynthesis with irradiance assumes that the distribution

Table 4

Photosynthetic fixation of carbon in mg $C.m^{-3}.h^{-1}$ (P) in the Gargas Løhnholdt incubator. The means of these two sets of pairs were used in construction of Fig. 6a.

	Oceanic (67°33'S)		Antarctic shelf (70°14'S)	
Irradiance level (%)	Scientific supply	"Challenger" bottle	Scientific supply	"Challenger" bottle
160	0,07	0,08	1,81	2,21
100*	0,09	0,10	2,13	1,95
50	0,07	0,08	2,56	1,82
25	0,05	0,05	1,96	1,41
15	0,03	0,01	1,03	0,94
10	0,01	0,01	0,39	0,58
5	0,01	0,00	0,20	0,18
PPP $\simeq \Sigma P$	2,34	2,60	17,92	15,47

* 385 μ Einsteins s^{-1}

Table 5

Chlorophyll, productivity and other chemical and physical data for *full* 5 metre depth stations on each leg of the *S.A. Agulhas* cruise, January 1981. The noon stations on the southbound leg are shown as CTD stations Fig. 1.

Date	GMT	Lat.	Longit.	Temp. (°C)	Salinity (‰)	Chl *a* ($mg.m^{-3}$)	P_{max} ($mgC.m^{-3}h^{-1}$)	PPP $\simeq \Sigma P$ ($mgC.m^{-2}h^{-1}$)	NO_3—N	PO_4—P	Si	pH	Total Alk	Carbon Alk.
									(μg at l^{-1})				(meg.l^{-1})	
		Leg 1					Southbound							
31.12.80	0600	36°17'S	20°22'E	21,5	35,403	0,64	0,27	4,8	0,5	1,20	0,2	8,16	2,05	1,95
31.12.80	1040	36°55'S	21°06'E	24,1	35,363	0,31	0,22	4,9	0,6	1,00	0,2	8,16	2,33	2,23
1.1.81	0412	29°55'S	24°14'E	15,0	35,251	0,76	0,18	3,0	3,0	0,18	0,7	8,03	2,36	2,31
1.1.81	1000	41°08'S	23°47'E	14,0	35,047	1,04	1,04	18,2*	3,4	0,13	0,0	7,93	2,30	2,25
2.1.81	0430	44°16'S	22°32'E	9,0	34,563	0,39	0,17	3,5	11,0	0,29	0,0	7,96	2,17	2,11
2.1.81	1200	45°47'S	21°57'E	8,0	33,859	0,28	0,31	7,0	18,4	0,60	1,8	7,73	2,28	2,25
3.1.81	0400	48°46'S	20°24'E	4,0	33,856	0,47	0,36	7,1	22,4	0,99	6,5	7,70	2,28	2,25
3.1.81	1030	50°06'S	19°41'E	4,0	33,830	0,67	0,94	18,8*	21,0	0,75	3,6	7,71	2,30	2,27
4.1.81	0530	53°39'S	17°40'E	1,0	34,148	0,11	0,06	1,7	25,1	0,91	28,2	7,58	2,30	2,28
4.1.81	1057	54°48'S	17°18'E	0,8	33,795	0,17	0,09	2,7*	23,9	0,77	29,5	7,70	2,25	2,23
5.1.81	0505	58°03'S	14°37'E	0,3	33,779	0,16	0,12	13,1	21,5	0,73	30,7	7,61	2,33	2,31
5.1.81	1130	59°13'S	13°48'E	—1,0	32,837	0,45	0,53	15,9*	21,0	0,70	28,5	7,59	2,23	2,21
6.1.81	0500	62°17'S	10°26'E	0,3	34,100	1,06	0,68	10,7	19,0	0,63	25,8	7,70	2,37	2,35
6.1.81	1100	63°25'S	09°12'E	0,5	34,147	1,03	0,51	8,9*	21,0	0,67	24,7	7,67	2,17	2,15
7.1.81	0600	66°20'S	04°50'E	0,3	33,748	0,16	0,11	2,9	23,9	0,85	33,4	7,61	2,30	2,28
7.1.81	1200	67°33'S	03°12'E	—0,1	33,808	0,14	0,09	2,3*	23,9	0,76	32,4	7,57	2,30	2,28
8.1.81	0615	70°14'S	02°48'W	—1,0	33,414	2,13	2,38	29,3*	15,2	0,44	26,0	7,85	2,29	2,26
					Polarbjorn-bukta									
9.1.81	1100	70°14'S	02°48'W	—1,0	33,431	2,19	2,66	24,4*	14,5	0,49	26,0	7,85	2,30	2,27
		Leg 2												
11.1.81	2340	69°31'S	15°21'W	—0,3	33,734	0,45	0,16	3,2	17,6	0,66	26,3	7,70	2,29	2,27
					Haakon VII Sea									
12.1.81	0620	69°33'S	01°34'W	—0,3	33,522	2,19	1,90	20,1	16,1	0,54	27,1	7,84	1,72	1,69
13.1.81	0720	69°49'S	02°04'W	—0,3	33,523	1,93	2,16	19,0*	13,4	0,53	25,4	7,79	2,29	2,26
14.1.81	1200	69°41'S	09°10'E	,0,3	33,130	2,38	2,71	21,6*	9,8	0,36	24,8	7,84	2,28	2,25
					Continental Shelf									
15.1.81	1200	69°49'S	01°17'W	—0,2	33,394	3,52	2,04	15,7	10,4	0,42	25,9	7,85	2,28	2,25
17.1.81	1200	70°14'S	02°48'W	—0,3	33,104	4,28	3,48	22,9	—	—	26,7	7,89	2,29	2,25
					Polarbjorn-bukta									
19.1.81	1200	70°14'S	02°48'W	—0,6	—	3,76	2,09	15,2	—	—	27,9	7,92	2,26	2,22
		Leg 3					Northbound							
21.1.81	1200	68°43'S	01°53'W	2,0	33,968	0,13	0,09	0,27	22,2	0,65	25,8	7,65	2,50	2,48
22.1.81	1200	63°41'S	01°53'W	2,0	34,063	0,36	0,16	3,4	18,4	0,53	21,3	7,73	2,30	2,27
23.1.81	1200	58°30'S	03°22'E	1,6	33,946	0,19	0,08	2,0	18,1	0,60	22,8	7,71	2,23	2,21
24.1.81	0800	54°26'S	03°27'E	1,5	33,847	0,30	0,35	7,8	22,6	0,82	26,5	7,66	2,30	2,28
24.1.81	1200	53°54'S	03°29'E	1,3	33,902	0,13	0,16	4,4	22,6	0,82	24,2	7,72	2,31	2,29
25.1.81	1200	49°13'S	06°43'E	5,0	33,845	0,75	0,60	10,1	20,7	0,45	1,1,	7,78	2,30	2,27
26.1.81	1200	44°45'S	10°28'E	9,0	33,072	0,30	0,18	4,0	13,9	0,47	0,2	7,91	2,28	2,24
27.1.81	1200	40°12'S	14°19'E	17,7	35,484	0,80	0,75	12,4	0,2	0,06	0,6	8,09	2,26	2,18
28.1.81	1200	35°33'S	17°07'E	21,0	35,421	0,26	0,59	13,8	0,3	0,02	0,2	8,15	2,31	2,21

* Stations at which $z_{0.1}$ PAR was measured directly.

of algal cells is homogeneous throughout the euphotic depth. While this is not altogether an acceptable assumption, the pattern of light attenuation did suggest that the algal stocks were uniformly distributed to the compensation point.

Unfortunately it was not possible to develop this analysis for each incubation series as light attenuation was only measured at local noon on the southward voyage and not at all on the return, northward voyage.

However, a useful semilog relationship has been established between the known depths of $z_{0,1}$ PAR and chlorophyll *a* concentrations, such that

$$\log y = 1{,}111 + 0{,}073\,x, \; (r^2 = 0{,}989,\; n = 16) \qquad (2)$$

where y is the chlorophyll concentration in mg m^{-3} and x the depth of 0,1PAR in metres. This expression has been used to estimate $z_{0,1}$PAR where only chlorophyll *a* concentration is known, and consequently ΣP. These data are given in Figs. 3c and 4b, and Tables 4 and 5, Table 4 serving to show the similarity of the results obtained from the scientific supply and "Challenger" bottles.

As might be expected, P_{max} and ΣP fall within the range reported by El-Sayed (1970) and emphasize the raised productivity of Antarctic shelf-water, increased activity in the vicinity of physical frontal systems and the depressive effect of warm summer water upon both phytoplankton standing stock and productivity.

Discussion

Physical frontal systems

Frontal zones in the Southern Ocean have received increasing scientific interest since the 1930's (Deacon 1937) and have since been defined in different ways by different authors. Gordon (1971) has given a useful summary of these definitions for the Antarctic Polar Front and Ostapoff (1962b) also for the Antarctic Divergence. In defining the various fronts in our temperature sections we have followed closely the definitions used by Sievers and Emery (1978).

On the southbound track (Fig. 3d) the five usual fronts were clearly manifest. The Subtropical Convergence (SC) was found at 41½ S at depth while its surface expression from the ship's thermograph was at 43½°S. This interpretation is supported by surface salinities measured at the same time (Fromme *et al.* 1982). The sub-Antarctic Front (SAF) at 46°S, is also so supported. Surface salinity gradients are recurring features associated with the SAF, but are not present on all occasions. Between the SAF and the Antarctic Polar Front (APF) a zone of varying width, the Antarctic Polar Front Zone (APFZ), is found. In the southbound track the surface expression of the APF (a drop of 2 °C centred at 4 °C) was found at 48½°S while the subsurface expression, namely the northern limit of the subsurface 2 °C water, was found at 49°S. The core of the Antarctic Divergence (AD) may be at 64½°S where a peak in the surface salinities was also observed (Fromme *et al.* MS, 1982). The continental water boundary (CWB) was at 69°S.

On the return trip (Fig. 4c) the CWB was at 69½°S, while a much narrower and strongly defined AD was found at 64½°S over the Maud Rise. While the surface expression of the APF lay slightly north of the subsurface expression on the southbound track (Fig. 4c), on the northbound track the surface expression lay south (51°S) of the subsurface expression (50 S). A well-defined SAF once again coincided with a surface salinity gradient at 46°S (Fromme *et al.* 1982) while the SC was at 43 °S.

The latitudinal position of the fronts changed little between the two tracks, the difference of about 100 km in the position of the APF being the greatest one.

Little work of sufficient detail has been done on oceanic fronts south of Africa with which these results may be compared. Sea surface temperatures have on occasion been used to locate fronts (Taljaard 1958, La Grange 1961, Nieman 1965, Lloyd 1974) and two expendable bathythermograph sections were presented by Taylor *et al.* (1978). All fronts located during the cruise of January 1981 lay well within the

Table 6

Pearson correlation coefficient matrix for 10 variables measured in the surface waters of the Southern Ocean during the summer cruise of the *S.A. Agulhas*, January 1981. The correlation coefficients (r) and levels of significance (P)[a] are given for each interrelationship.

Chl *a*	P_{max}	PPP	Temp.	NO_3(N)	PO_4(P)	Si	pH	Alkalinity	Carbon Alkalinity
Chl *a*	0,9215	0,7153	−0,2988	−0,2596	−0,3144	0,2586	0,2484	−0,1861	−0,174
	0,001***	0,001***	0,043*	0,076	0,040*	0,070	0,078	0,146	0,162
	P_{max}	0,8738	−0,3081	−0,2211	−0,3288	0,2514	0,2242	−0,1627	−0,162
		0,001***	0,038*	0,112	0,033*	0,076	0,101	0,179	0,180
		PPP	−0,2203	−0,2039	−0,3595	0,1346	0,1832	−0,1705	−0,153
			0,105	0,131	0,022*	0,224	0,150	0,167	0,194
			Temp.	−0,8222	−0,1967	−0,8395	0,8020	−0,0081	−0,184
				0,001***	0,140	0,001***	0,001***	0,482	0,148
				NO_3(N)	0,4747	0,6457	−0,9517	0,1118	0,276
					0,003**	0,001***	0,001***	0,271	0,063
					PO_4(P)	0,3085	−0,3985	−0,0788	−0,037
						0,043*	0,012*	0,334	0,421
						Si	−0,6701	0,0035	0,139
							0,001***	0,492	0,216
							pH	−0,1785	−0,347
								0,156	0,022*
								Total	0,982
								Alkalinity	0,001 ***
									Carbonate Alkalinity

[a]*** $P \leq 0{,}001$
** $P \leq 0{,}01$
* $P \leq 0{,}05$

historic spread of geographic positions determined in this manner, as well as within the spread of positions that have been determined by the programme of which these two XBT-sections form part (Lutjeharms *et al.* 1981).

The characteristics of the fronts during this cruise compare well with likenamed fronts that have been studied in other parts of the Southern Ocean, notably in the Drake Passage (Sievers & Emery 1978), in the Pacific Ocean (Emery 1977) and south of Australia (Savchenko *et al.* 1978). One may therefore assume that they are circumpolar, with the possible exception of the AD.

Relationship between parameters

The statistical correlation between measured values for productivity and chemical parameters, as well as sea surface temperature given in Table 5, have been calculated and are presented in Table 6.

This correlation matrix emphasises the highly significant correlation at the sea surface between chlorophyll *a* and potential primary production or a component of such, the maximum hourly photosynthetic fixation of carbon, P_{max}. $PO_4(P)$ exhibits a weak negative correlation with all three production components of the matrix, while $NO_3(N)$ shows significant correlations. The remainder of the chemical components measured seem not to be factors in contention for the fine control of potential production, although consideration must be given to the water mass in which they are measured. Within themselves they provide a number of interesting negative correlations hinted at in the above reporting of our results. For example, $NO_3(N)$, $PO_4(P)$ and Si are all strongly negatively correlated with pH, while temperature exhibits a positive correlation.

It may also be noted in Table 6 that temperature shows a strong negative correlation with $NO_3(N)$ and Si and a strong positive correlation to pH. This is to be expected, since both nitrate and silica increase southwards, while the temperature decreases. The phosphorus does not show this strong correlation. Clearly this is unacceptable as $PO_4(P)$ follows very much the same pattern as $NO_3(N)$. The likely explanation is that the first two values for SRP reported in Table 5 are as a result of poor technique. Our values on the northward leg are more likely to be good estimates.

A comparison between the components of Figs. 3 and 4 establishes some interesting correlations between the nutrient, biological and physical regimes. On the southbound track (Fig. 3) a slight increase in the Chl *a* and primary productivity was found between the Agulhas Current water and the Subtropical Convergence. A similar, but better resolved, increase was found in the same area on the return trip (Fig. 4). In both cases the increases in nitrate and phosphorus did not coincide with the SC, but commenced here and only levelled off at the APF. This is particularly so for the southward cruise track (Fig. 3).

Station spacing for nutrients was not sufficient to pick up detail of the sub-Antarctic Front; Chl *a* station spacing was. On the southward cruise (Fig. 3), the SAF was weakly developed; no change in Chl *a* concentrations across it was observed. On the northbound voyage it was strongly developed and correlated geographically with a moderate increase in Chl *a* (Fig. 4).

On the northbound track (Fig. 4) the subsurface expression of the Antarctic Polar Front was simple and singular, while the surface expression was resolved by a continuously registering thermograph. A significant peak in Chl *a* concentration, indicating increased primary productivity, was observed to lie between these two expressions of the APF. On the southward track (Fig. 3) the thermograph did not record; sea surface temperatures were recorded about every 30 nautical miles by Crawford bucket (Crawford 1965). Two increases in sea surface temperature were recorded in the general geographic vicinity of the APF. The one lies at $50\frac{1}{2}$°S, the other at $48\frac{1}{2}$°S. The northernmost one corresponds most closely to the predicted APF sea surface expression given by Mackintosh (1946), namely lying between 3,9° and 5,3 °C. It was thus selected as the most likely position of the surface expression. The subsurface expression is a complicated one in this case with the tongue of water with temperatures less than 2 °C broken at about 53°S (Fig. 3d). A sharp peak in the Chl *a* concentration coincides with the core of this semi-detached body of Antarctic Surface Water. If the southernmost gradient in the sea surface temperature were selected as the surface expression, then the peak in primary productivity would in this case also lie more or less between the surface and subsurface expression of the Antarctic Polar Front, as it did on the return voyage.

This productivity peak at the Antarctic Polar Front on the northward voyage corresponded well with a sharp decrease in nitrate (Fig. 4a). On the southbound voyage nutrient measurements were too widely spaced to resolve precisely the productivity peak, but a general decline in nutrients was observed here. Marked increases in silica were on both occasions measured south of the subsurface expression of the APF. On the northward cruise the silica gradient (measured at the sea surface) lay across the surface expression of the APF (Fig. 4). If the southernmost thermal gradient were selected as the true surface expression of the APF on the southbound voyage (Fig 3), the silica increase would lie across the surface expression of the APF here also.

On the southbound cruise the winter water in the Antarctic zone was only partially covered by summer water, having temperatures in excess of 0 °C. Where the presence of summer water was most marked, between about 63° to 69°S, the primary productivity was noticeably damped (Fig. 3c). On the northward track, about three weeks later, a more distinct layer of summer water had developed (Fig. 4c) with a corresponding decrease in primary productivity south of the Antarctic Polar Front. In the vicinity of the Antarctic Divergence, on the northbound track geographically coincident with the Maud Rise, there was a corresponding increase in silica, decrease in nitrate and, at the sea surface, a sharp decrease in Chl *a*.

South of the Continental Water Boundary there was a marked increase in Chl *a* concentrations for both legs of the cruise, which closely match the range reported by Fukuchi (1980) for Antarctic surface water south of 63°S in the Western Indian Ocean. On the southbound track this was matched by a poorly resolved decrease in all nutrients; on the return voyage only incomplete measurements of nutrients were carried out here (Fig. 4a). A synopsis of these data is given in Table 5.

Although somewhat different in longitude and time, these results indicate some consistent relationships. The first is the low Chl *a*, and thus primary productivity, in Antarctic Surface Waters once summer water has formed. Jacques and Minas (1981) have carried out a similar transect at 66°E. They observed that at the end of summer, biomass and production levels are close to those observed in oligotrophic waters. They concluded that the low fertility of the nutrient rich water may be due to an absence of certain trace metals. Although the view expressed by El-Sayed (1970), namely that striking regional differences in standing stock and primary productivity exist in the Southern Ocean may hold true, the strong similarities between our results and those of Jacques and Minas (1981) would suggest that the tentative conclusions they have put forward are important and should be tested.

A second consistent relationship involves the productivity increase at the location of the Antarctic Polar Front. This was also noted by Jacques and Minas (1981) as well as Pomazanova (1980). The latter even suggested that the correlation was so stable that current fields might be used to identify productivity zones. That the Antarctic Polar Front might, at the sea surface, be a divergence instead of a convergence, thus giving rise to the upwelling of nutrient rich water, was first mooted by Wexler (1959). Ostapoff (1962a) did some theoretical work in this regard and showed that upwelling would occur in the southern portion of the Antarctic Polar Front. According to his theory a second narrow zone of ascending motion, the sub-Antarctic Front, is found 5° - 6° of latitude north of the Antarctic Polar Front. These predictions agree well with our results, if it is assumed that upwelling would induce nutrient regeneration and thus an increase in primary productivity. The fact that decreased nutrients were measured at the location of the increased primary productivity suggests that indeed some other factor, such as trace metals, may play a role.

The increase in nutrients spanning the sub-Antarctic Surface Water, instead of occurring at the Subtropical Convergence, may be explained by the variability and large-scale turbulence of the area (Lutjeharms & Baker 1980, Lutjeharms 1981). The increase in productivity of the waters north of the Subtropical Convergence may thus also be due to the mixing of nutrient rich sub-Antarctic Surface Water from south of the Subtropical Convergence across it.

Conclusions

Although these measurements were by way of a preliminary, exploratory study, a certain number of tentative conclusions seem indicated, even at this early stage in what is hoped will become an extended research project.

1. A strong correlation between potential primary production and Chl *a* was found for the surface water between Africa and Antarctica.
2. Marked increases in primary production were seen at the Antarctic Polar Front, which correlated well with its surface expression. This may be caused by upwelling although there was evidence for ascending motion on these occasions.
3. Increases in primary production may occur at the sub Antarctic Front.
4. The formation of summer water in the Antarctic Surface regime may decrease primary production.
5. The factors limiting primary production in the area were not resolved and require further investigation.

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Microbial populations in Marion Island soils

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Mire and bog peats on Marion Island (46° 54'S, 37° 45'E) yielded higher plate-count estimates of viable aerobic bacteria and of fungi than did soils from slope areas when expressed on a soil dry weight basis. The single fjaeldmark *site investigated contained very low numbers of soil microorganisms. Manuring by seabirds and seals markedly enhanced soil N and P contents and manured sites exhibited greater populations of soil bacteria and fungi than non-manured sites. Plate-count estimates of soil microorganisms from the various island habitats were approximately similar to those reported for comparable habitats at other southern subpolar areas. The microorganisms were associated with the particulate rather than the peat solution fraction. At manured sites large numbers of microorganisms capable of reducing NO_3^- to NO_2^- and, tentatively, of bacteria forming NH_3 from NO_3^- were found. The numbers of bacteria at these sites capable of reducing NO_3^- to N_2 were low.*

Moerasveengrond op Marioneiland (46° 54'S, 37° 45'O) het by berekening op 'n grondslag van die droë grondmassa hoër plaattellings aërobe bakterieë en swamme gelewer as grond van hellinggebiede. Klein getalle mikroörganismes het in 'n fjaeldmark-*gebied voorgekom. Die uitskeidings van seevoëls en robbe het die grond se N- en P-inhoud asook die mikrobebevolking verhoog. Die getalle grondmikroörganismes in verskeie habitats op Marioneiland het ooreengekom met wat in soortgelyke habitats op ander suidelike subpoolgebiede gevind is. Die mikroörganismes was met gronddeeltjies eerder as met die grondwaterfraksie geassosieer. By gebiede wat deur diere*