A CONTRIBUTION TO THE OCEANOLOGY OF THE PRINCE EDWARD ISLANDS

Dissertation
Submitted in Partial Fulfilment of the
Requirements for the Degree of
MASTER OF SCIENCE
of Rhodes University

by
LLEWELLYN DEREK PARKER
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1. PREFACE

This study is part of a continuing enquiry into the ecology of the seas immediately surrounding the Prince Edward Island Group. It was sponsored initially by the South African National Committee for Oceanographic Research and later by the South African Special Committee for Antarctic Research. I would like to thank both these bodies for their support. My thanks are also due to the South African Department of Transport and the Sea Fisheries Research Institute for ship time on the vessels S.A. Agulhas (Master; W. Leith) and R.S. Africana (Master; D. Krige).

I wish also to acknowledge the support lent to me by my supervisor Professor B.R. Allanson and the aid rendered by Dr B.P. Boden.

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3. ABSTRACT

While the terrestrial ecosystem of the Prince Edward Island Group has been subject to intensive research, the marine ecosystem has to a large extent been neglected. This together with the possible existence of an "island effect" at these islands, as was first proposed after the visit to these islands of the French vessel *Marion Dufresne*, led to the initiation of a programme to determine the distribution of standing stocks and the productivity of phytoplankton and zooplankton in the neritic seas of these islands.

To do this and before a detailed biological survey could be attempted, it was first necessary to define the physical and chemical properties of the circuminsular waters. This dissertation discusses the results of several surveys to these islands in the light of a possible "island effect" and comments upon processes likely to influence such an effect.

4. INTRODUCTION

The knowledge that islands some distance from major land masses have viable benthic communities and to a lesser extent endemic zooplankton communities, establishes the premise that islands, especially those in the path of persistent ocean currents, have associated with them and in their immediate vicinity, hydrographical features that retain the feebly swimming components of the planktonic community close to the islands. The validity of this premise is appreciated when it is considered that were such hydrographical features lacking, any passive or semi-passive pelagic forms would be swept away from the islands. The result of this would be that no recruitment of the benthic fauna, most of which reproduce by planktonic larval stages (Thorson, 1957), could take place and only a few forms would be able to survive and colonise the available structural niches successfully.

In December 1873 when H.M.S. Challenger visited the Prince Edward Island Group, they found an established and diverse benthic community comprising about 200 species between and to the east of the islands (Thomson & Murray, 1885). Later cruises in the 1930's by the British vessel R.R.S. Discovery and the French vessel Bougainville contributed very little to our knowledge regarding these islands because very little research was conducted by R.R.S. Discovery in the immediate vicinity of the islands and the samples collected by the Bougainville have never been studied and are presumed to be lost (De Villiers, 1976). It was not until the cruise of the French vessel Marion Dufresne in March 1976, over one hundred years after H.M.S. Challenger, that further evidence to support the idea of an "island effect" at the Prince Edward Islands was put forward (El-Sayed et al., 1979a).

The term "island effect" or "island mass effect" was coined after the discovery that areas near islands could be characterised by elevated phytoplankton stocks and increased primary production levels (Raymont, 1980; Parsons et al., 1982). While the actual areas exhibiting enhanced phytoplankton growth were usually located some distance in the lee of islands (160 km for Johnston Atoll and 190 km for Madiera; Barkley, 1972), there are also reports of increased phytoplankton growth in the immediate vicinity (less than 10 km) of some islands. A review of available literature reporting possible "island effects" in the immediate vicinity of islands is presented as a later section as part of this study.

In the view of many researchers, the islands of the Southern Ocean are integral parts of the marine ecosystem (Knox, 1960; El-Sayed, 1977). The validity of this viewpoint is supported by the fact that at least 1.5×10^6 seabirds make their way to Marion Island, the larger of the Prince Edward Island Group, each year to breed and rear their young (Siegfried et al., 1978). The possible link between these terrestrial predators and the accumulation of food resources, both planktonic and benthic upon which some species feed, by conservative hydrographic processes in the immediate vicinity of the islands needs closer examination.

Consequently this study examines the results of a survey conducted by the Marion Dufresne in March 1976 (Arnaud & Hureau, 1979) and data collected, by the author, of five cruises to the Prince Edward Islands in 1982, 1983 and 1984 in an attempt to;

1. establish the likelihood or otherwise of an "island effect" in the immediate vicinity of the Prince Edward Island Group,
2. to characterise this effect in terms of the physical, chemical and biological parameters measured on these cruises and
3. to examine the evidence of upwelling in the lee of Marion Island as the principal mechanism contributing to the enhanced food stocks in the island seas.

5. PROCESSES LIKELY TO CONTRIBUTE TOWARDS THE ESTABLISHMENT AND MAINTENANCE OF AN "ISLAND EFFECT".

Vortices in the wakes of objects in the paths of currents were shown in the laboratory by Von Karman as early as 1911 (White, 1973) and the association between vortices or eddies and plankton has been known since 1948 when Sargent & Walker (1948) found that diatom growth within eddies off the southern Californian coast was enhanced and they suggested that enrichment of the surface nutrients by upwelling in the centres of these eddies led to the enhanced growth. Boden (1950), while examining the distribution patterns of euphausiids also in the southern Californian waters, established a correlation between sigma-t values associated with eddies and the concentrations of these crustacea. He concluded that while the increased sigma-t values were the result of upwelling in the centres of the eddies, the increased euphausiid concentrations were due to sluggish circulation within the centres of the eddies and not directly related to nutrient or phytoplankton levels.

The link between eddies, islands and plankton was first demonstrated in 1952 when Boden (1952), from sigma-t values, determined the summer circulation pattern over the Bermuda seamount and found that an anticyclonic eddy dominated the system (Fig. 1A). When the summer zooplankton community was examined, he found that the plankton was conserved or entrained by this eddy. Later Boden & Kampa (1953) conducted a similar survey this time in the winter months and found that the pattern was reversed with a cyclonic eddy as the dominant feature (Fig. 1B).

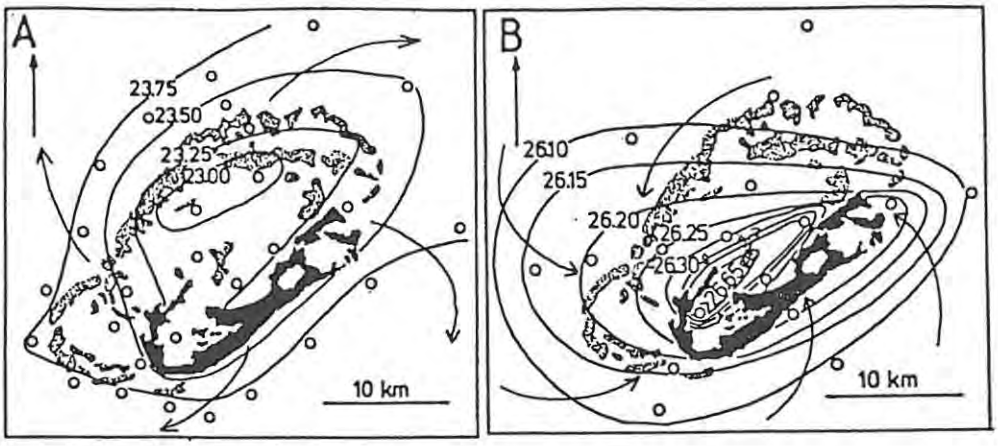

Fig. 1. A - Summer and B - Winter circulation patterns over the Bermuda seamount inferred from sigma-t contours. These diagrams were redrawn from Boden (1952) and Boden & Kampa (1953) The dark areas represent those areas above mean sea level and current direction is indicated by the arrows.

An examination of previous plankton records from Bermuda showed that the more feeble swimmers amongst the plankton disappeared during the winter months. From the results of these two surveys, Boden & Kampa (1953) concluded that the summer circulation pattern favours the survival of an endemic plankton population by entraining the more feeble swimmers and retaining them close to the island while the adverse winter circulation pattern permits the survival only of those forms that possess dormant winter stages which enable them to survive in local pockets until the summer.

The distribution of primary production in relation to the distance offshore from islands was investigated in 1955 when Doty & Oguri (1956) determined the rate of primary production at monthly intervals over fourteen months at four stations to the east of the island of Oahu in the Hawaiian chain. They found that the amount of carbon assimilated per cubic metre per hour decreased exponentially by two orders of magnitude between the closest and furthermost stations (Fig. 2).

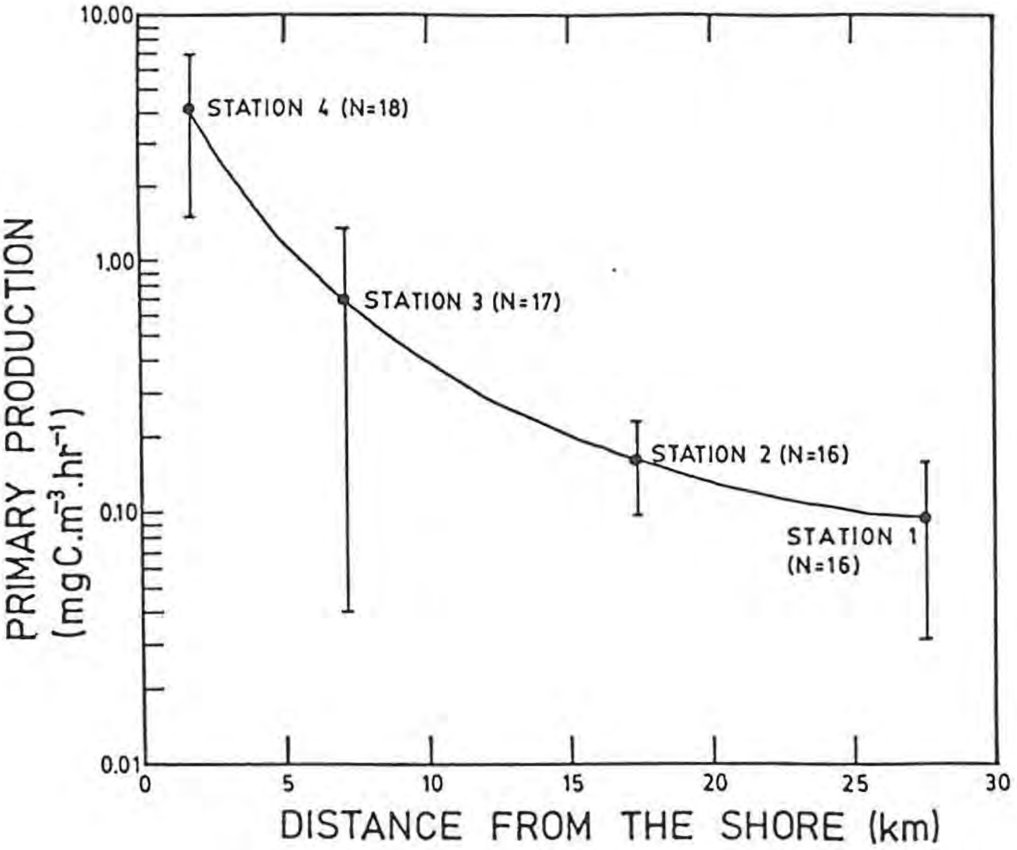

Fig. 2. Mean values of primary production ($mgC.m^{-3}.hr^{-1}$) measured over a period of fourteen months at four stations east of Oahu Island (Hawaii). The vertical bar represents the standard deviation about the mean and the value N indicated the number of observations or measurements. Redrawn from Doty & Oguri (1956).

No explanation for this inverse relationship between production and distance from the island was offered by the authors other than a tentative suggestion that the increase in primary production could be in response to the release into the water of inorganic nutrients from benthic algae. They offer the suggestion that these algae accumulate and concentrate nutrients from passing waters and run-off. These nutrients could then be released into the water column through the action of bottom feeding herbivores.

At Barbados in 1962 and 1963, Emery (1972) using both direct and indirect measurements postulated the existence of a stable eddy system in the immediate vicinity (within 10 km) of the island. Direct measurements included current meter measurements in the lee of the island and drift bottle experiments. He found that the current vectors obtained by the current meters underwent periodic oscillations and assumed that these oscillations were due to eddies formed in the lee of the island being shed at regular intervals. Drift bottle recoveries, some of the bottles were recovered from or near to the island 48 days after their deployment, supported this assumption.

Indirect measurements (zooplankton samples and capture-mark-recapture experiments with flying fish) provided further support for this eddy hypothesis. When the distribution of the chaetognath *Sagitta hispida*, which is almost always associated with coastal waters was examined, Emery found that it was more abundant in the lee or west coast of the island and all stages of maturity were observed. These observations indicated that *S. hispida* was able to reproduce in this area, 475 km from the nearest large land mass, and Emery in an attempt to account for this suggested that the west coast of Barbados represented a localised area of coastal water sufficiently stable for *S. hispida* to maintain a population.

Evidence of an "island effect" in the subAntarctic at the Kerguelen, Heard, Crozet and Prince Edward Islands was reported by El-Sayed & Jitts (1973) and El-Sayed *et al.* (1979a) after discovering substantial increases in phytoplankton standing stocks and primary production in the vicinity of these islands.

Recent research conducted around small Australian islands and coral reefs in the path of tidally induced currents (Wolanski *et al.*, 1984 and Wolanski & Imberger, 1984) using current meters, drogues, temperature sensors and aerial and satellite imagery, has demonstrated the existence of eddies and wakes in the lee of these islands, similar to those observed in the laboratory.

It is reasonable to assume that eddies in the immediate vicinity of islands would also be characterised by increased phytoplankton and zooplankton stocks. These increases could be due to either decreased current velocities in the centres of the eddies or to the eddies "collecting" or entraining plankton. The ability of eddies to conserve the community structure and biomass of plankton has been observed in eddies from the Gulf Stream and Polar Front (Owen, 1981). Although these eddies attenuate and lose their physical characteristics with time, they may be biologically distinguishable for long periods of time because they retain the plankton isolated from the front when they formed. These eddies can also transport a zooplankton community far out of their normal range. This has been demonstrated for the cold water euphausiid *Nematoscelis megalops* by Wiebe & Boyd (1978). They found that repeated occurrences of *N. megalops* in the Sargasso Sea, far out of its normal range in the slope water off the east coast of North America, could be related to cold core rings from the Gulf Stream decaying in the Sargasso Sea.

Corioli's force which, in the southern hemisphere, directs a component of a current to the left of the direction of flow (Ekman, 1905), may play an important part in this ability of eddies to retain plankton in counterclockwise eddies by directing a component of the flow towards the centre of the eddy and trapping the more feeble swimmers of the zooplankton and the phytoplankton which cannot swim against this inward component. The effectiveness of Corioli s force in this type of circulation depends upon the current velocity, the depth of the water and the size of the eddy (Sverdrup et al., 1942).

Eddies in the wake of islands that are regularly bathed by ocean currents have been demonstrated by White (1973) and Hogg et al. (1978) to mention just two. These eddies are located at some distance from the islands and are therefore, unlikely to have any effect on the nearshore environment investigated in this study which attempts to establish the likelihood or otherwise of an "island effect" in the immediate vicinity of the Prince Edward Island Group through an examination of physical, chemical and biological data collected in the sea surrounding the islands.

6. STUDY AREA

The Prince Edward Island Group (47°S,38°E) is located within the Southern Ocean, 2 400 km southeast of Cape Agulhas. In this study, the Subtropical Front is regarded as the northern boundary of the Southern Ocean so as to include the whole of the Antarctic Circumpolar Current or West Wind Drift (Sverdrup *et al.*, 1942; Kort, 1962; Valentine & Lutjeharms, 1983) instead of the Antarctic Polar Front which is favoured by British researchers (Knox, 1970). Like the Hawaiian islands, the Prince Edward Islands are thought to represent the twin peaks of coalescing shield volcanoes which arose from the mid-ocean ridge (Verwoerd, 1971) about 250 000 years ago (McDougal, 1971).

Marion, the larger of the two islands, has a surface area of 290 km^2 and rises to an altitude of 1 230 m while Prince Edward which lies 22 km north-northeast of Marion has a surface area of only 44 km^2 and reaches an altitude of 672 m (Verwoerd, 1971). The shoal platform separating these islands has a mean depth of 180 m and falls off rapidly to the 1000 m contour (Fig, 3).

It is generally accepted that the Prince Edward Islands lie within the subAntarctic zone, between the Antarctic Polar Front and the Subtropical Front (Fig. 4) but there has been recent speculation as to the validity of this supposition (Deacon, 1983). The Antarctic Circumpolar Current or West Wind Drift bathes the islands with a maximim velocity of 15 $cm.sec^{-1}$ (Pickard & Emery, 1982) and together with the the westerly winds which predominate in these latitudes (Fig. 5), is responsible for the complex and variable hydrographic patterns which are described later. There is no seasonal or monthly variation in either wind velocity or direction (Fig. 5) and the prevailing wind blows mainly from the north-western quadrant with an average velocity of 10 $m.sec^{-1}$.

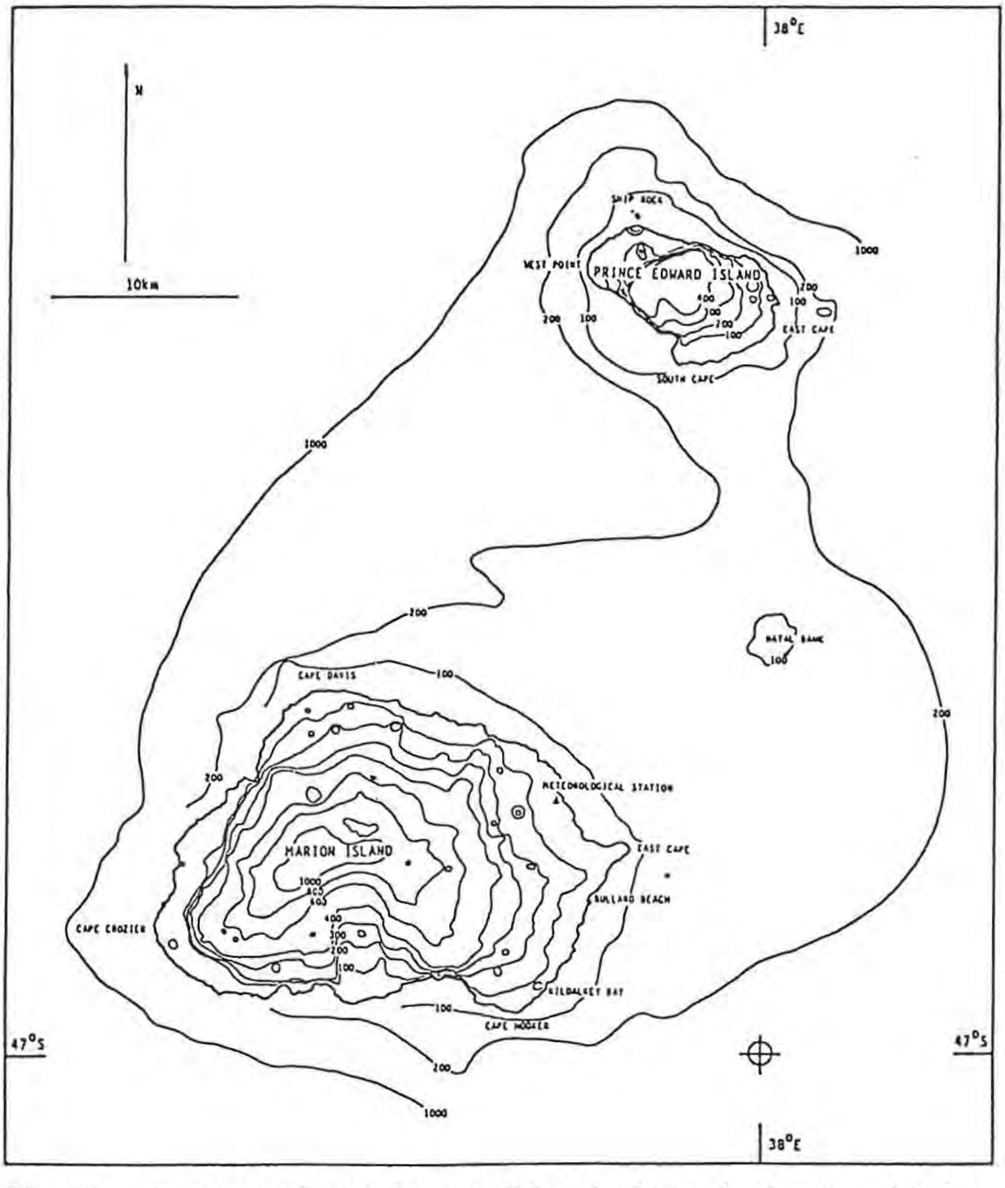

Fig. 3. A map of the Prince Edward Island Group showing topographic and hydrographic features. Redrawn from S.A. Navy chart number 2003. Contours are in metres.

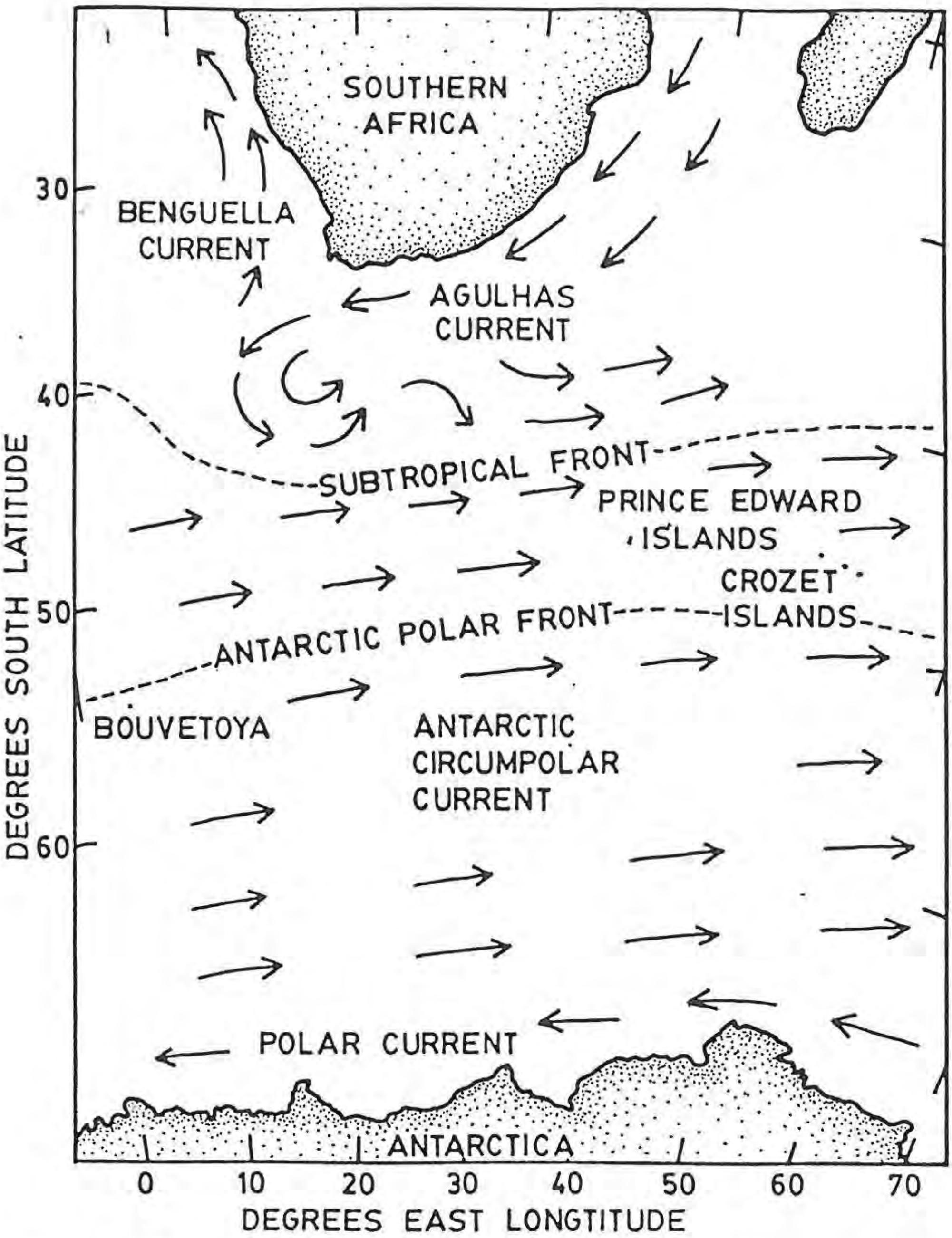

Fig. 4. The Prince Edward Islands in relation to major frontal systems and ocean currents. Adapted from Raymont (1980).

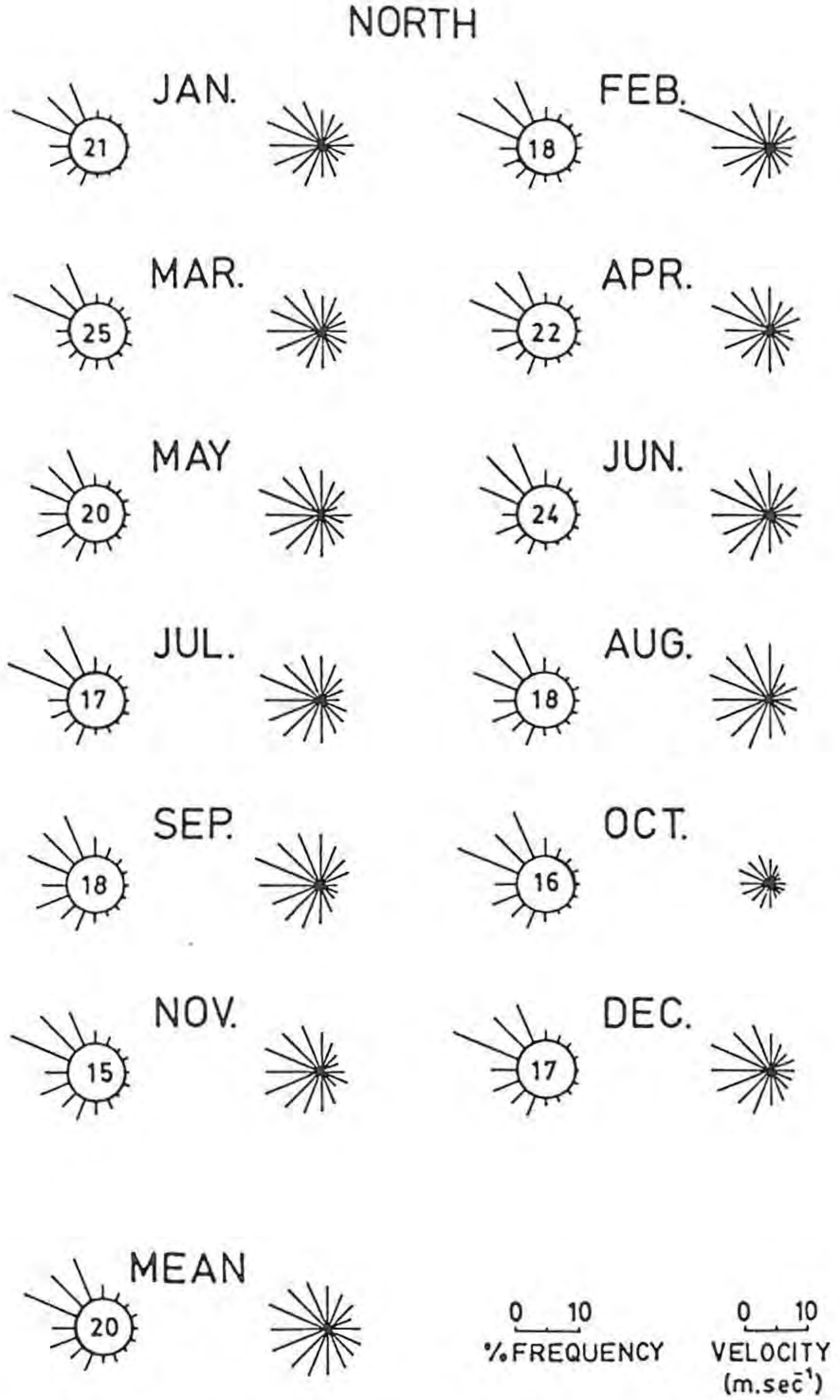

Fig. 5. Monthly wind direction frequency and velocity (m.sec^{-1}) measured at the meteorological station on Marion Island from 1965 to 1975. The value indicated in the centre of each wind rose represents the percentage of calm days. Unfortunately, a detailed analysis of the wind vectors at the islands was available only from 1965 to 1975 but the lack of variation suggests that these data are valid to the present time. These data were made available by the South African Weather Bureau.

The mean monthly precipitation (Fig. 6) measured at the meteorological station on the northeast coast of Marion island (Fig. 3) is an almost constant 0.211 m.month^{-1} (range: 0.172 - 0.243 m) and two peaks can be distinguished, one in the late spring and early summer (December/January) and the other in the early autumn (April/May).

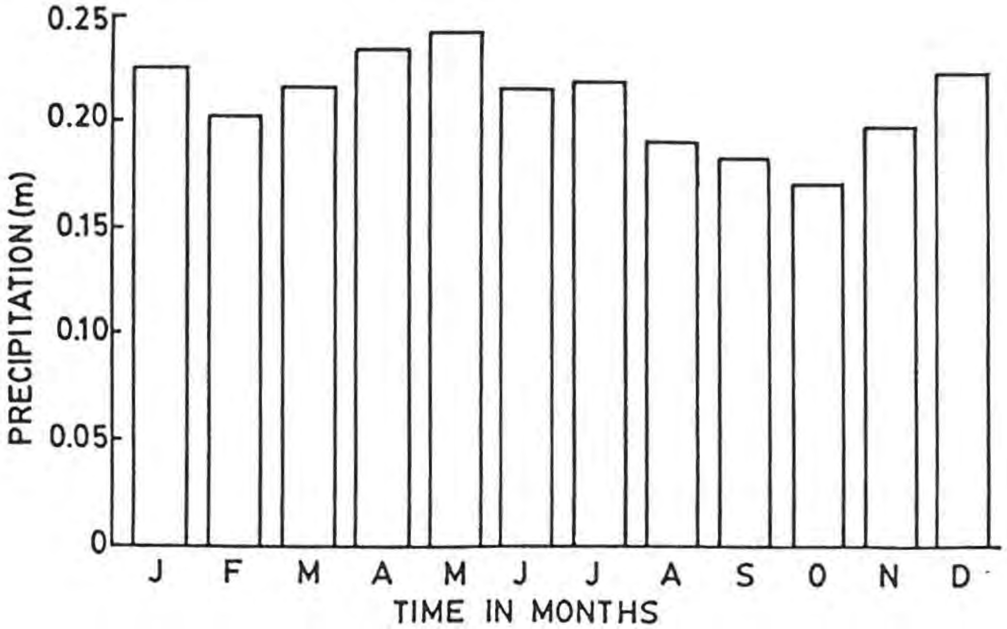

Fig. 6. The mean monthly precipitation (m) from 1954 to 1975, measured at the Marion Island meteorological station. These data were made available by the South African Weather Bureau.

7. MATERIALS AND METHODS

Track charts showing station details of all cruises discussed in this study are shown in figure 7. The methods pertaining to this study are discussed under the following headings:

7.1. Physical
7.2. Chemical
7.3. Biological

7.1. Physical

Values for temperature and salinity were obtained either directly from the thermosalinograph on the bridge of S.A. Agulhas in the case of the surface stations occupied while underway, or from a Neil Brown conductivity temperature depth (CTD) probe cast to 1000 m or the bottom, whichever was reached sooner. Because of infrequent calibration of the CTD probe on S.A. Agulhas, it is likely that readings obtained from this instrument were subject to errors but it is as likely that these errors remained constant within cruises and hence, the use of data collected by this probe to detect patterns where relative rather than absolute values are important, is not unreasonable. Specific gravity anomaly (sigma-t) values were calculated from the temperatures and salinities obtained by the CTD probe and the formulae of Knudsen (1901). These formulae were used instead of more recent expressions because the more recent expressions differ only slightly from those computed by Knudsen (Foffonof, 1962) and sigma-t values for the cruise of Marion Dufresne, with which much of my data are compared, were calculated following Knudsen.

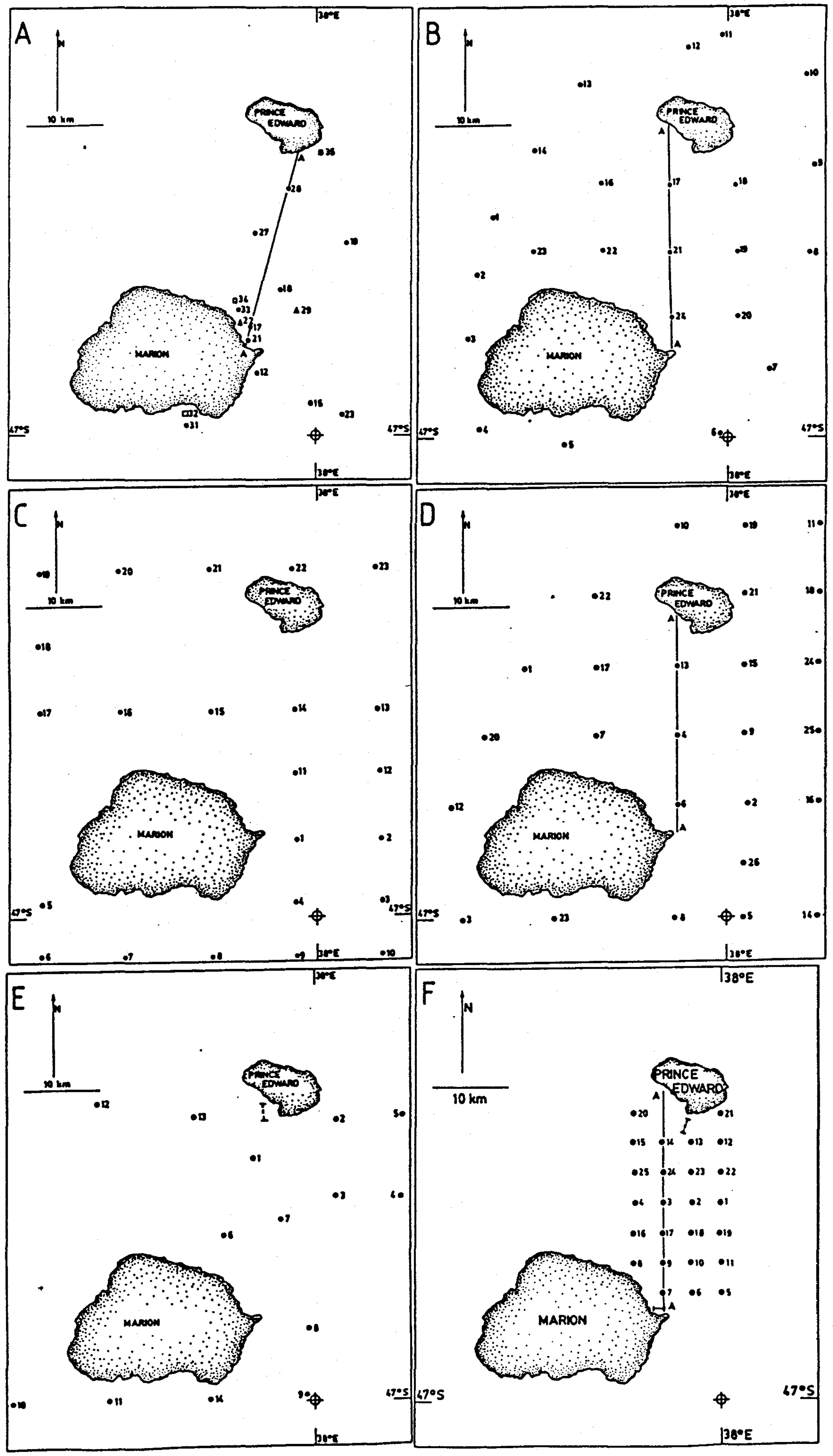

Fig. 7. Track charts showing station details for six cruises to the Prince Edward Islands. The author participated on cruises B,C,D,E & F. The transect A - A is shown where applicable.

A. Marion Dufresne, March 1976.
● Chlorophyll a and nutrient determinations, CTD casts and zooplankton vertical hauls (WP II net).
○ Chlorophyll a and nutrient determinations only.
▲ Chlorophyll a, nutrient determinations and in situ primary production measurements.
△ Nutrient determinations only.
■ Nutrient determinations and zooplankton vertical hauls.
□ Zooplankton vertical hauls only.
Redrawn from Arnaud & Hureau (1979).

B. S.A. Agulhas, April 1982.
● Surface chlorophyll a determinations, nutrient analyses and potential primary production measurements.
○ As above, but including a CTD cast to 1000 m and a zooplankton net haul (WP II) from 300 - 0 m.

C. R.S. Africana, September 1982.
● CTD cast to 500 m, 11 bottle rosette cast to standard depths for nutrient determinations.
○ XBT cast.

D. S.A. Agulhas, May 1983.
● CTD cast to 1000 m or the bottom if shallower, Niskin bottle cast at 50 m intervals to 300 m or bottom for chlorophyll a, nutrients and potential primary production determinations, and zooplankton vertical hauls (WP II) from 100 - 0 m, 300 - 100 m and 500 - 300 m.

E. S.A. Agulhas, November 1983.
● Surface chlorophyll a determinations, current vector readings at 5 m intervals to 50 m and a vertical haul from 75 - 0 m with a small 25 μm mesh net for phytoplankton.
⊢-⊣ Dredge station.

F. S.A. Agulhas, March 1984.
● Surface chlorophyll a and nutrient determinations and current vectors at 5 m intervals to 50 m.
⊢-⊣ Dredging stations.

Light attenuation profiles for green light, the only component of the spectrum that could be measured with the equipment on hand, was measured at a number the stations occupied (Fig. 7). A narrow band green filter (λ_{max} between 520 and 530 nm) was placed over the photocell of a Carbon 14 Centralen submarine photometer which was then lowered through the water column until 1% of the surface irradiance (I_{max}) was reached. The attenuation curves obtained in this way (Fig. 8) were used to determine the potential primary production integral (discussed later).

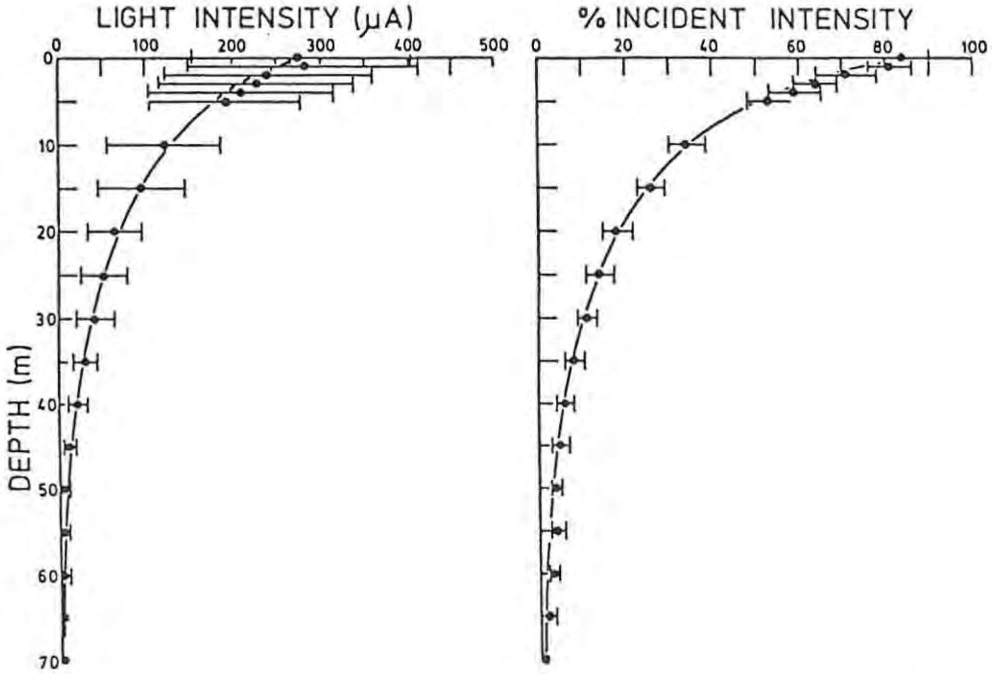

Fig. 8. Light attenuation curves, expressed directly as microamperes (obtained from the light meter) and as a percentage of the total incident radiation reaching the surface. These curves were constructed from mean values obtained from 8 stations in the immediate vicinity of the islands. The horizontal bar bisecting each point represents the standard deviation about the mean.

Current vectors were measured at 5 m intervals from the surface to 50 m with a HYDRO PRODUCTS current meter. These vectors were adjusted to account for ship's drift (determined from radar fixes at two minute intervals while on station) by applying the cosine law which states that for any triangle with angles a,b and c and having the sides A,B and C opposite the angles with the same letter, the angle

$$c^2 = A^2 + B^2 - 2AB\cos(c) \qquad \text{(Korn \& Korn, 1968).}$$

This equation was incorporated into a computer program and used in its various permutations (Appendix 1) to adjust the current vectors obtained from the current meter to account for the ship s drift. Mean current vectors for the upper 50 m, used to discount variation between observations at single stations, were obtained by averaging the measurements taken at 5 m intervals.

7.2. Chemical

Water samples for nutrient analysis, chlorophyll _a_ and potential primary production determinations were collected from either the scientific seawater supply pump while the ship was underway or, by Niskin bottles when stationary.

7.2.1. Scientific seawater supply pump

An Iwaki Magnet Induction Pump fabricated from polyvinyl fluoride and ceramic materials drew water from the sea 5 m below the waterline of _S.A. Agulhas_ at a rate of 100 $l.min^{-1}$. The quality of the scientific seawater supply had been checked on a previous cruise (Allanson _et al._, 1981) and no significant difference between this supply and overboard samples was found.

7.2.2. Niskin bottles

On the 1982 cruise of R.S. Africana, a rosette of 11 Niskin bottles was used to collect water samples for analysis at 0, 10, 25, 35, 50, 65, 80, 110, 150 and 200 m while on the 1983 S.A. Agulhas cruise, 6 Niskin bottles were deployed to 50, 100, 150, 200, 250 and 300 m. On this last cruise, the surface water was sampled from the scientific seawater supply.

The methods used for the determinations are shown in Table 1. With the exception of the silicate determinations where the sample was filtered through a 0.45 μm Sartorius membrane filter and stored in polyethylene bottles for analysis in Grahamstown after the voyage, all analyses were completed on board S.A. Agulhas. On R.S. Africana, 100 ml aliquots were drawn from each Niskin bottle and frozen to -20 ^{o}C in a blast freezer for nutrient analysis in Cape Town using the methods outlined in Table 1.

TABLE 1. A list of the hydrochemical methods used on the cruises of S.A. Agulhas and R.S. Africana.

PARAMETER	METHOD
pH	Strickland & Parsons (1968), pp. 29-31.
total alkalinity	Strickland & Parsons (1968), pp. 31-32.
carbonate alkalinity	Strickland & Parsons (1968), pp. 33-34.
soluble reactive phosphate	Allanson (MS).
reactive nitrate	Strickland & Parsons (1968), pp. 77-80.
soluble reactive silicate	Strickland & Parsons (1968), pp. 65-70.

7.3. Biological

7.3.1. Phytoplankton

The concentration of chlorophyll *a* was used as an indication of phytoplankton stocks. Five litres of seawater were filtered through Whatman GF/C filters under 1/3 atm and treated according to the the method of Strickland & Parsons (1968). Calculations used were based on the SCOR/UNESCO method (Lorenzen & Jeffrey, 1980).

Values for the potential primary productivity for the surface water at many of the stations occupied (Fig. 7) were obtained by determining the uptake of $NaH^{14}CO_3$ (Steemann & Nielsen, 1953) in incubated samples in a Gargas/Lonholdt onboard incubator (Fig 9; Gargas *et al.*, 1978).

Fig. 9. The Gargas/Lonholdt onboard incubator used in this study.
KEY:
- F - neutral density filter array, the filters absorb 50, 75, 85, 90 and 95 % of the incident light flux provided by the light box.
- L - light box fitted with Phillips "Daylight" fluorescent tubes.
- R - refrigeration coils to maintain the incubator at the temperature of the sea.
- T - thermostat.
- V - rotating vane ensures a continual mixing of the samples.

Water was collected from the scientific seawater supply and 25 ml aliquots drawn into each of 16 pyrex incubation flasks. These were inoculated with 250 ul of a 4 uCi $NaH^{14}CO_3$ solution obtained from the

Carbon 14 Centralen, Horsholm, Denmark. This series was incubated for 4 hrs under a light regime set up by an array of neutral density filters with transmission values of 50, 25, 15, 10 and 5 % of the incident light (Fig. 9). Two bottles were exposed to 100 % of the incubator incident light flux from the bank of Phillips Daylight fluorescent tubes and a tin foil backing was used to increase the light to 150 % for another 2 bottles. The last 2 bottles were wrapped in tin foil to determine the amount of $NaH^{14}CO_3$ taken up by passive diffusion and which had absorbed onto the surfaces of the phytoplankton. To lessen the chances of light shock. the samples were kept shielded from direct sunlight and other light sources as much as was possible.

After 4 hrs in the incubator, the samples were filtered through 0.45 µm Sartorius membrane filters under 1/3 atm and fumed over concentrated HCl for 2 mins to remove excess $NaH^{14}CO_3$. The filters were transferred to liquid scintillation counting vials to which 10 ml Beckmann 'Ready-solv HP' scintillation cocktail had been added. These vials were then stored and their ^{14}C levels assayed at Rhodes University in a Beckmann model LS 3150T liquid scintillation counter.

The activities of the samples, expressed as counts per minute (cpm) were converted to disintegrations per minute (dpm) with the following formula:

$$\text{dpm} = \frac{\text{cpm X } 100}{\text{a x ext.std. x b}}$$

The divisor in the above equation represents the counting efficiency of the scintillation counter. This was determined after each cruise by counting a standard Beckmann ^{14}C quenched set, calculating the percent efficiency from the known dpm of the standard sample and the cpm value yielded by the counter, and plotting the external standard ratio (ext.std.) of each quenched standard against the calculated percent efficiency. The constants a and b in equation 1 represent the gradient and intercept of the regression line of the plot which was linear over the range of external standard ratios yielded by the field samples. The dpm values were used, together with the equations of Strickland & Parsons (1968) to calculate the potential primary production, expressed as the amount of carbon absorbed per cubic metre of water per hour ($mgC.m^{-3}.hr^{-1}$).

7.3.2. Zooplankton

Zooplankton were collected by vertical hauls with a 0.6 µm WP II closing net. This was lowered cod-end first and then hauled vertically to the required depth where the release mechanism was triggered, the net throttled and hauled to the surface closed. Details of net hauls at the various stations are given on in figure 7. The samples were preserved in 10% buffered formaldehyde.

Subsequent laboratory treatment of the samples usually entailed subsampling which required that the whole sample be poured into a graduated cylinder, adjusted to a standard volume and agitated into a state of uniform suspension before the subsample was poured into a counting chamber. Taxa present in the plankton were identified and counted on a standardised basis of 1000 m^3 of water strained. The errors inherent in such a collecting method are well known and have frequently been discussed (Anon, 1968). The subsample served for counts of dominant taxa while the entire sample was scanned for rarer species.

7.3.3. Zoobenthos.

The benthic epifauna was sampled at three localities on the saddle between the islands (Fig. 7) with a small ($0.5\ m^2$ aperture) D-net fitted with a depressor plate and a weight both of which served to keep it on the bottom. This net was lowered from the stern of S.A. Agulhas and towed along the bottom at about $0.5\ m.sec^{-1}$ for 30mins.

A preliminary sorting of the fauna into taxa was attempted on board the ship and a more refined sorting was conducted at Rhodes University. Volumes of the major taxa in each dredge were obtained by placing the animals in a measuring cylinder, adding water to a set volume (this volume varied according to the volume of the animals) and then decanting the water in the cylinder through a 200 um mesh gauze into another measuring cylinder. The difference between the standard volume and the volume of water in the second measuring cylinder provided a measure of the volume of animals in that taxon.

8. RESULTS

Data from the five cruises to the Prince Edward Island Group on which the author participated and data collected in March 1976 from the French vessel Marion Dufresne are presented under the following subheadings:

8.1. Physical properties.

8.2. Chemical properties.

8.3. Biological characteristics.

In many instances, data collected in March 1976 were resynthesised to be compatible with data collected by the author.

8.1. Physical properties.

Temperature and salinity profiles, drawn from data collected with CTD probes in March 1976, April 1982, September 1982 and May 1983, while coming from widely separate surveys, when presented according to the time of year in which the stations were occupied (Fig. 10) represent a sequence of real events which depict the structure and seasonal breakdown of a seasonal thermocline characteristic of the middle latitudes (Pickard & Emery, 1982). In these latitudes during the summer months, the sea absorbs solar energy and the sea surface temperature increases. Wind induced turbulence distributes this heated surface water down to the depth of frictional influence and where this warm surface water meets the cooler deeper water, a thermocline develops

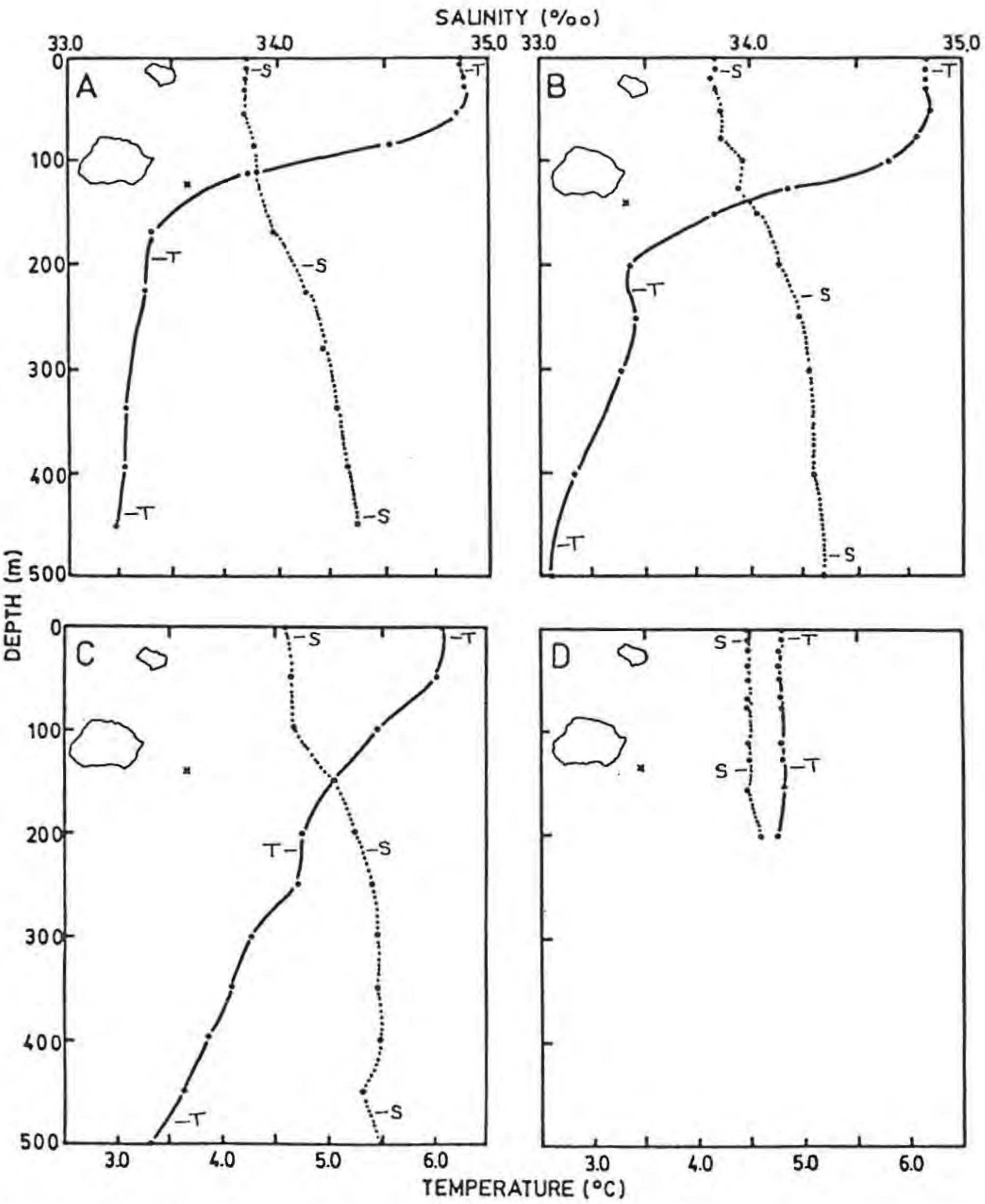

Fig. 10. Temperature and salinity profiles to the east of Marion Island as measured in:
A. March 1976 (Marion Dufresne).
B. April 1982 (S.A. Agulhas).
C. May 1983 (S.A. Agulhas).
D. September 1982 (R.S. Africana).
The positions where these measurements were made is shown in the upper left hand corners.

In March (Fig. 10A) towards the end of summer, the thermocline is well established and the temperature of the surface water is 6.25 °C. In April, as autumn approaches, the days get shorter and less energy enters the system. This, together with heat loss through evaporative effects and turbulence, leads to a cooling of the surface water and the depth of the thermoclinal zone increases (Fig. 10B). Because the rate of decrease of temperature with decreasing depth decreases, the slope of the thermocline increases. This gradual cooling process continues as winter approaches when there is a net loss of heat energy from the system and continued wind induced mixing erodes the thermocline until the isothermal condition found in September (Fig. 10D) is reached. At the end of winter, the temperature of the surface water increases once more due to the absorbtion of solar energy and the cycle is repeated once more.

A halocline cannot be seen in any of the traces shown in figure 10 but salinity increases gradually with depth through March, April and May while the September trace does not extend deep enough to indicate whether this feature is consistent throughout the year.

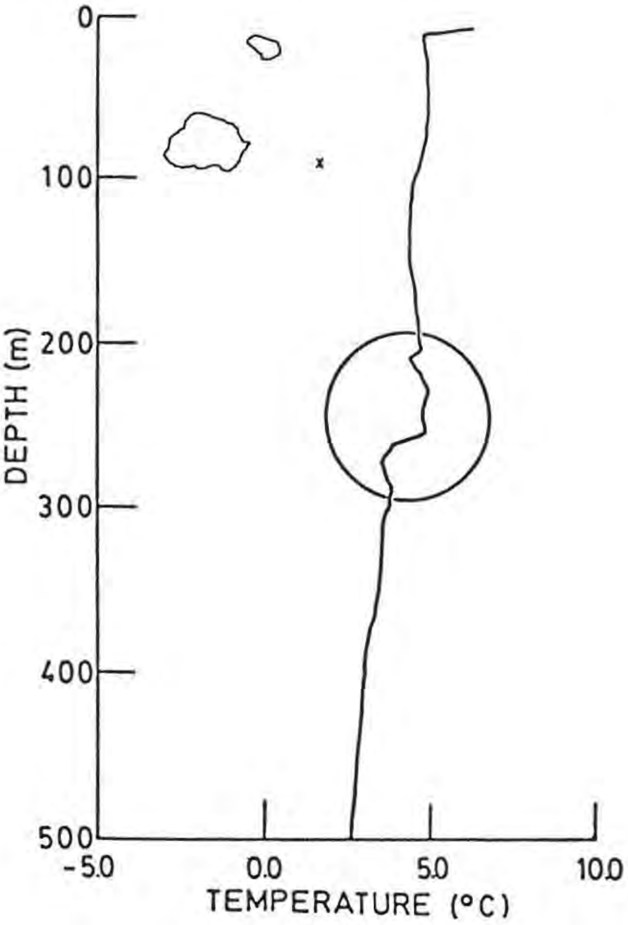

Fig 11 An XBT trace showing the temperature profile down to 500 m at a station in the lee of Marion Island (the station position is indicated in the upper left corner) in September 1982. It is thought that the feature between 200 and 300 m (ringed) is either an artefact caused by a radio transmission or an indication of an unstable-diffusive layer.

T-S diagrams for the same stations (Fig. 12) like the temperature profiles. show two water masses to the east of Marion Island in March. April and May while only one is present in September. They also show that while the temperature and salinity criteria of Antarctic Intermediate Water (temperature, 3-4 ^{0}C; salinity 34.4-34.5 ^{0}/oo) are approached below 200 m, subAntarctic water was present in the upper mixed layer at all times.

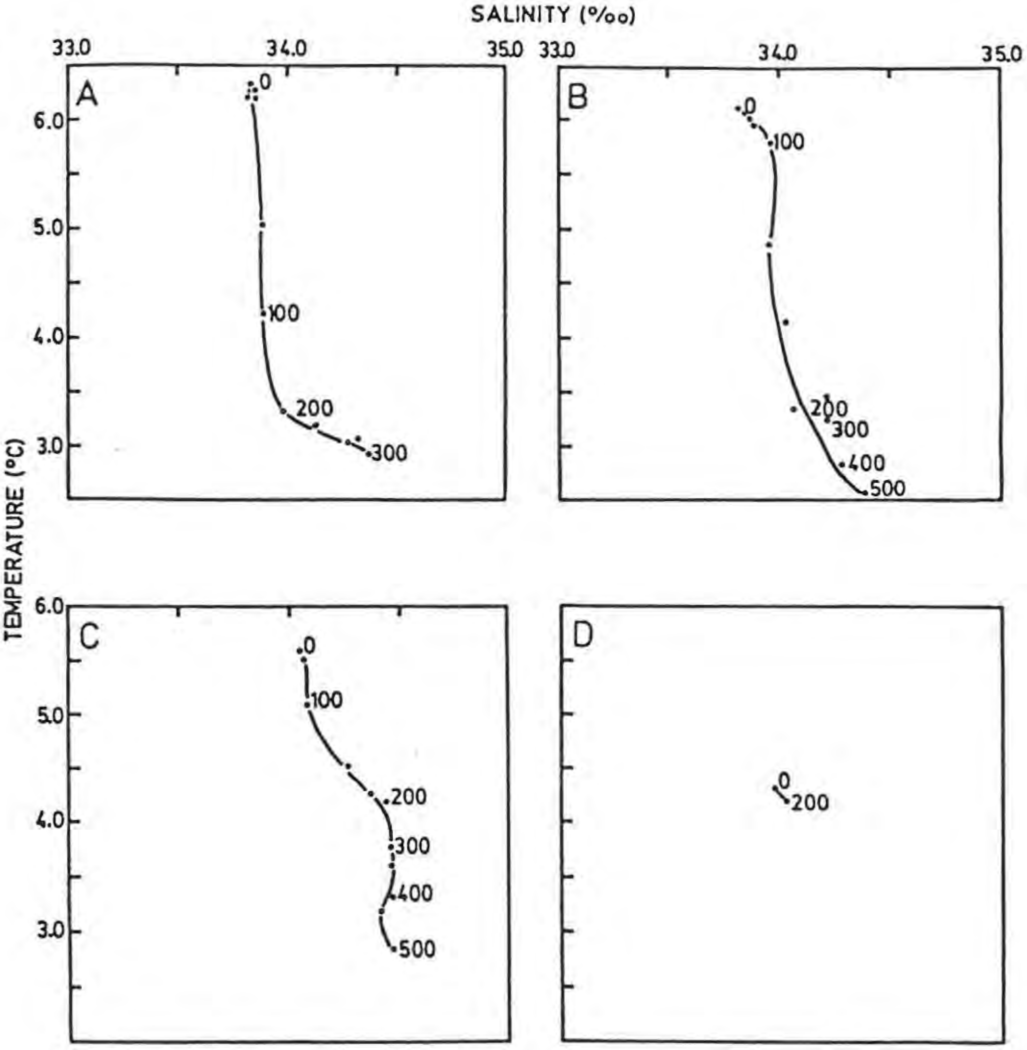

Fig. 12. T-S diagrams for the same cruises and stations as shown in fig. 10.

These diagrams follow closely the seasonal cycle of the thermocline but, unlike the CTD profiles, they indicate an upward movement of Antarctic Intermediate Water in the winter. This trend is evident in figure 12C by the reversal of the curve below 400 m. Also evident from these diagrams is the contraction of the T-S curves during winter. This phenomenon is most pronounced in September and, were the trace to extend to 500 m, it would very likely show Antarctic Intermediate Water much closer to the surface than it was in May. At no time however was there any indication of the upwelling of deep water in the lee of Marion Island.

Surface isotherms (Fig. 13), isohalines (Fig. 14) and isopycnals (Fig. 15) measured in March 1976 and 1984, April 1982, May 1983 and September 1982 show considerable variation and the only recurring feature is a core of water with a density slightly less than the surrounding ocean (observed in April 1982 and May 1983) just north of Prince Edward Island. In May 1983, a tongue of water, slightly warmer and less saline than the surrounding sea, was observed extending eastwards from Marion Island and there is a suggestion of a similar phenomenon in March 1976. In March 1984 however, there is evidence of a tongue of slightly cooler water extending eastwards from Marion Island even though the actual temperature of the water in the tongue was warmer than on the two previous occasions, 7.3°C as opposed to 6.3°C. There is also a suggestion of a tongue of water also 7.3°C to the southeast of Prince Edward Island. This tongue has a slightly lower salinity than the surrounding sea but unfortunately the grid of stations occupied in May 1984 does not show the origin or extent of this feature.

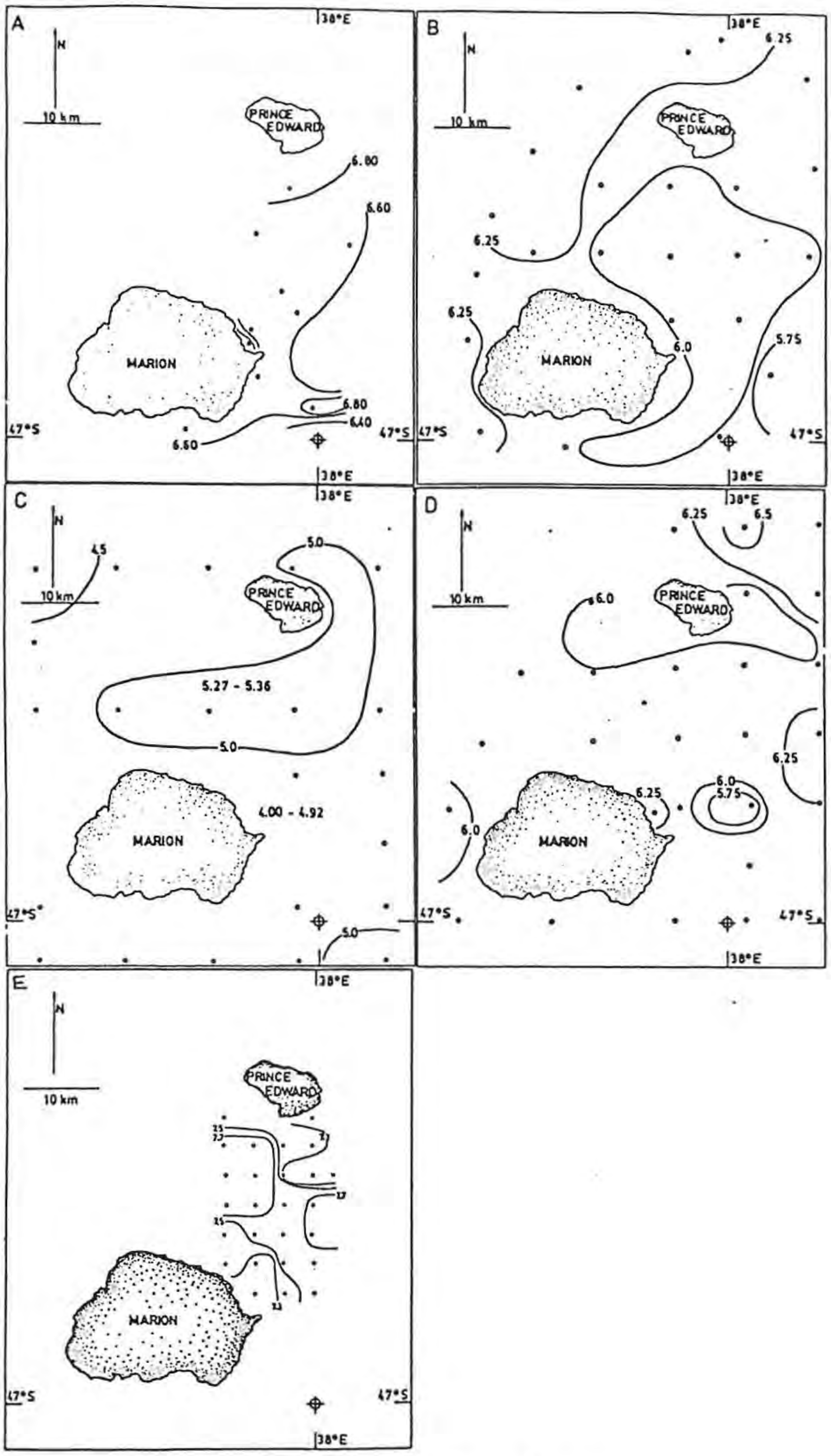

Fig. 13. Surface isotherms (^{o}C) drawn for the cruises of:
A - Marion Dufresne (March 1976).
B - S.A. Agulhas (April 1982).
C - R.S. Africana (September 1982).
D - S.A. Agulhas (May 1983).
E - S.A. Agulhas (March 1984).

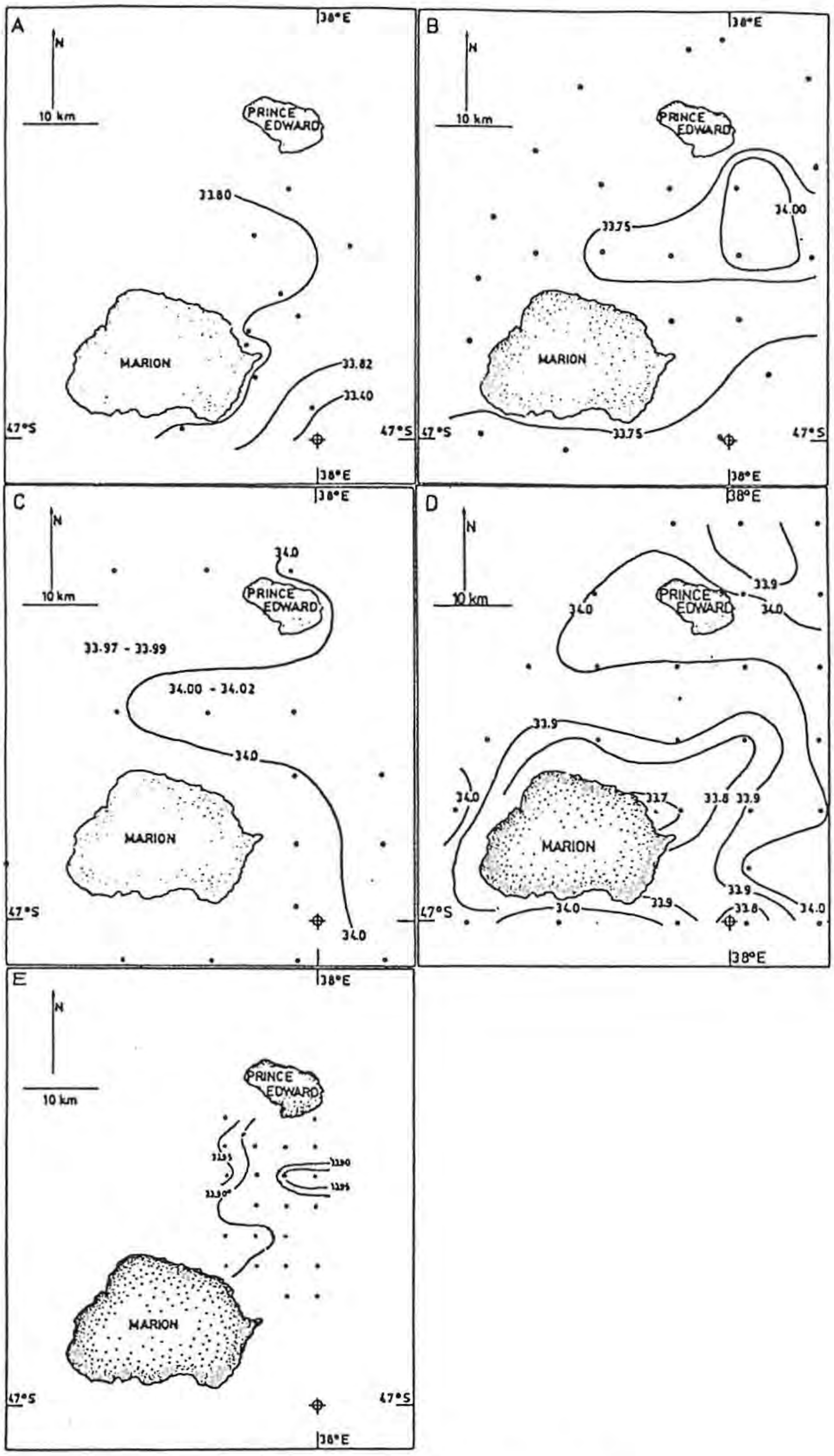

Fig. 14. Surface isohalines ($^{0}/oo$) for the same cruises indicated in fig. 13.

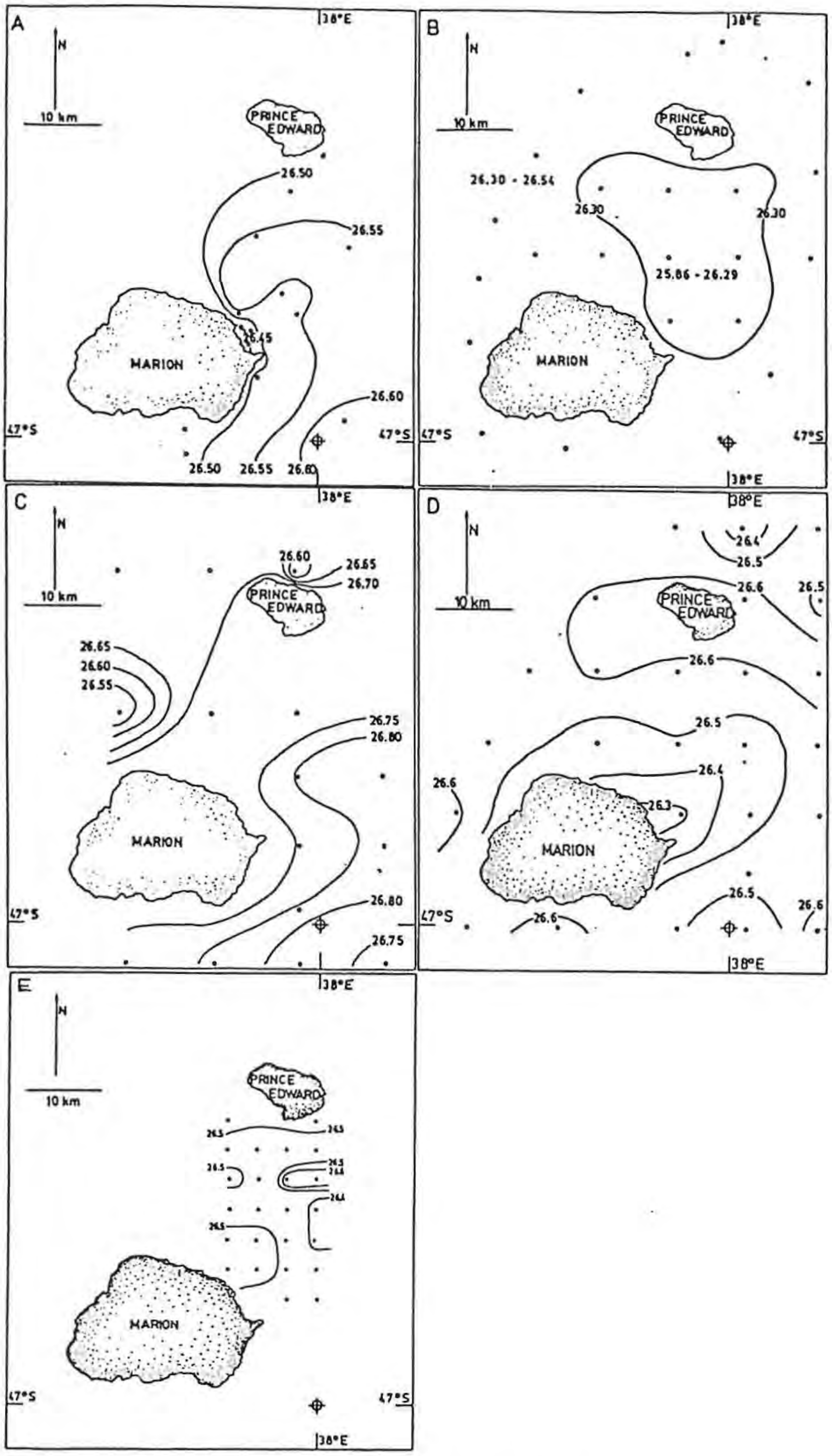

Fig. 15. Surface sigma-t contours for the same cruises as the isotherms and isohalines, figs. 13 & 14.

The lack of orderly and repeating temperature, salinity and density patterns hints at the existence of complex and highly variable hydrographic features in the immediate vicinity of the islands. This was confirmed by two surveys in November 1983 and March 1984 when current vectors close to the islands were measured (Fig. 16). In March 1984, the station pattern was concentrated over the saddle between the islands to give greater resolution in this area as a result of the observations made in November 1983.

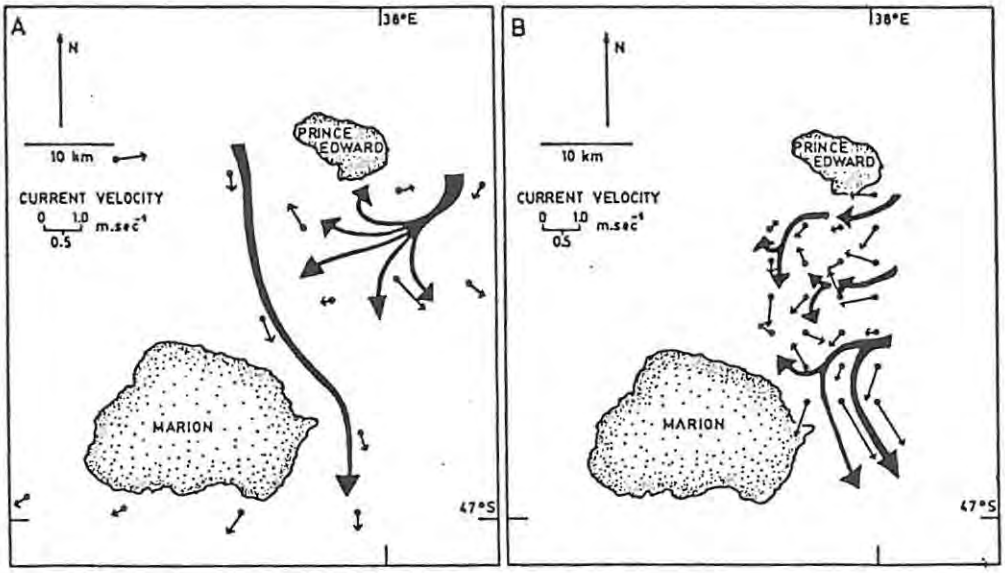

Fig. 16. Current vectors measured in November 1983 (A) and March 1984 (B). These data represent an average vector calculated from a set of measurements taken at 5 m intervals to 50 m. The 'heading' of the vector arrow indicated the direction of flow while the magnitude or velocity is proportional to the length of the arrow. The bold arrows show the likely net current flow over the saddle. The winds during both surveys blew from the northwest quadrant with an average velocity of 10 - 20 kts, the maximim velocity was 46 kts recorded in the 1984 survey.

Current vectors from both surveys suggest that the net flow of surface water (less than 50 m) over the saddle is from north to south with a region of confused or variable flow between the islands. This north-south flow is unexpected, because of the Antarctic Circumpolar Current which flows from west to east, and can only be due to local wind conditions modifying the surface shallow manifestation of the Antarctic Circumpolar Current.

The region of confused flow between the islands is not totally unexpected when considered in conjunction with the effects that the islands themselves have on the currents. Because of the relatively small area above the 100 m isobath, it is reasonable to assume that the north-south flow would not be affected until fairly close to Prince Edward Island when an eastward deviation of the main flow would be favoured. Currents west of Prince Edward would remain undisturbed until the steeply shelving bottom leading up to Marion Island was reached. This causes the current to split into two components, one passing to the west of Marion and the other to the East.

The component of the main current passing to the east of Prince Edward would tend to flow around the island until it reached the narrow neck of the saddle where, as indicated by the current vectors, part of it continues to flow in a north-south direction to link up with the main flow while the other part of this current flows around the southern coast of Prince Edward in a westerly direction. When this current reaches the descending floor of the saddle, a confused almost directionless flow pattern is the result. A schematic representation of the general flow around the islands is shown in figure 17.

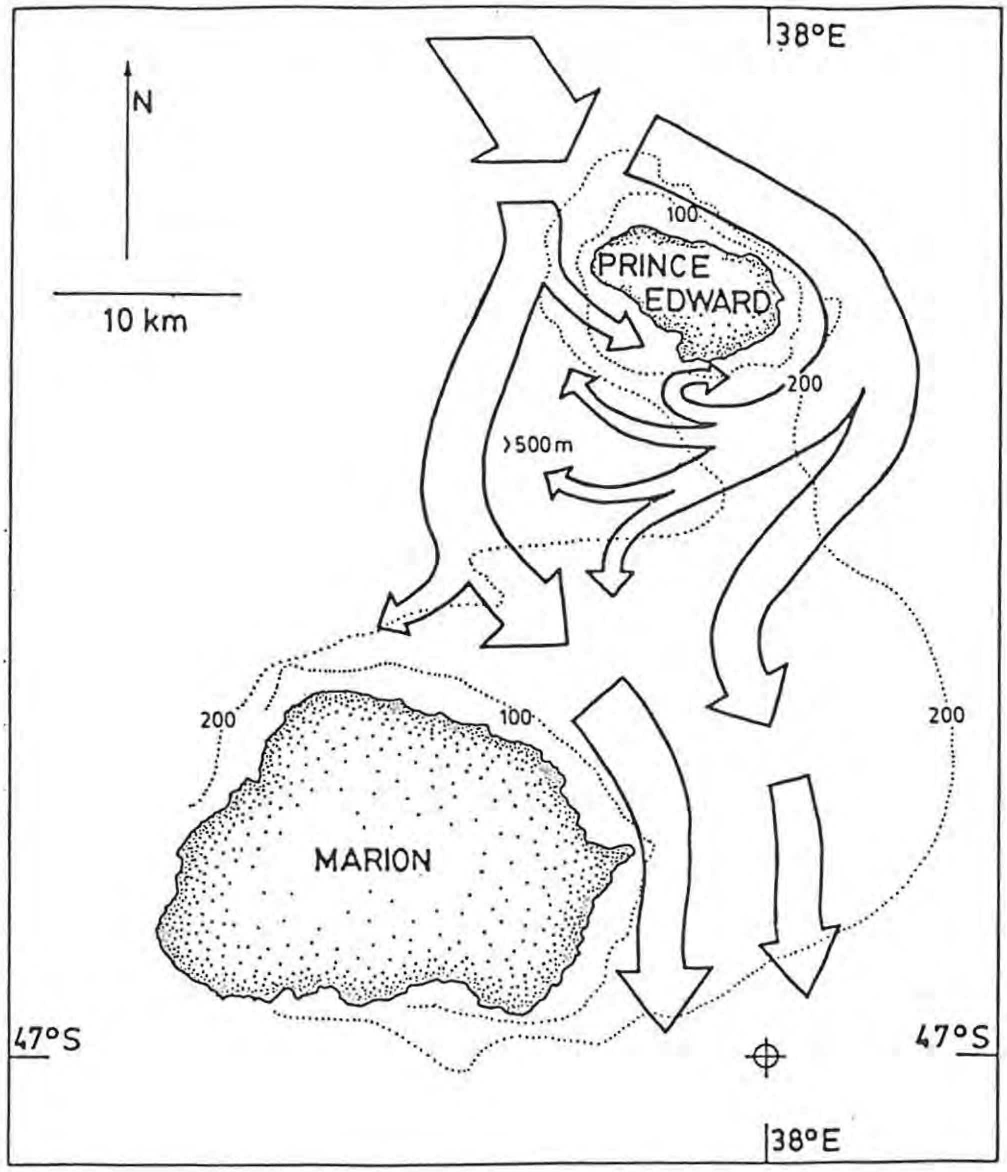

Fig. 17. A schematic impression of the surface currents around the Prince Edward Islands. This diagram was constructed from current vectors measured in 1983 and 1984.

If the water flowing around the islands does tend to lose direction as shown in figure 17, then the lack of consistent features observed for the surface temperature, salinity and sigma-t contours can be explained because they are associated with the current patterns. In the same way as patterns on the surface are affected by the currents, so is the vertical structure at least down to a depth of 50 m.

Vertical temperature profiles drawn for a line of station extending across the saddle between the islands along the transect A-A (Fig. 18) show a depression of the isotherms towards the centre of the saddle. This depression is not unexpected because when the components of the main current which split to pass on either side of Prince Edward meet, the effect would be a downwelling of the surface water. Because this depression exceeds 50 m, it is suggested that the effects of wind stress are manifest down to 100 m at least.

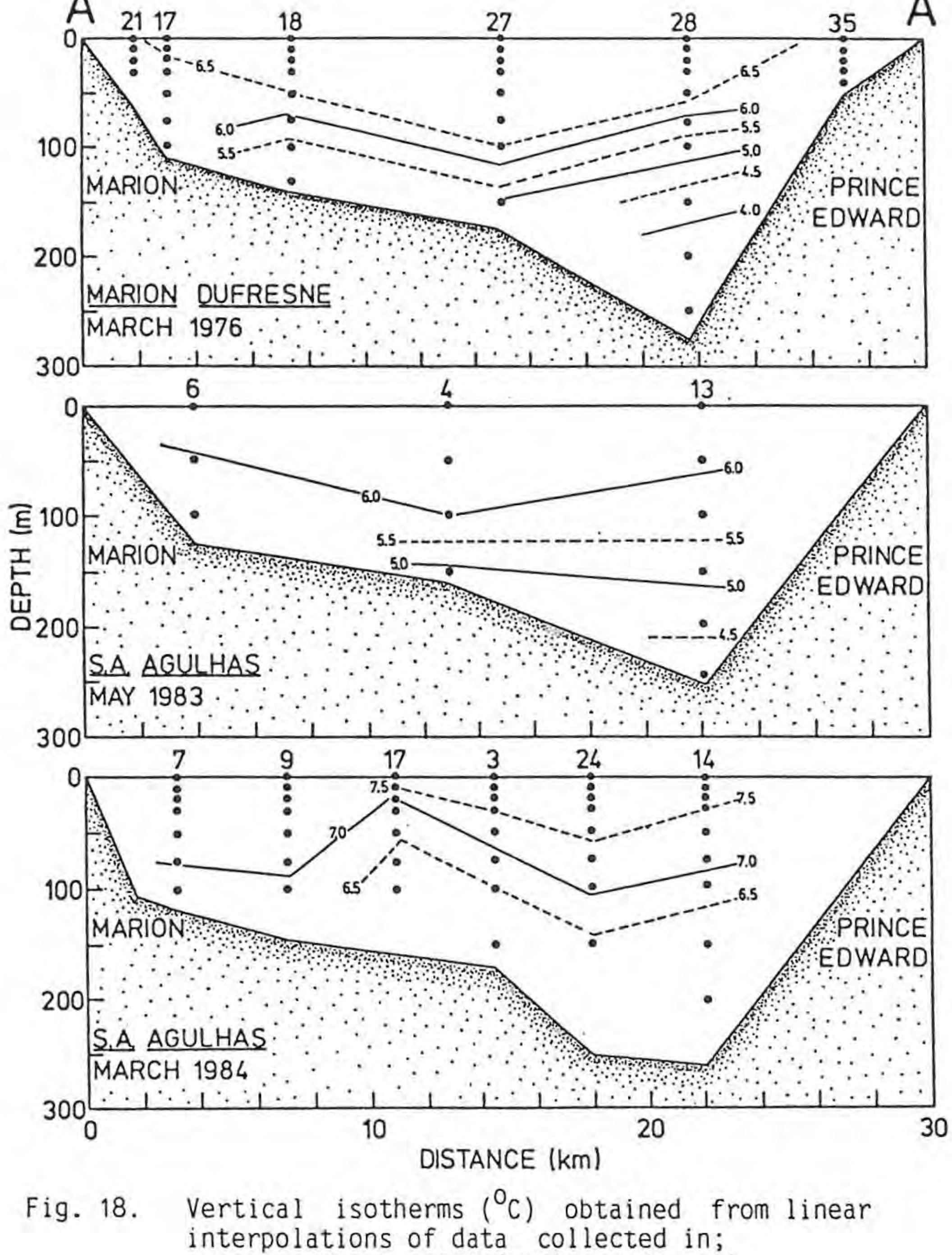

Fig. 18. Vertical isotherms (^{0}C) obtained from linear interpolations of data collected in;

1. March, 1976 (Marion Dufresne),
2. May, 1983 (S.A. Agulhas) and
3. March, 1984 (S.A. Agulhas).

The stations for which this diagram was constructed lie along the transect A-A (Fig. 7).

8.2 Chemical properties

Like the physical variables, surface contours for soluble reactive phosphate (Fig. 19), reactive nitrate (Fig. 20) and soluble reactive silicate (Fig. 21) are indicative of a highly complex and variable system.

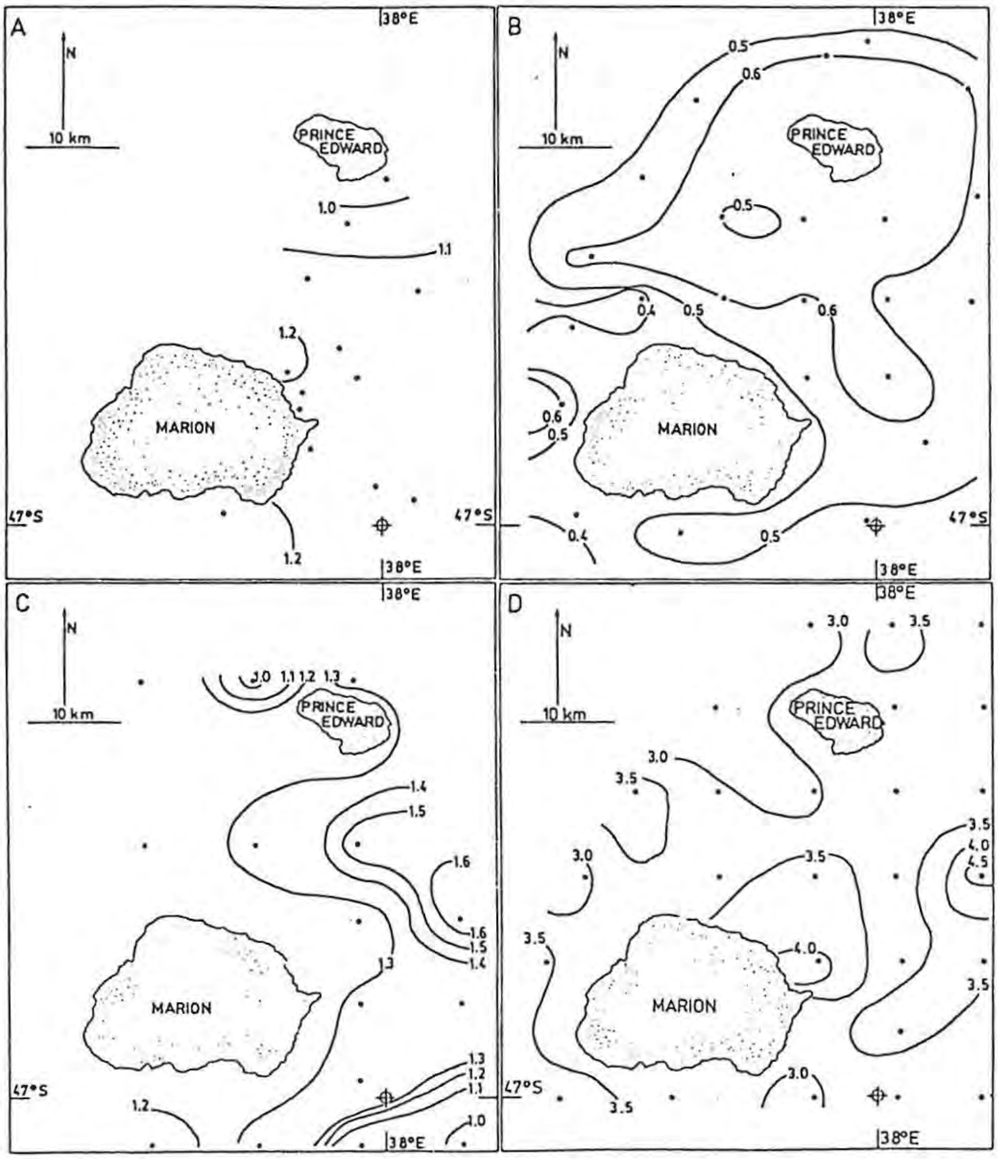

Fig. 19. Surface contours of soluble reactive phosphate (mmol.m^{-3}) determined in:
A - March 1976 (*Marion Dufresne*).
B - April 1982 (*S.A. Agulhas*).
C - September 1982 (*R.S. Africana*).
D - May 1983 (*S.A. Agulhas*).

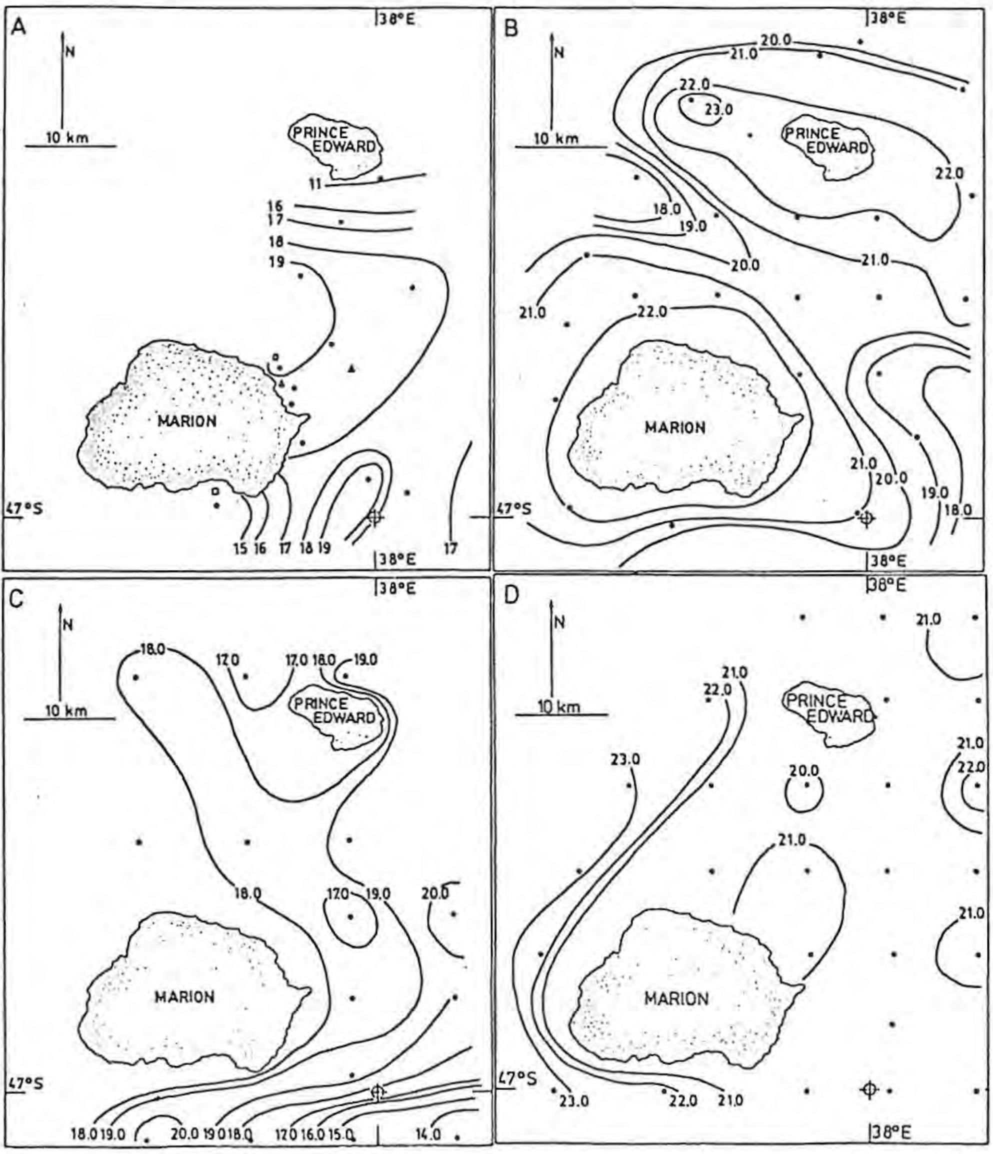

Fig. 20. Surface reactive nitrate contours (mmol.m^{-3}) determined on the same cruises as the soluble reactive phosphate contours in fig. 19.

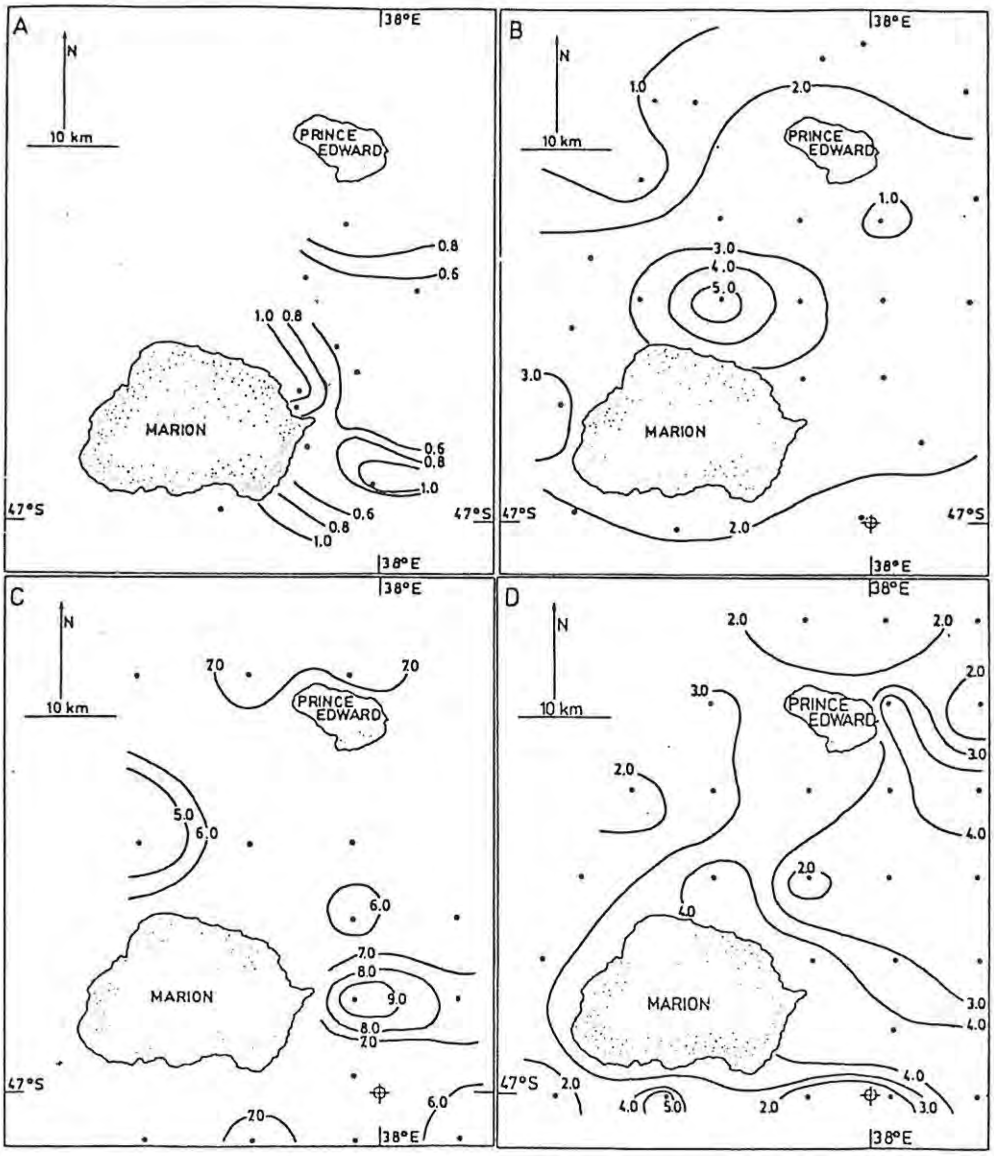

Fig. 21. Surface soluble reactive silicate contours (mmol.m^{-3}) determined on the same cruises as the soluble reactive phosphate contours in fig. 19.

Soluble reactive phosphate and soluble reactive silicate contours are, in terms of the sampling in this study, unremarkable and no similarities between the different cruises can be detected. Reactive nitrate contours on the other hand show a gradation of concentration from east to west across the saddle in March 1976 and May 1983 while a pattern of almost concentric rings, the higher concentration in the centres closest to the islands, was found in April 1982

Concentrations of these nutrients exhibit considerable variation between cruises (Fig. 22). This is especially evident for soluble reactive phosphate and soluble reactive silicate which range in concentration from 0.6 - 3.4 and 0.7 - 6.6 mmol.m^{-3} respectively as opposed to a range of 17.7 - 21.6 mmol.m^{-3} for reactive nitrate. Consequently, the ratio of nitrate to phosphate varied considerably (Fig. 23).

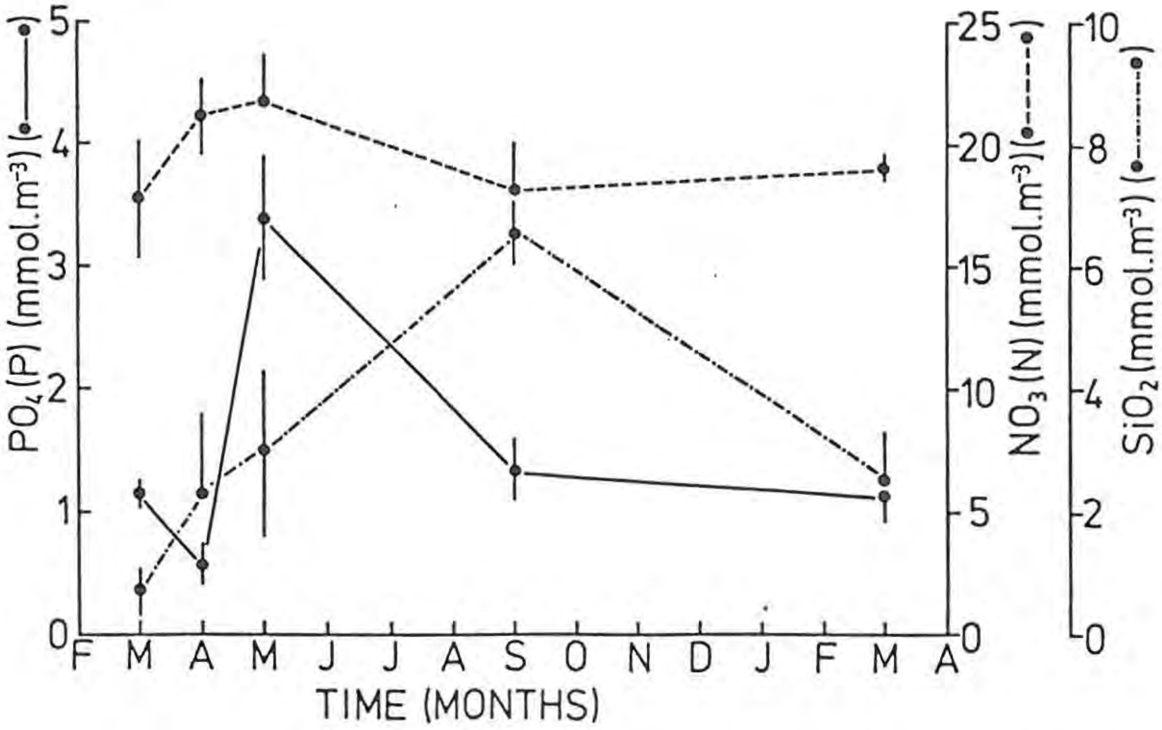

Fig. 22. Concentrations of soluble reactive phosphate (PO_4P), reactive nitrate (NO_3N) and soluble reactive silicate (SiO_2) plotted against time in months irrespective of the year of sampling. The vertical bars represent the standard deviation about the mean.

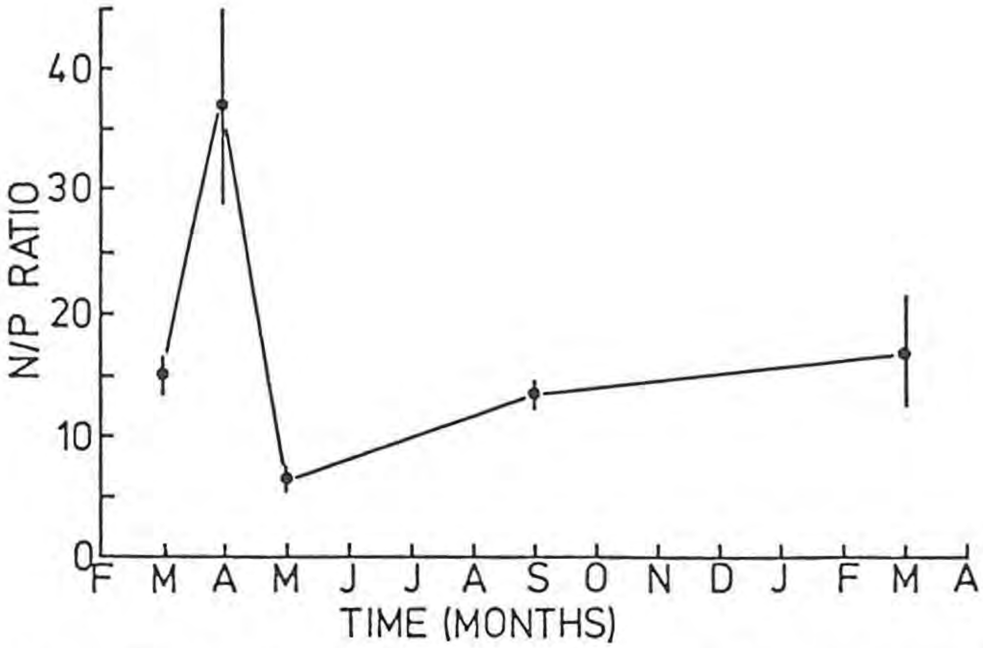

Fig. 23. Nitrate:phosphate ratios, obtained from the surface determinations, plotted against time in months. The vertical bars represent the standard deviation about the mean.

An examination of the concentrations of soluble reactive phosphate, reactive nitrate and soluble reactive silicate in March 1976 and March 1984, show very little difference between the concentrations of soluble reactive phosphate and reactive nitrate and a large difference (0.5 - 1.5 $mmol.l^{-1}$) difference in soluble reactive silicate. Student's t tests applied to the values obtained for the concentrations of these nutrients and the nitrate:phosphate ratio in March 1976 and March 1984 (Table 2), to determine whether or not the differences in concentration between years were significant, show that while no significant difference exists between the concentration of soluble reactive phosphate, the nitrate:phosphate ratio and, to a lesser extent, reactive nitrate, a highly significant difference was found in the concentrations of soluble reactive silicate.

TABLE 2. Student's t values, the number of degrees of freedom and the probability of accepting the null hypothesis ($H_0 = H_1$) for tests applied to the concentrations of the major macronutrients and the nitrate:phosphate ratio measured in March 1976 and March 1984.

	Student's t value	Degrees of freedom	Probability
Soluble reactive phosphate	0.0658	32	0.474
Reactive nitrate	3.2484	46	0.001
Soluble reactive silicate	8.0485	46	0.000
N:P ratio	1.4860	32	0.074

On the basis of these observations, it is suggested that there is a seasonal pattern in the distribution of soluble reactive phosphate and reactive nitrate in these neritic waters which is closely related to the occupational cycles of predators, mainly penguins, at these islands.

Williams & Berruti (1978) have estimated that 5 X 10^5 kg of feathers are shed on Marion Island each year and of this. 1.5 X 10^5 are shed in March (Fig. 24A). Allowing a suitable time interval (2 - 3 months) for mineralization, most of the nutrient salts in these feathers would be washed into the sea. In addition to the feathers, Burger et al., (1978) present data indicating that in excess of 1.3 X 10^6 kg dry weight of guano is deposited by penguins on Marion Island in December and January (Fig. 24B). Myrcha (pers. comm.) has indicated that even with the high rate of precipitation at Marion Island and the fact that over 90 % of the guano is deposited on rocky shores (Burger et al., 1978), it would take some months for the nutrient salts in the guano to leach into the surrounding ocean.

While the high concentrations of soluble reactive phosphate measured in May 1983 can perhaps be regarded as the results of run-off from the islands a similar increase in the concentration of reactive nitrate was not found. This can be explained when one considers that most of the nitrogen in guano is present as uric acid (Burger et al., 1978) which is rapidly converted into ammonia by bacteria. Pietr et al. (1983) found that 50 % of the nitrogen deposited by penguins on King George Island was converted into ammonia within 20 days of being deposited) This ammonia then volatilizes into the atmosphere leaving the phosphorus salts behind. Tatur & Myrcha (1983) suggest that this reduction and subsequent volatilization of the nitrogen salts leads to a decrease in the ratio of nitrate to phosphate on land and it is reasonable to expect that these events would be manifest in the ocean a few months after they occurred on land and lead to the nitrate:phosphate ratios measured at the islands.

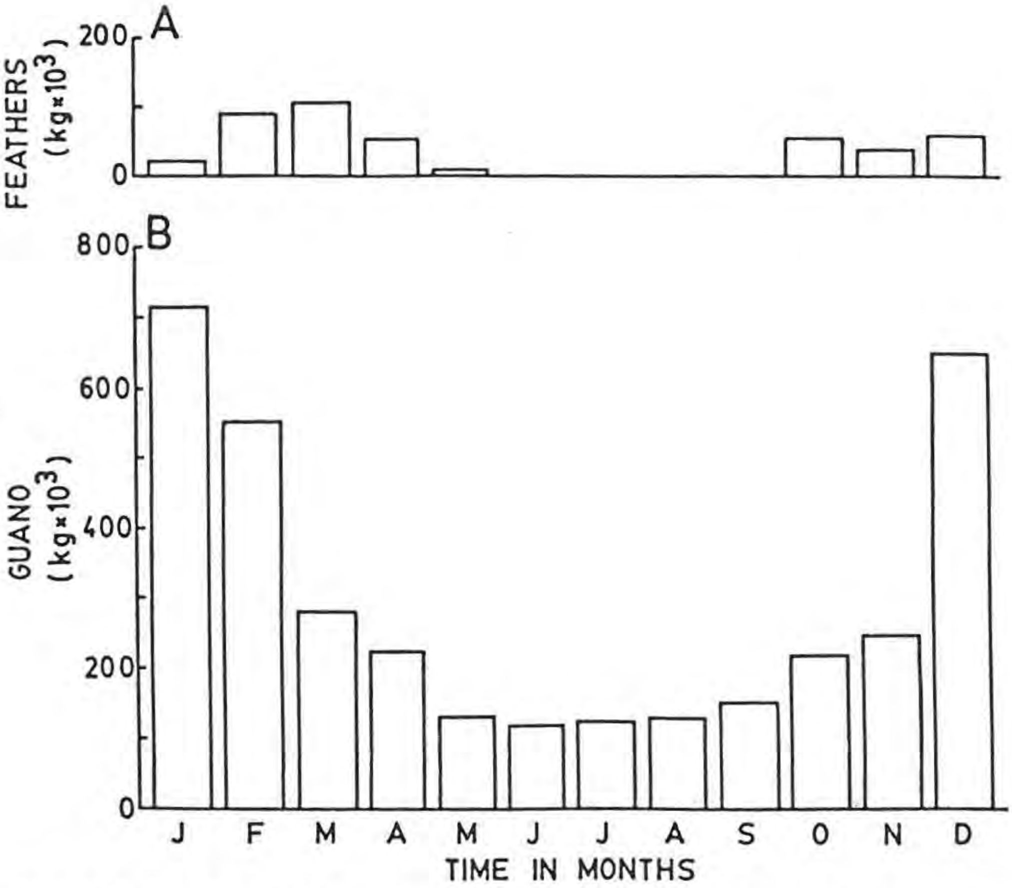

Fig. 24. Monthly means of A - feathers and B - guano, expressed as kg dry weight, deposited on Marion Island. Fig. 24A. was drawn from data presented by Williams & Berruti (1978) and fig. 24B from data presented by Burger _et al._ (1978).

The nitrate:phosphate ratio is low at the beginning of winter in April because more phosphate than nitrate is entering the ocean via run-off from the penguin colonies. During winter and early spring, the ratio increases because the effects of run-off at this time are minimal, most of the birds having left the islands, and currents in the ocean having carried the phosphate salts away from the islands. In the late spring and early summer, the birds return and the effects of run-off become apparent once more.

Because silicate is almost totally lacking in the diets of the terrestrial predators, it is reasonable to assume that the cycle of soluble reactive silicate at these islands does not correspond with the cycles of soluble reactive phosphate and reactive nitrate. It is likely therefore that the high concentrations of this nutrient measured in September could be as a result of either a seasonal decrease in phytoplankton, predominately diatoms, stocks or some hydrographic feature.

With the summer phytoplankton bloom, indicated by the high chlorophyll _a_ values measured in March, April and May (Fig. 27), the concentration of silicate in the ocean around the islands is depleted because of uptake by diatoms. Then in winter when the amount of solar radiation decreases, the phytoplankton stocks diminish and silicate is released into the ocean. Because the solution of silicate from diatom frustules follows a different course to the regeneration of nitrogen and phosphorus (Redfield _et al._, 1982) and may therefore be released at different depths to nitrate and phosphate, it is reasonable to expect the seasonal cycle of silicate to differ from the cycles of nitrate and phosphate.

An alternative explanation to account for the different concentrations of soluble reactive silicate at these islands makes use of eddies or extrusions of water from the Antarctic Polar Front passing close to or decaying in the vicinity of the islands and enriching the local silicate content of the ocean.

When the latitudinal variations in the concentrations of these nutrients between South Africa and Antarctica (Fig. 25) are examined, it can be seen that while the concentration of soluble reactive phosphate and reactive nitrate increases rapidly at the Subtropical Front, the concentration of soluble reactive silicate remains low. At the Antarctic Polar Front on the other hand, the concentration of soluble reactive silicate increases rapidly while the other two nutrients remain at the same levels as they were in the sub-Antarctic.

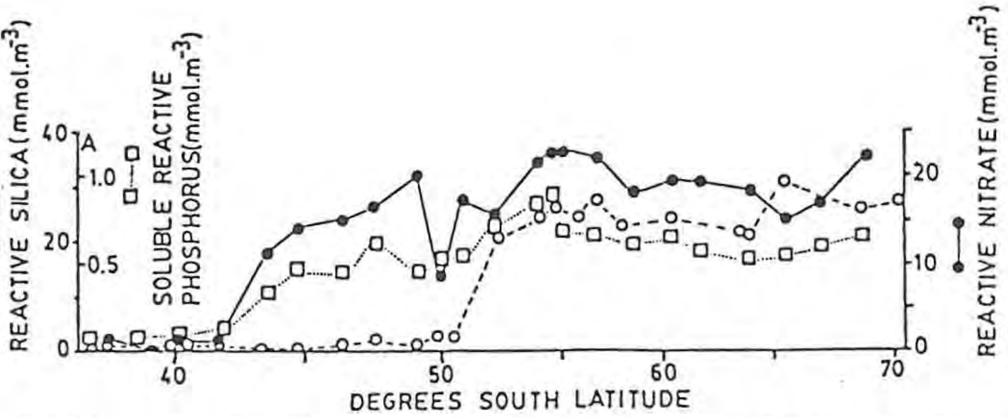

Fig. 25. Latitudinal variation in the concentrations of the major macronutrients-soluble reactive phosphate, reactive nitrate and soluble reactive silicate between South Africa and Antarctica. Redrawn from Allanson _et al._ (1981).

When fronts are vigorous for their size the flow becomes unstable and frontal meanders are formed. These meanders may pinch off and form eddies (Owen, 1981). This has been demonstrated for the Gulf Stream (Richardson, 1976) and the Agulhas Current (Lutjeharms, 1981). Parker (1971) has shown that eddies from the Gulf Stream can retain their physical characteristics for as long as two years while the chemical properties may be retained for longer periods. An eddy or an extrusion from the Antarctic Polar Front could quite conceivably reach the Prince Edward Islands and lead to the elevated levels of soluble reactive silicate measured in September 1982 (Reid, pers.comm.). The concentrations of soluble reactive phosphate and reactive nitrate would not increase by any great amount because their is no substantial increase across the Antarctic Polar Front.

8.3. Biological characteristics

8.3.1. Phytoplankton.

When the standing stocks of phytoplankton, indicated by the concentration of chlorophyll a. the level of primary production and zooplankton biomass in the immediate vicinity of the Prince Edward Islands are compared with the surrounding ocean and nearby frontal systems (Table 3.), it is evident that the level of biological enhancement at the islands parallels that of the frontal systems which are regarded as highly productive regions (Allanson *et al.*, 1981; Allanson & Parker, 1983; Lutjeharms *et al.*, 1983). An examination of the latitudinal variation in the concentration of chlorophyll *a* in the subAntarctic between 42 and 51 ^{o}S (Fig. 26) shows that the increase in phytoplankton stocks is limited to the latitude of the Prince Edward Islands.

TABLE 3. The standing stock of phytoplankton, the level of primary production and zooplankton biomass at the Prince Edward Islands compared with the surrounding ocean and the nearby frontal systems.

Sampling locality	Chlorophyll *a* ($mgChla.m^{-3}$)	Potential primary production ($mgC.m^{-3}.hr^{-1}$)	Zooplankton biomass (mg dry weight.m^{-3})
Prince Edward Islands	2.3	175	40
Open ocean* (subAntarctic)	0.2	10	5
Subtropical* Front	1.7	88	15
Antarctic* Polar Front	1.5	31	47

*. These data were collected by the author from *S.A. Agulhas* in January 1983 during the annual relief cruise to the South African National Antarctic Expedition base in Antarctica.

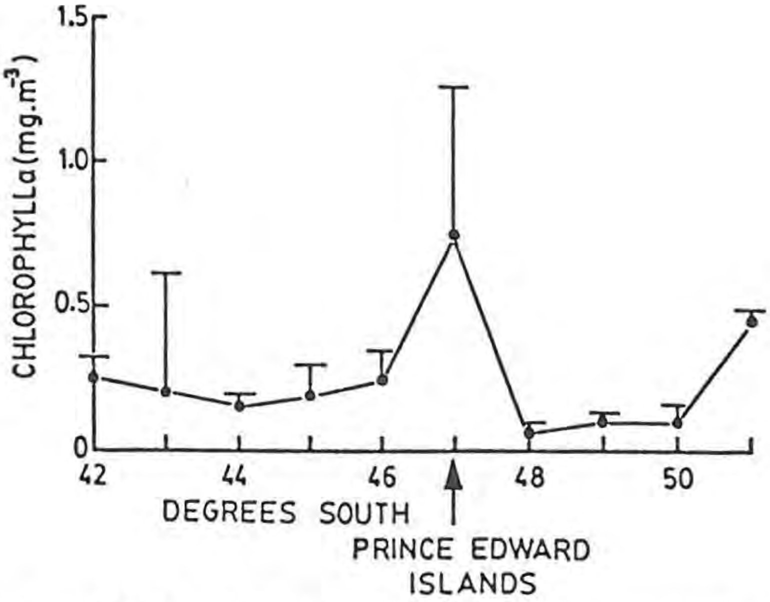

Fig. 26. Latitudinal variation in the concentration of chlorophyll _a_ in the subAntarctic in relation to the Prince Edward Islands. These data represent the mean values from collections made on all cruises to and from the islands on which the author participated. The vertical bars extending from the chlorophyll _a_ values represent the standard deviation about the mean.

Phytoplankton collected in vertical hauls with a WP II zooplankton net in May 1983 and with a fine meshed net hauled vertically in November 1983, showed a predominance of the chain-forming diatom _Chaetoceros radicans_ (Fig. 27A) in bloom across the saddle. At many of the stations, _C. radicans_ formed a dense mat (Fig. 27B) and were impossible to count. In November 1983, _C. radicans_, together with diatoms of the genus _Nitzchia_ and the silicoflagellate _Dictyocha speculum_ (Fig. 28) dominated the catches and were undoubtedly the cause of the high chlorophyll _a_ and primary production values. El-Sayed _et al._, (1979b) also reported high concentrations of _C. radicans_ and the pennate diatom _Rhizosolenia curvata_ at the islands in March 1976.

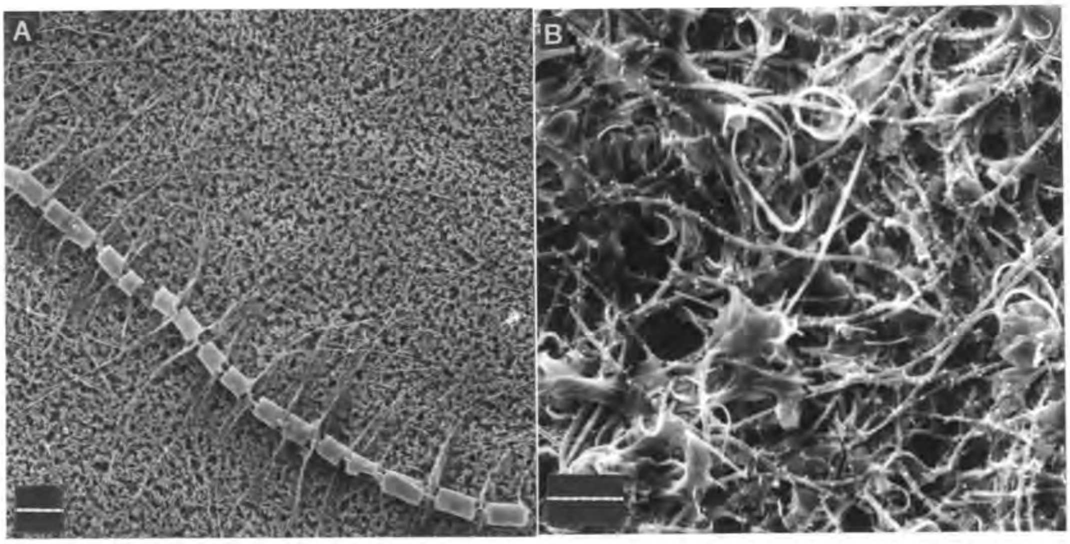

Fig 27 A: an electron micrograph of the diatom Chaetoceros radicans which dominated catches at the Prince Edward Islands in May and November 1983. B: an electron micrograph showing the dense mat of C radicans which made it impossible for investigators to quantify stocks. The scale bar represents 10 µm.

Fig 28 An electron micrograph of the silicoflagellate Dictyocha speculum which, together with diatoms of the genera Chaetoceros and Nitzchia dominated catches in November 1983. The scale bar represents 10 µm.

The difference between the maximim and minimum values of chlorophyll _a_, measured on the surface in the immediate vicinity of the islands for all cruises except that of _R.S. Africana_ in September 1982 (Table 4.), show that the difference within or between cruises is almost an order of magnitude. Surface chlorophyll _a_ contours for the same cruises (Fig. 29), show that in all cases, the highest concentrations of phytoplankton were located over the saddle between the islands.

TABLE 4. Maximim and minimum surface chlorophyll _a_ values determined in the immediate vicinity of the Prince Edward Islands for all cruises except September 1982.

Cruise	Chlorophyll_a_	
	Minimum	Maximim
March 1976 (_Marion Dufresne_)	0.09	1.88
April 1982 (_S.A. Agulhas_)	0.15	1.82
May 1983 (_S.A. Agulhas_)	0.11	1.24
November 1983 (_S.A. Agulhas_)	0.06	0.87
March 1984 (_S.A. Agulhas_)	0.10	0.87

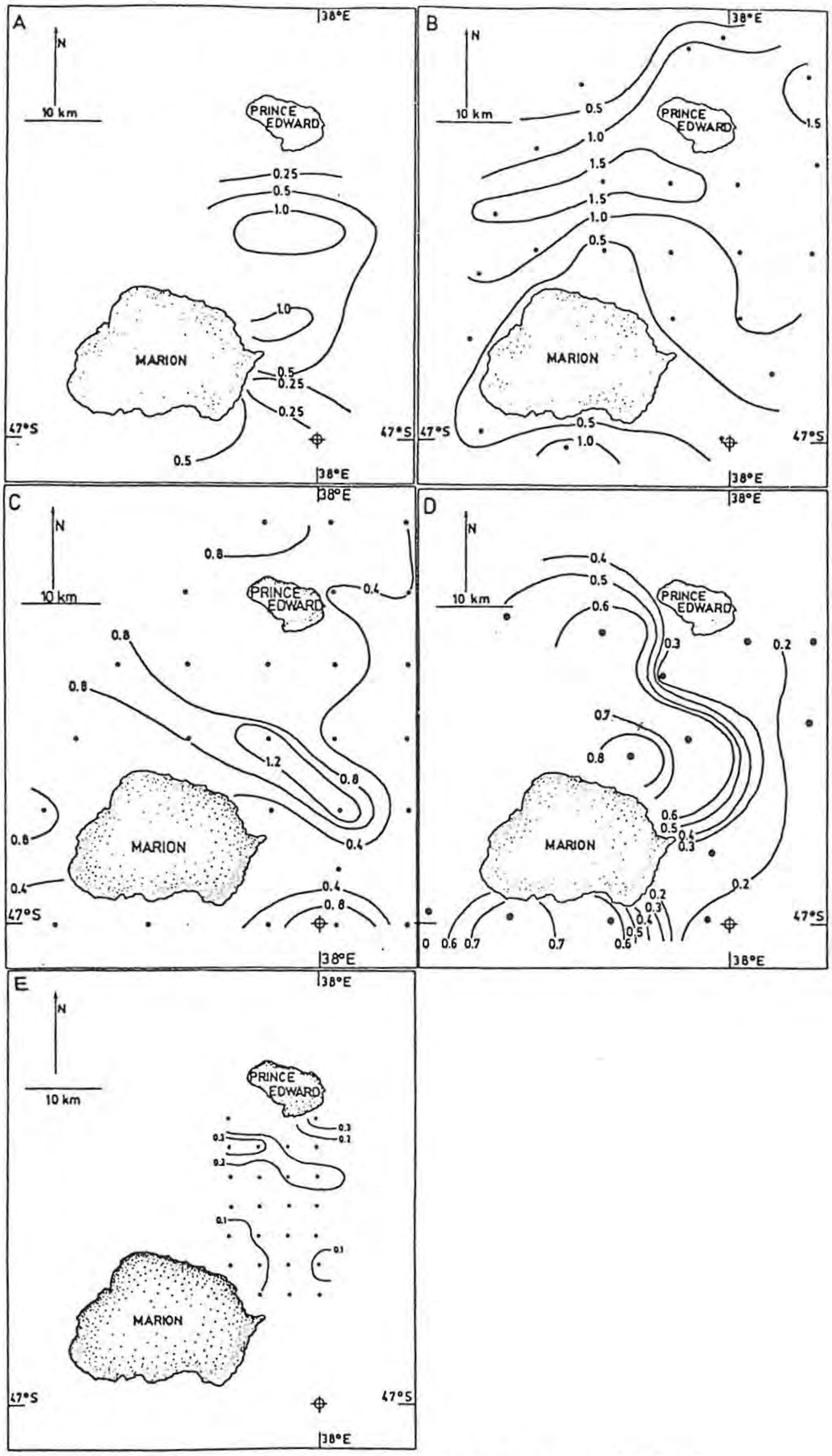

Fig. 29. Surface chlorophyll *a* contours (mgChla.m^{-3}) determined on the following cruises:

- A - March 1976 (*Marion Dufresne*)
- B - April 1982 (*S.A. Agulhas*)
- C - May 1983 (*S.A. Agulhas*)
- D - November 1983 (*S.A. Agulhas*)
- E - March 1984 (*S.A. Agulhas*)

Measurements of potential primary production integrated with depth. expressed as the amount of carbon absorbed per square metre per hour ($mgC.m^{-2}.hr^{-1}$)as used in this study, were obtained by the application of Talling's photosynthetic model as modified by Rodhe (1965) (Fig. 30). The limited nature of the primary production work prevented the application of the more recent model of Platt et al., (1980) in which photosynthesis is described as a continuous function of the available light. Talling (1957) from his work on the freshwater diatom Asterionella formosa, found that the principal source of variation in the rate of photosynthesis with depth was determined by the the relation between photosynthesis and light intensity in conjunction with the relationship between light intensity and depth.

He found that an estimate of the photosynthetic integral could be obtained by the product of the light saturated photosynthetic rate (a_{max}) and the optical depth at which the subsurface light intensity was reduced to a level defined by the onset of light saturation of photosynthesis (I_k)(Fig. 30). This level was determined by planimetry to equal 0.5 I_k and the mathematical representation of this model is as follows:

$$\sum a = 0.5\ I_k.a_{max} \qquad (2)$$

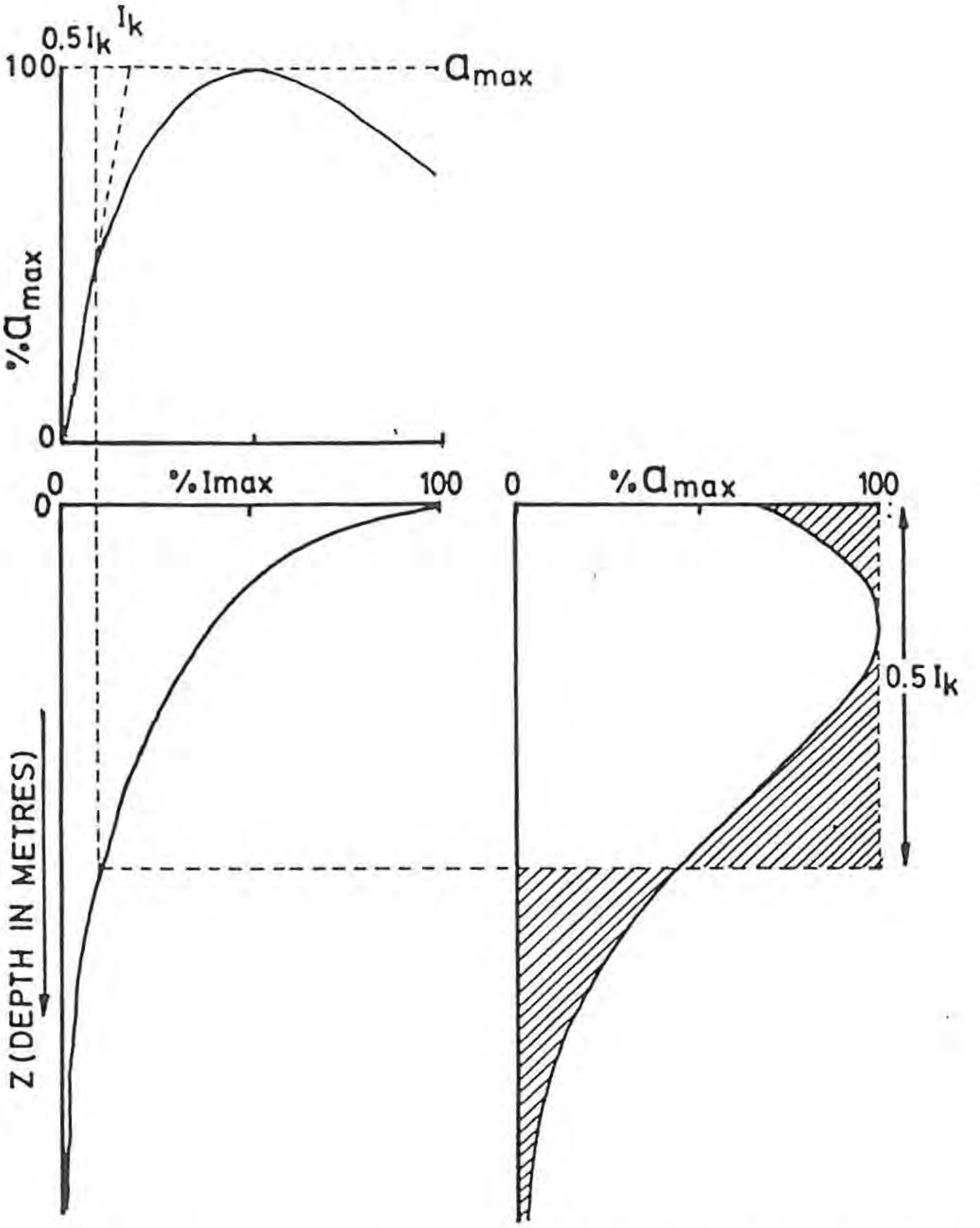

Fig. 30. Talling's photosynthetic model for light inhibition as modified by Rodhe (1965) and used in this study to determine the primary production integral. Adapted from Rodhe (1965).

Later, Rodhe (1965), seeking to simplify the model of Talling while retaining the intensity and quality of light and the assimilation of carbon by phytoplankton as the basis of the model, established a correlation between the optical depth 0.5 I_k used by Talling and that depth in metres at which 90% of the most penetrating component of incident light was absorbed (Fig. 30). He then modified Talling's original expression to read:

$$\Sigma a = Z_{0.1mpc} \cdot a_{max} \qquad (3)$$

The validity of this model is based on the following assumptions:

i. The phytoplankton population concerned must be monospecific or nearly so.

ii. The distribution of phytoplankton through the water column must be uniform.

iii The water column must be isothermal.

In November 1983 the phytoplankton community at the Prince Edward Islands was sampled by hauling a small (25 cm diameter) fine meshed (25um) net verticaly from 75 - 0 m (Fig. 7). The results from this survey (Table 5) show that the diatom genus *Chaetoceros*. in particular *C. radicans* was in terms of numbers. the most dominant component at all bar three of the stations. When the actual numbers are compared, it is evident that at the time of sampling, the community at these islands was to all intents and purposes monospecific.

In March 1976, *C. radicans* were found in bloom at station 18 of the *Marion Dufresne* cruise (El Sayed *et al.*, 1979a) which suggests that at these islands the dominance of a single phytoplankton species is not exceptional.

TABLE 5. The dominant genera of diatoms and silicoflagellates within the phytoplankton community at the Prince Edward Islands in November 1983. Concentrations are expressed as numbers X 10^5 per cubic metre.

STATION	GENUS		
	Chaetoceros	*Nitzchia*	*Dictyocha*
2	13.2	3.6	-
3	4.0	2.8	16.0
4	1.6	2.4	17.8
5	36.0	3.8	-
6	TOO MANY *C. radicans* TO COUNT ANY OTHER COMPONENTS		
7	22.4	3.8	-
8	8.4	11.6	0.6
9	1000*	16 4	2.0
10	1000*	1.6	-
11	1000*	3.0	1.0
12	1000*	4.4	2.0
13	1000*	4.4	-
14	1000*	1.6	0.4

*. These values are estimates because *C radicans* was too dense to count with precision.

Chlorophyll *a* profiles for the upper 100 m measured on the cruises of *Marion Dufresne* (March 1976) and *S.A. Agulhas* (May 1983) (Fig. 31) show that the distribution of phytoplankton in the upper mixed layer is uniform. The depth of the upper mixed layer was determined from temperature profiles (Fig. 10) as being between 50 and 100 m which correlated well with the calculated depth of frictional influence of 88 m. The depth of frictional influence was calculated from the formula:

$$D = \frac{7.6\ W}{\sqrt{\sin \text{theta}}} \qquad \text{(Sverdrup } \textit{et al.}\text{, 1942)} \qquad (4)$$

where:

D = the depth of frictional influence (m)

theta = latitude (degrees)

W = wind stress (m.sec^{-1}). In equation 4, a mean value of 10 m.sec^{-1} (Fig. 5) was used.

Temperature profiles (Fig. 10) demonstrate that the temperature regime in the upper mixed layer is almost isothermal at all times of the year. This, together with the distribution of phytoplankton in the upper 100 m and the examination of the phytoplankton community satisfies the assumptions necessary to validate the use of Talling's photosynthetic model in this study.

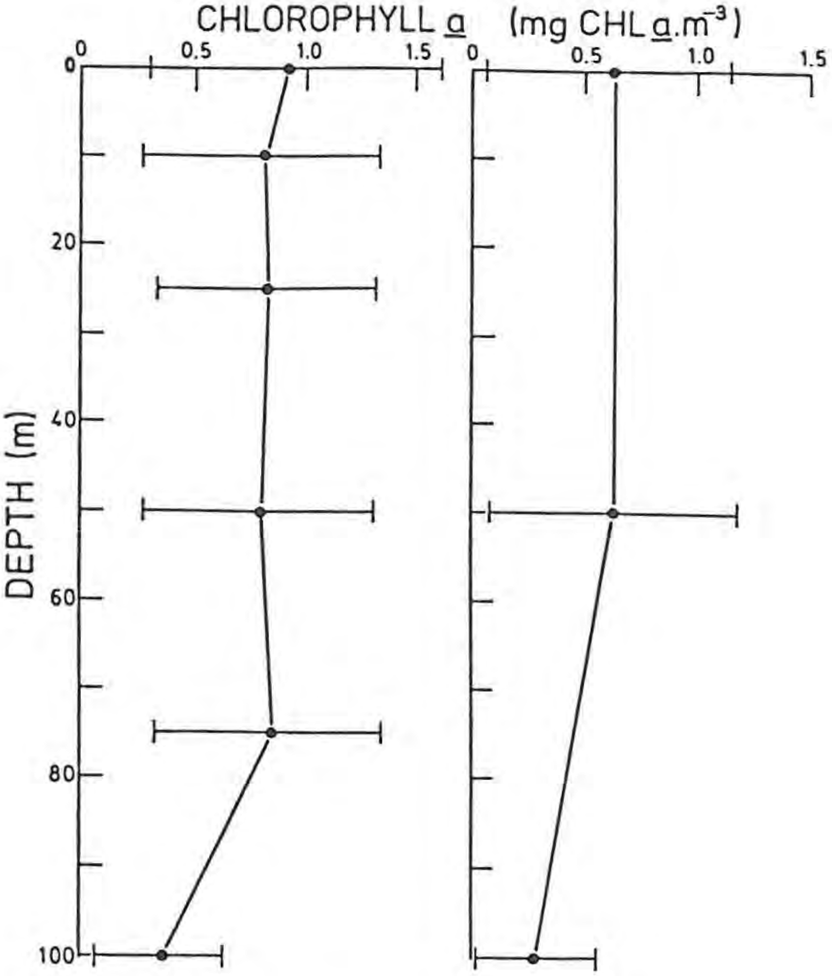

Fig. 31. Chlorophyll a profiles for the upper mixed layer measured in March 1976 (Marion Dufresne) and May 1983 (S.A. Agulhas).

When the distribution of potential primary production measured in April 1982 and May 1983 (Fig. 32) is examined, a close relationship between production and chlorophyll a is seen. This relationship is especially apparent for the May 1983 survey where the contours of chlorophyll a and production follow each other very closely.

Values for specific production ($mgC.mgCHLa^{-1}.hr^{-1}$) for the April and May cruises were obtained from the quotient of the mean photosynthetic rate ($mgC\ m^{-3}.hr^{-1}$) and the mean surface chlorophyll a concentration ($mg\ CHLa.m^{-1}$). Values of 2.87 (S.D. 1.33) and 2.80 (S.D. 2.80) were obtained for April 1982 and May 1983 respectively.

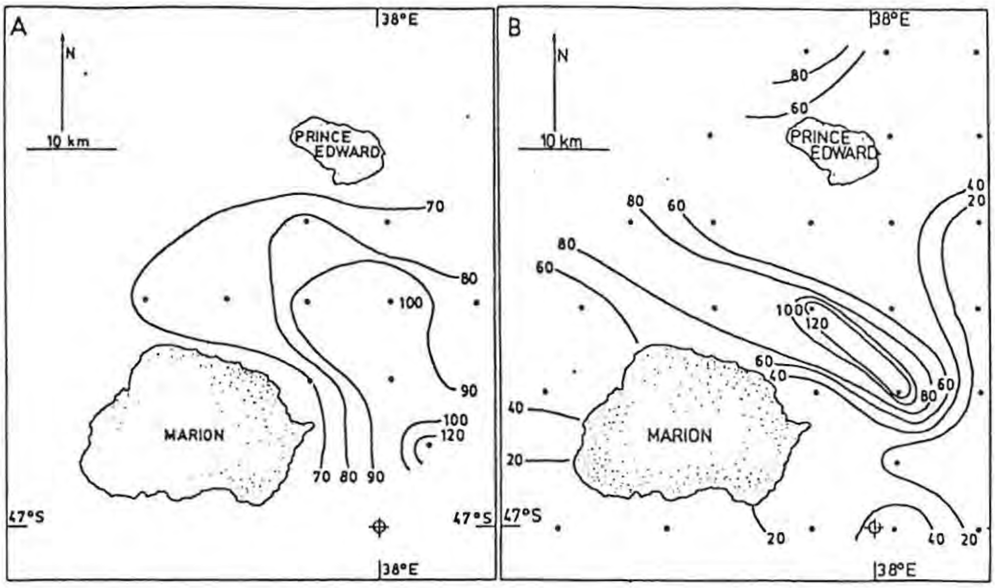

Fig. 32. Potential primary production contours expressed as (mgC.m^{-2}.hr^{-1}) determined with the Gargas/Lonholdt incubator in A - April 1982 and B - May 1983 from S.A. Agulhas.

8.3 2. Zooplankton.

The numerically dominant orders of zooplankton collected in April 1982 and May 1983 from S.A. Agulhas, when presented as a percentage of the total dry weight at each station for each of the surveys (Figs. 33 & 34), like the physical and chemical properties give some idea of the variability of the system. In April 1982 chaetognaths dominated the zooplankton followed by the euphausiids while in May 1983, the plankton was dominated by copepods. In addition, in 1982 the ostracods were negligible and were ignored while they made a notable contribution in 1983.

A systematic account of the zooplankton collected in May 1983 (Appendix 2) shows that at the time of sampling, the zooplankton community at the islands was cosmopolitan in nature with representitives from Antarctic, subtropical and tropical waters. This implies recruitment from far afield and lend support to the hypothesis that eddies or extrusions from fronts may pass close to the islands and decay in their vicinity.

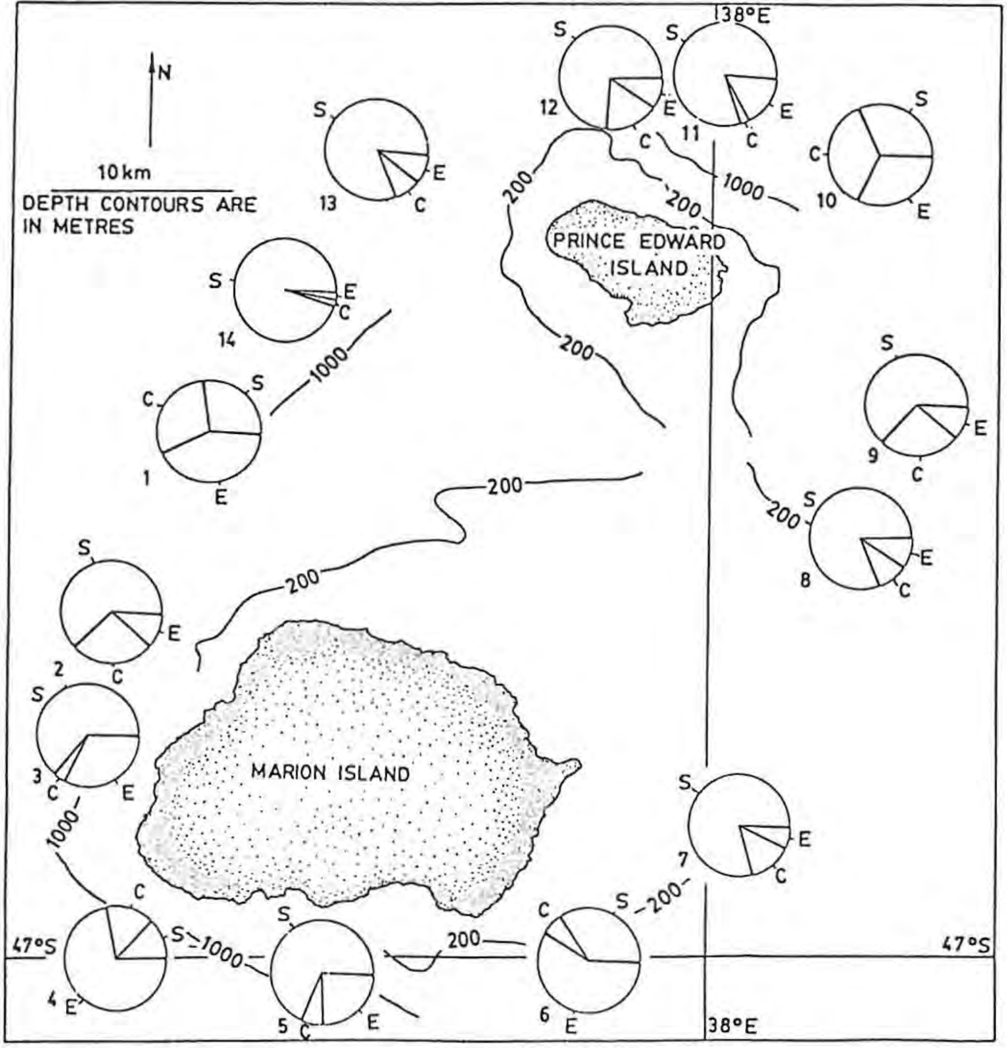

Fig. 33. The numerically dominant components of the zooplankton collected in April 1982 and displayed in relation to the islands. They are expressed as a percent of the total dry weight at each station. Station numbers appear on the lower right hand corner.

KEY: C - copepods
E - euphausiids
S - chaetognaths

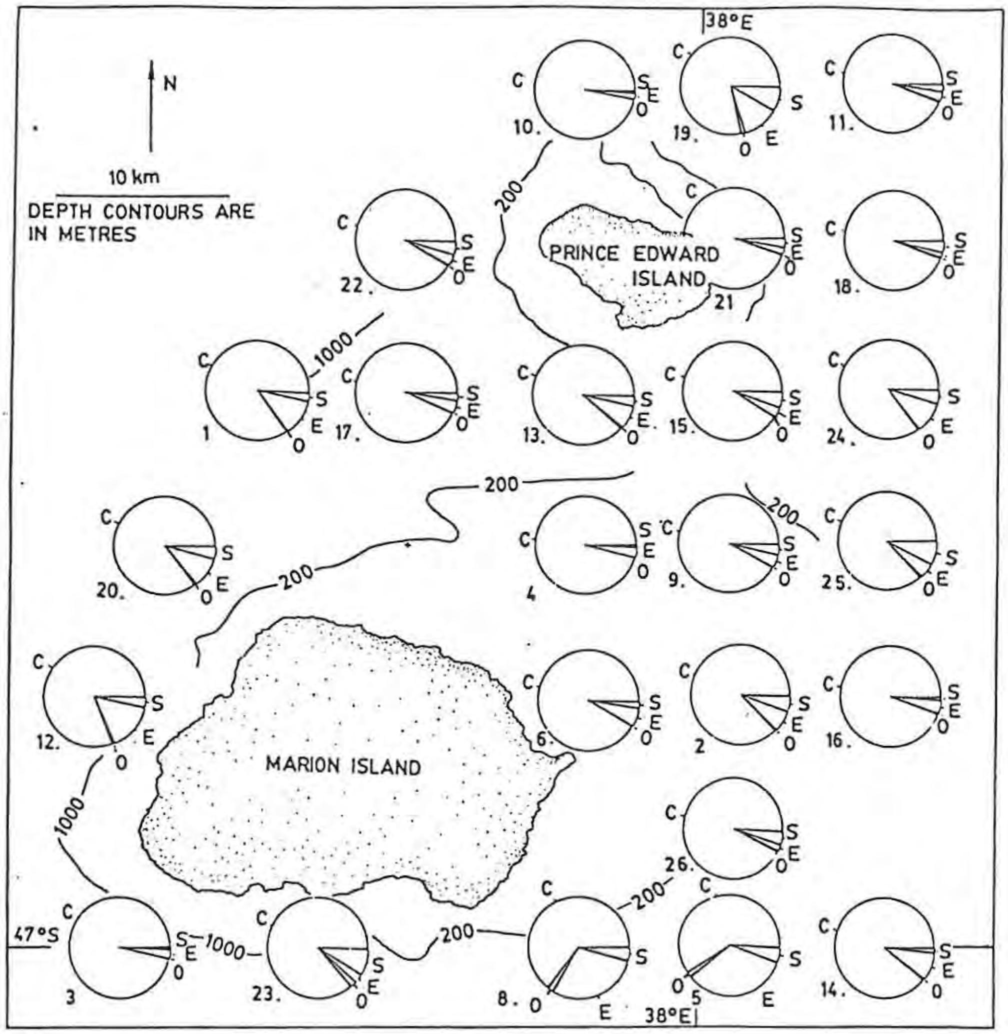

Fig. 34. The numerically dominant components of the zooplankton collected in May 1983 presented as for fig. 33.

KEY:
C - copepods
E - euphausiids
S - chaetognaths
O - ostracods

The use of the same net throughout this study makes it possible for direct comparisons of zooplankton biomass to be made even though avoidance of the net by the larger zooplankton species does occur (Anon, 1968). A fathogram taken at station 16 of the May 1983 survey (Fig. 35) shows that the biomass estimates cited in this study are likely to be gross underestimations because of net avoidance.

This record was made at 15h00 local time (too early for the twilight ascent of the sonic scattering layers) and the multiple nature of the trace shows that the zooplankton was layered. Below the outgoing signal is a distinct layer at about 50 m which could be composed of small zooplankters arrested at the interface of the thermocline. This observation is strengthened by the lack of avoidance when the net passed through this layer which implies that the animals are slow moving.

Diffuse scattering is evident at a depth of 120 m where another rather dense but uniform layer can be distinguished. The animals in this layer do avoid the nets. Below this layer there is diffuse scattering and two further dense layers can be distinguished at 270 and 360 m. The net traces due to echos off the "hardware" of the net can be seen passing through the layers on both the up and down casts. When the net passes through the deeper plankton layers, it can be seen quite clearly that the plankton in these layers aggregate out of the path of the net. When this occurs, the net fishes a reduced community and an underestimation of the standing stock is inevitable.

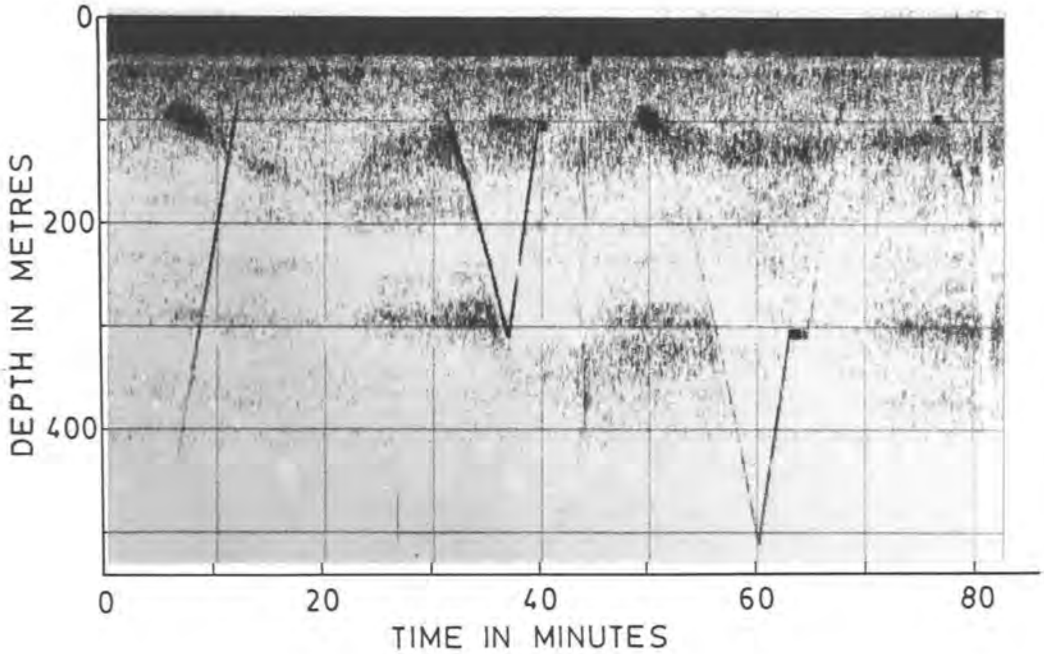

Fig. 35. A fathogram taken at station 16 of the May 1983 (Fig. 7) Prince Edward Island survey. The depth interval between horizontal lines represents 100m and the time interval between vertical lines is 10 mins. The solid oblique traces are the echos returned by the "hardware" of the nets. The echo sounder was operating at 12.5 kHz.

8 3 3. Zoobenthos.

Three dredging stations, one occupied in November 1983 and two in March 1984 (Fig. 7), confirmed the profusion of benthic faunal taxa at these islands reported after the voyage of H.M.S. Challenger (Thomson & Murray, 1885). Estimates of standing stock, obtained from the volume of animals in millilitres per square metre of substratum, displayed in relation to the islands (Fig. 36) show considerable variation which cannot be totally accounted for by the clumping nature of zoobenthos (Thorson, 1957) and can perhaps be explained in terms of currents around the islands affecting the settling of pelagic larvae of the benthic animals.

The current flowing past the east coast of Prince Edward Island would tend to carry any pelagic organisms towards the south coast where the reversal of the current close inshore would facilitate settlement by retaining the larvae in an eddy formed by the retroflective area (Fig. 16). This would explain the difference in stocks between the southeast and southwest coasts of Prince Edward. An examination of current vectors measured in March 1984 (Fig. 16B), shows an onshore component of the current flowing between the islands just north of the Marion Island coastline in the vicinity of the third dredging station. This current would tend to slow down when the shore is reached and once again this would facilitate the settlement of larvae leading to the large stocks of animals collected in this area.

The relative abundance of the major taxa comprising the benthic community (expressed as a percentage of the total volume for each station) (Fig. 37), also shows considerable variation in the structure of the community. One common feature is the dominance of the porifera and bryozoa (the relatively small percentage measured south of Prince Edward Island is probable an artefact created by inefficient sorting). These components are filter feeders and it is likely that they provide an additional substrate for the more active components. In all cases, the crustacean *Nauticaris marionis* made up the bulk of the crustacean component.

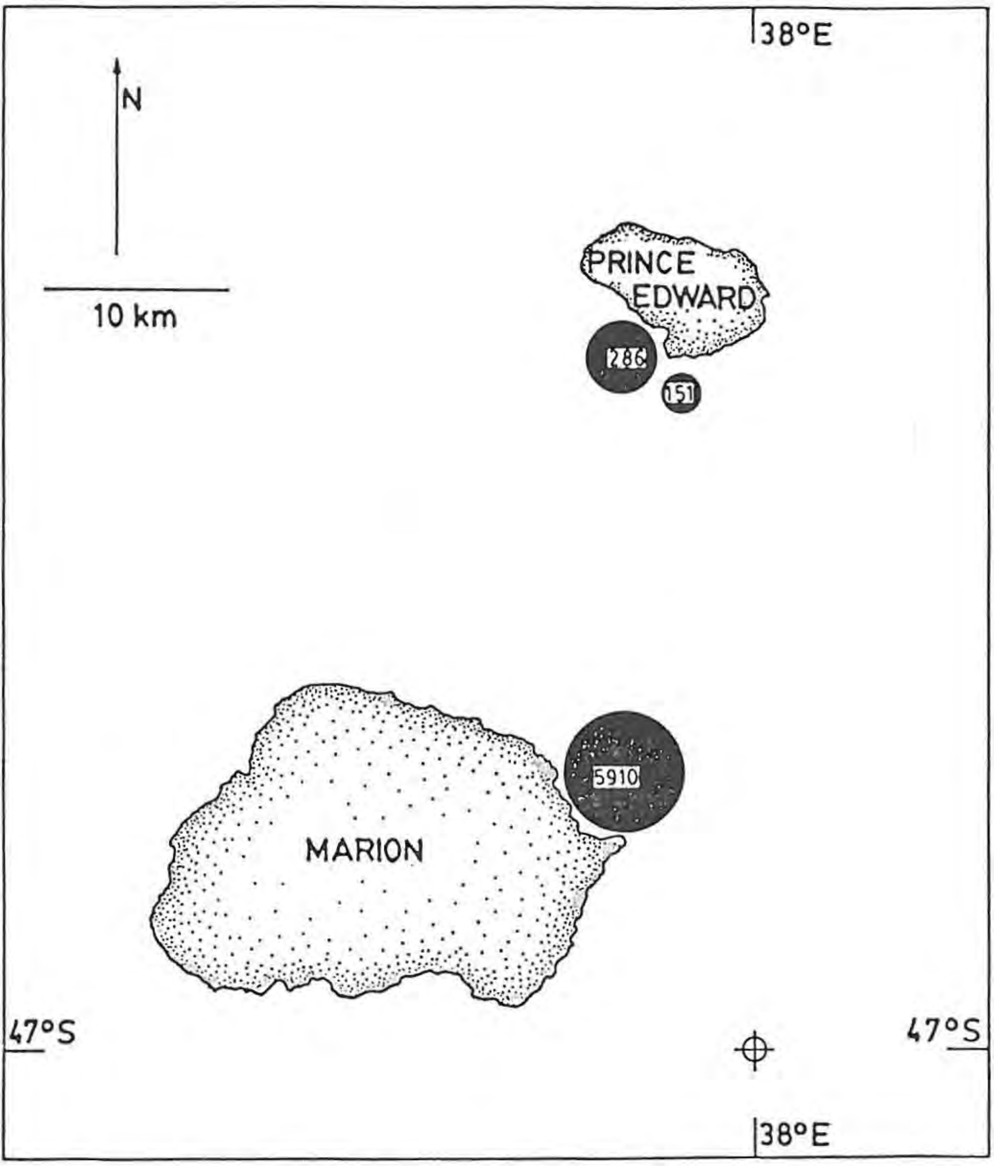

Fig. 36. The standing stock of the benthic community displayed in relation to the islands. The values within the circles represent the volume of animals (ml.m^{-2} of substratum).

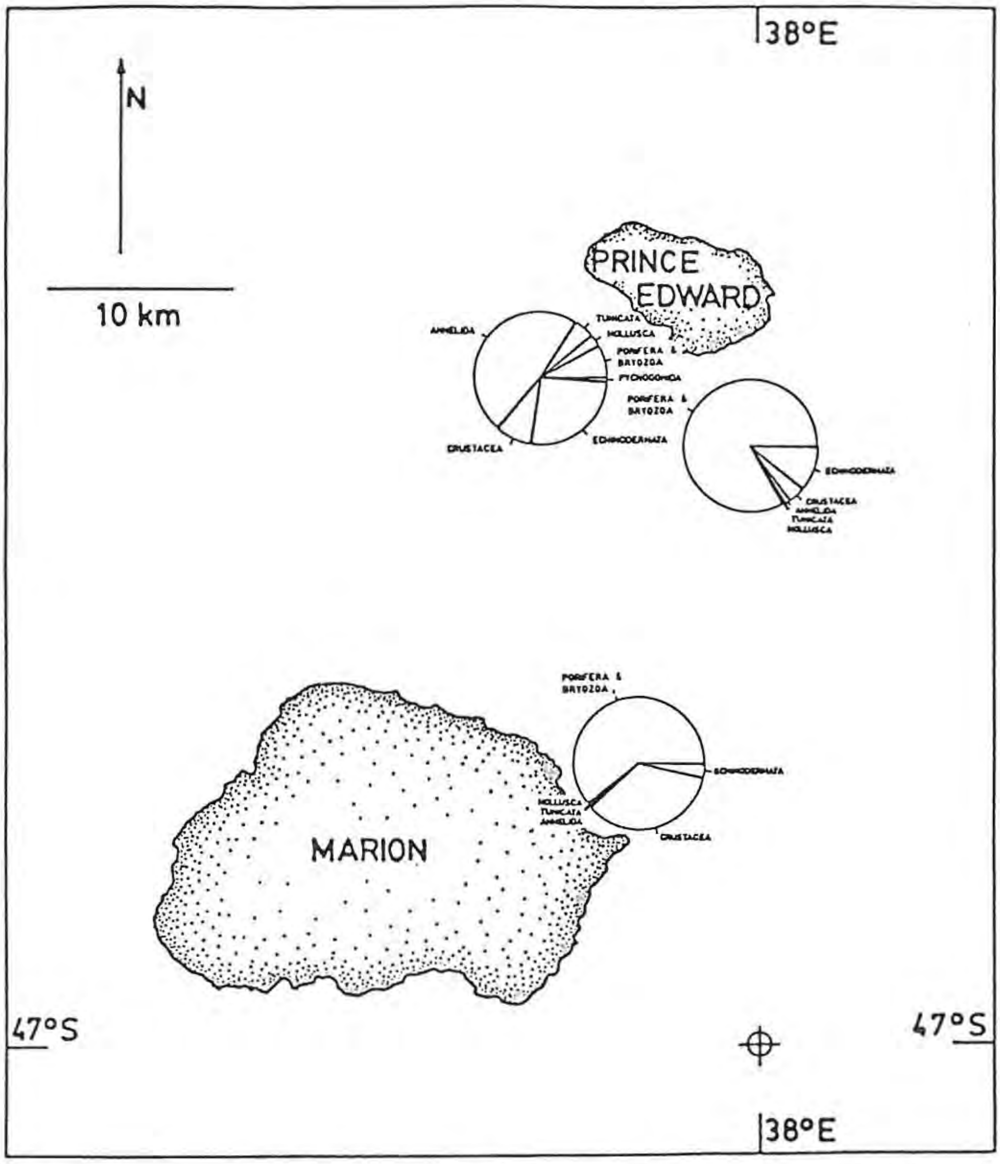

Fig. 37. Relative abundances of the major components of the benthic community, expressed as a percentage of the total volume measured at each station.

9. DISCUSSION

From the physical data set presented in this study, some repetitive features can be seen even though the surface temperature, salinity and sigma-t contours suggest a highly variable system. There is every indication of a seasonal thermocline which is not unexpected in these latitudes (Pickard & Emery, 1982) and current vectors for the surface 50 m from two cruises four months apart, show similar current patterns, namely a diffuse eddy over the saddle between the islands. It is likely that this eddy is the result of wind stress modifying the surface flow of the Antarctic Circumpolar Current and, because of the lack of apparent variation in wind speed and direction during the year (Fig. 5), it is feasible to expect this type of circulation to persist for most of the year.

Minor fluctuations in wind direction and speed are likely to lead to small variations in the surface currents between the islands and these in turn would lead to an changes in surface temperature, salinity and nutrient contours. Such changes could then give rise to the observed lack of consistency of surface contours even though the general pattern of flow over the saddle remains relatively stable. These data also suggest that the distribution of soluble reactive phosphate and reactive nitrate is further confused by inputs via run-off from the islands themselves. The effect of run-off is perhaps best illustrated by the annual pattern of phosphate and nitrate in the sea surrounding the islands. This cyclical pattern seems to follow the seasonal occupation of the islands by terrestrial predators mainly penguins.

The substantial increase in the concentration of chlorophyll a (Table 3, Figs. 26 & 29) and the rate of primary production (Table 3, Fig. 32) in the immediate vicinity of the islands demonstrated conclusively the existence of an "island effect" (similar to that demonstrated at the Hawaiian Island of Oahu by Doty and Oguri in 1956). What is less clear though is the actual mechanism whereby this effect is established and maintained.

Because of the "collecting" effects of eddies which are well known and have been studied at the islands of Bermuda (Boden, 1952; Boden & Kampa, 1953) and Barbados (Emery, 1972), it is reasonable to expect higher concentrations of phytoplankton, especially diatoms which are non motile and are therefore easily entrained by currents, towards the centre of the saddle between the islands. These diatoms would be entrained by the diffuse eddy shown by the current vectors. Clustered histograms representing the concentrations of the macronutrients along the transect A-A (Fig. 38) show slight increases towards the centre of the saddle while clustered histograms representing the biological parameters chlorophyll a, potential primary production and the dry weight of zooplankton over the same transect (Fig. 39) show a more pronounced to increase towards the centre of the saddle.

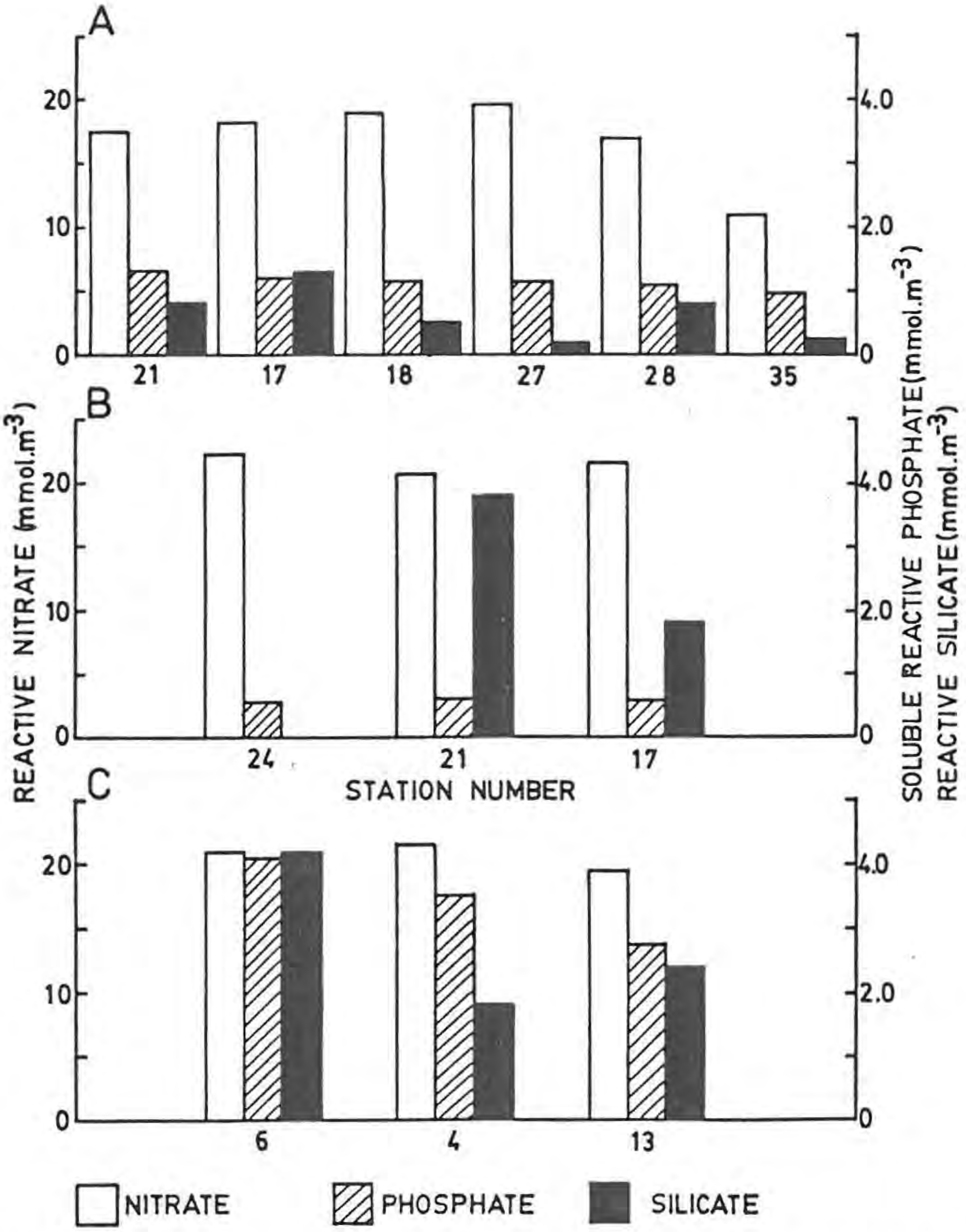

Fig. 38. Clustered histograms representing the concentrations of soluble reactive phosphate, reactive nitrate and soluble reactive silicate in the surface water along the transect A - A (see fig. 7) for the cruises of:

A - Marion Dufresne (March 1976).
B - S.A. Agulhas (April 1982).
C - S.A. Agulhas (May 1983).

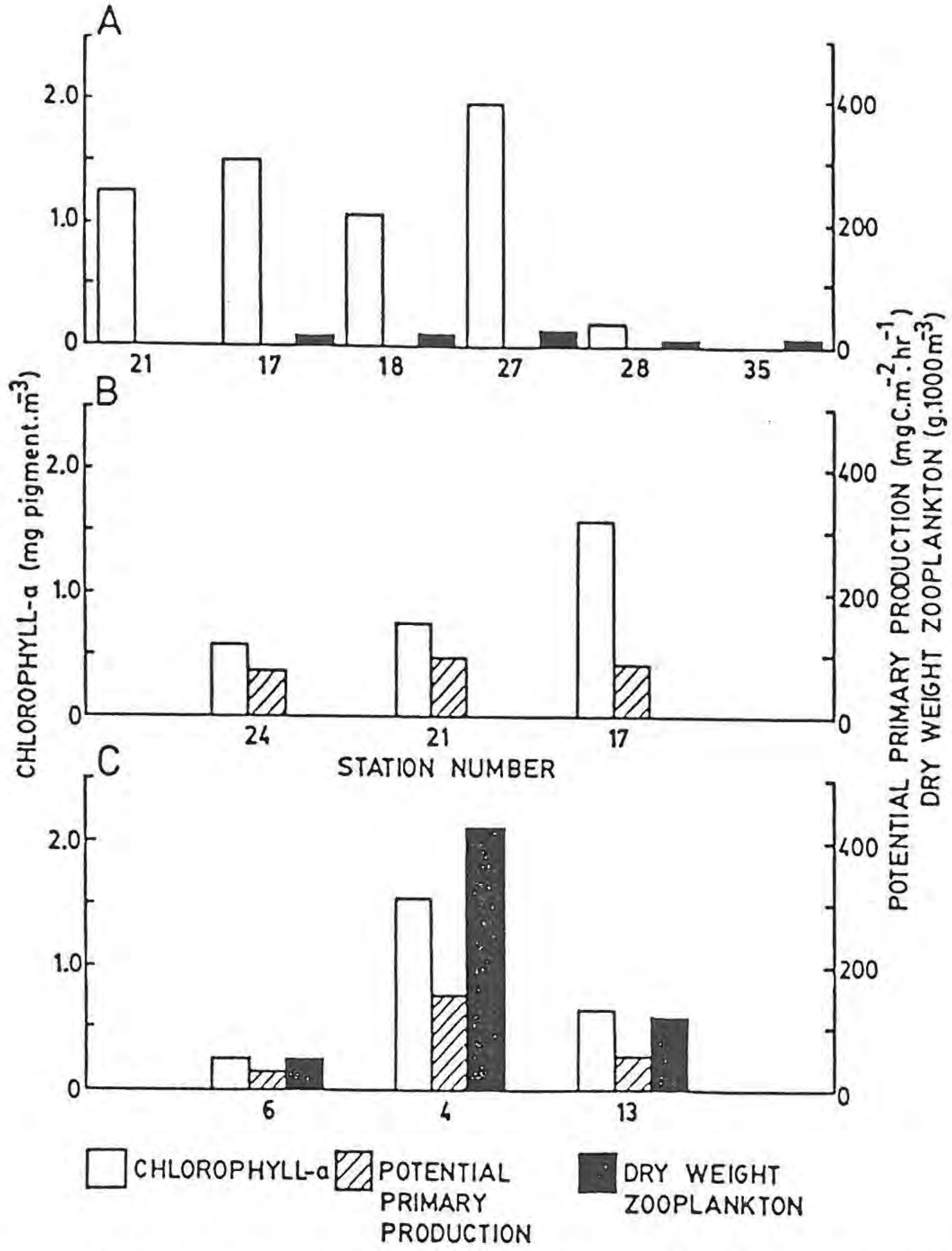

Fig. 39. Surface chlorophyll a, potential primary production and the dry weight of zooplankton expressed as clustered histograms for the same stations and cruises shown in fig. 38.

While the increase in the concentration of chlorophyll a towards the centre of the saddle can be explained in terms of the currents and it is likely that the zooplankton would tend to congregate where the concentration of phytoplankton was highest, one might expect the nutrients to exhibit negative correlations. This was tested by a regression analysis for which Pearson's product moment coefficients of -0.535. -0.504 and -0.547 were obtained for the regression of the concentration of chlorophylla with soluble reactive phosphate, reactive nitrate and soluble reactive silicate respectively.

There can be no doubt that the benthic community at these islands is well established and that the animals are able to reproduce. This can be seen from the carapace size distribution of the dominant crustacean component Nauticaris marionis (Fig. 40), and the observation that many of the nauticarids measured were in berry. In the same way that the surface currents across the saddle can be used to explain the distribution of phytoplankton and zooplankton, they can also be invoked to account for the distribution of the benthic fauna which reproduce using pelagic larval stages and it is likely that the distribution of the standing stock of the benthic fauna may also be related to the currents. It is suggested that the large difference between the volumes of samples collected just south of Prince Edward Island and just to the northeast of Marion Island can be attributed to an onshore component of the main current flowing past the northeast shore of Marion Island, creating a sluggish backwater which facilitates the settlement of any pelagic larvae in this region. The currents cannot however be used to explain the distribution of the bryozoa and porifera which are able to reproduce asexually.

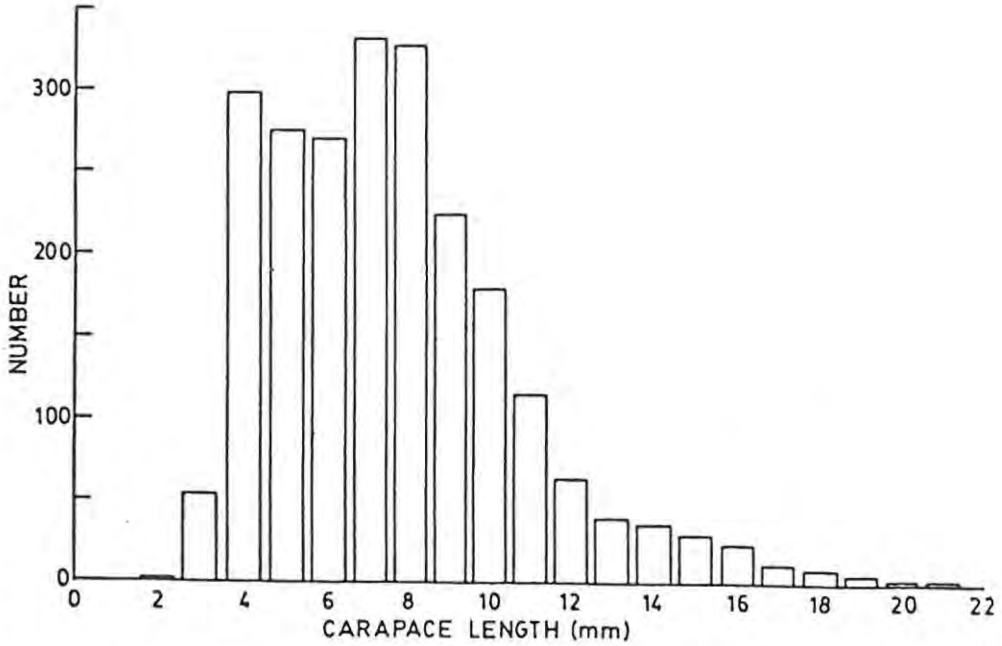

Fig. 40. Histograms showing the size distribution of the carapace length of Nauticaris marionis, the dominant component of the benthic crustacea, collected in the immediate vicinity of Marion Island. The sample from which this figure was constructed contained 2295 animals.

Another mechanism which could account for the increases in phytoplankton stocks and nutrients at the Prince Edward Islands, that of localised wind induced upwelling of deep water in the lee of the islands, was proposed by Grindley & Lane (1978) and Grindley & David (1983) after the cruise of Marion Dufresne in March 1976. To support this hypothesis, Grindley & Lane (1978) make use of the Antarctic affinities of the copepod community collected on this cruise while Grindley & David (1983) cite hydrographic and nutrient data.

While a predominance of Antarctic copepods in samples collected in the subAntarctic could adequately be explained by upwelling of Antarctic Intermediate Water which would transport the copepods into the surface water, at no time was there any physical evidence to lend support to this hypothesis. In fact, the physical criteria of Antarctic

Intermediate Water were approached far below the upper mixed layer (Fig. 12). Vertical temperature profiles for a station in the lee of Marion Island shows a marked thermocline in March 1976, quite the contrary to what would be expected were upwelling taking place. In addition, Grindley & Lane based their assumptions on the geographical distribution of the copepods on the work of Vervoort (1965) but since then, the distribution of copepods in the Southern Ocean has been revised in the light of further research and many of the species listed by Grindley & Lane (1979) as Antarctic forms. are now listed as common in the subAntarctic as well.

A more plausible explanation for the Antarctic affinities of the zooplankton community is that they were transported from the Antarctic in an eddy or extrusion from the Antarctic Polar Front.

10. CONCLUSIONS

From this study. it is possible to draw the following conclusions:

1. There is a definite "island effect" which can be characterised by elevated phytoplankton and zooplankton stocks as well as the presence of a viable benthic community in the immediate vicinity of the Prince Edward Islands.
2. Current vectors for the surface 50 m, suggest very strongly that a diffuse eddy formed as a result of wind stress modifying the surface flow of the Antarctic Circumpolar Current, is the major factor contributing to the establishment and maintenance of the "island effect" at these islands.
3. There is no evidence to support the suggestion that upwelling of deeper water in the lee of the islands leads to the elevated phytoplankton stocks at the islands.

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12. APPENDICES

APPENDIX 1. A BASIC computer program for a Casio PB-100 personal computer to calculate the current velocity (m.sec^{-1}) and direction (magnetic) from current vectors obtained from a current meter (velocity in knots and magnetic heading) and values for the ship's drift (velocity as m.sec^{-1} and true heading).

```
100  PRINT "PROGRAM TO  CALCULATE THE"
110  PRINT "RESULTANT CURRENT VECTORS"
120  PRINT "FROM THE SHIP'S DRIFT AND"
130  PRINT "CURRENT METER VECTORS.   "
140  PRINT "                    L. PARKER"
150  SET F3
160  INPUT "NO. OF  OBSERVATIONS = ",N
170  INPUT "SHIP'S  DIRECTION (T)= ",A
180  INPUT "SHIP'S  SPEED (M/SEC)= ",B
190  FOR I=1 TO N
200  INPUT "C/METER  DIRECTION(M)= ",C
210  INPUT "C/METER  SPEED (KTS.)= ",D
220  C=C+35.92
230  IF C<360 THEN 250
240  C=C-360
250  D=D+0.514764
260  IF A=C THEN 300
270  IF A=(C+180)-360 THEN 300
```

(Appendix 1 continued)

```
280  GOSUB 1000
290  GOTO 320
300  GOSUB 2000
310  GOTO 350
320  G=SQR (B*B+D*D-(2*B*D*COS (E)))
330  F=ACS ((G*G+B*B-D*D)/(2*G*B))
340  GOSUB 3000
350  PRINT "CURRENT DIRECTION (T)= ";F
360  PRINT "CURRENT SPEED (M.SEC)= ";G
370  NEXT I
380  INPUT "ANOTHER STATION (Y/N) ",Z$
390  IF Z$="Y" THEN 160
400  END
1000 IF A≥90 THEN 1110
1010 IF C≥90 THEN 1050
1020 IF A>C THEN 1090
1030 E=270-(90-A)-C:RETURN
1040 E=180-A+C:RETURN
1050 IF C≥180 THEN 1070
1060 GOTO 1030
1070 IF C≥270 THEN 1100
1080 IF A+180>C THEN 1030
1090 E=(270-90-A)-270-C):RETURN
1100 E=180-(90-A)-(360-C);RETURN
1110 IF A≥180 THEN 1210
1120 IF C≥90 THEN 1140
```

(Appendix 1 continued)

```
1130 GOTO 1040
1140 IF C≥180 THEN 1170
1150 IF A>C THEN 1040
1160 E=360-(180-A)-C:RETURN
1170 IF C≥270 THEN 1190
1180 GOTO 1160
1190 IF 360-(180-A)>C THEN 1160
1200 E=C-(360-(180-A)):RETURN
1210 IF A≥270 THEN 1330
1220 IF C≥90 THEN 1260
1230 IF A-180<C THEN 1250
1240 E=(A-180)-C:RETURN
1250 E=C-(A-180):RETURN
1260 IF C≥180 THEN 1280
1270 GOTO 1250
1280 IF C≥270 THEN 1320
1290 IF A<C THEN 1310
1300 E=(270-A)+90+(C-180):RETURN
1310 E=(A-180)+90+(270-C):RETURN
1320 E=(A-180)+(360-C):RETURN
1330 IF C≥90 THEN 1350
1340 E=(360-A)+(90-C):RETURN
1360 IF 360-A>180-C THEN 1380
1370 E=(360-A)-(C-90):RETURN
1380 E+(A-270)-(C-90):RETURN
1390 IF C≥270 THEN 1410
```

(Appendix 1 continued)

```
1400 E=360-A)+(C-180):RETURN

1410 IF A<C THEN 1430

1420 GOTO 1400

1430 E=(180-(360-A))+(360-C):RETURN

2000 IF A=(C+180)-360 THEN 2020

2010 F=A:G=B+D:RETURN

2020 IF B>D THEN 2040

2030 F=C:G=D-B:RETURN

2040 F=A:G=B-D:RETURN

3000 IF A<C THEN 3020

3010 F=A-F: GOTO 3070

3020 IF C>A+180 THEN 3040

3030 F=A+F:GOTO 3070

3040 IF A<F THEN 3060

3050 GOTO 3020

3060 F=360-(F-A)

3070 IF F<360 THEN 3090

3080 F=F-360

3090 RETURN
```

APPENDIX 2: A systematic account of the zooplankton collected in May 1983 together with their known distributional ranges and pertinent comments.

TAXON	DISTRIBUTION AND COMMENTS
PROTOZOA	
Foraminifera	
Globigerina sp.	These orders are common in the subAntarctic and were insignificant in numbers.
Globigerinoides sp.	
Radiolaria	
gen. et spp. non det.	
COELENTERATA	
Medusa spp.	Both the coelenterata and annelida were insignificant in numbers with just a few randomly distributed over the survey area.
Siphonophora spp.	
ANNELIDA	
Polychaeta	
Tomopteris spp.	
larvae gen. et spp non det.	

(Appendix 2 continued)

CHAETOGNATHA	
Eukrohnia hamata	Cosmopolitan
Sagitta gazellae	Antarctic and subAntarctic
S. lyra	Temperate oceanic cosmopolite
S. maxima	Widespread mesobathypelagic form
S. tasmanica	SubAntarctic
	These were all within their ranges and cannot be regarded as indicators.
MOLLUSCA	
Pteropoda	The mollusca were represented at a few stations and in insignificant numbers
Limacina sp.	
Clione sp	
Clio sp	
larvae sp.	
Gastropoda	
gen. et spp non det.	
Pelecepoda	
Lamellibranch sp.	
ARTHROPODA	
Crustacea	
Ostracoda	These appeared in large numbers at most stations.
gen. et spp. non det.	

(Appendix 2 continued)

Copepoda

Aetidius armata	This species has been regarded as Antarctic but is now considered to be eurythermal with tropical subtropical affinities.
Calanus simillimus	Characteristic of the subAntarctic (Vervoort, 1965).
Euchaeta sp.	Reported as characteristic of the warm deep water in the Antarctic (Vervoort, 1965; Bradford. 1971).
Haloptilus sp.	sp. non det.
Heterorhabdus sp.	*H. austrinus* is listed as an Antarctic form (Baker, 1954; Vervoort 1965).
Microcalanus sp.	This was the numerically dominant genus and is regarded as cosmopolitan (Bradford, 1971).
Oithona sp	Not identified to species but this genus is regarded as cosmopolitan (Bradford, 1971; Vervoort. 1965).
Metridia gerlachei	Regarded as a mesopelagic form and it has been reported near pack ice (Bradford, 1971).
Pleuromamma robusta	Abundant in the Antarctic and subAntarctic (Vervoort. 1965).

(Appendix 2 continued)

Rhincalanus gigas *R. nasutus*	Both of these are listed as Antarctic (Vervoort. 1965) but *R. Nasutus* has been reported as common off South Africa (De Decker 1973).
Scaphocalanus magnus	This species appeared rarely in this survey and is considered as endemic in temperate and subtropical waters.
Scolicithricella glacialis	Considered as a purely Antarctic form, found to coexist with *Scaphocalanus magus*.
Spinocalanus spp.	These were uncommon and not identified to species.
Amphipoda	
Primno macropa	This is a Southern Ocean form of which the detailed distribution is not known.
Phronimella elongata	Cosmopolite with a preference for warm deep (500 m) water.
Scina latifrons *S. rattrayi kielhacki*	Both *Scina* spp. are tropical forms with *S. rattrayi kielhacki* circumpolar into the Antartctic.
Themisto gauchicaudii	Worldwide in subpolar and temperate waters of both hemispheres.
Viblia antarctica	Antarctic form.
V. armata	Tropical temperate form.

(Appendix 2 continued)

Euphausiacea	
Euphausia lucens	Occurs mainly in the northern subAntarctic zone but can be found as far south as 50°S (Baker, 1965).
E. similis	This species extends into all but the coldest subAntarctic water while the variety is confined to the warmer surface water (Baker, 1965; John, 1936).
E. similis v.*armata*	
Nematoscellis megalops	Occurred rarely and is regarded as subAntarctic in the Pacific and Indian Oceans. It is a cold water form.
Stylocheiron elongatum	Cosmopolitan species.
Thyanoessa macrura	Antarctic form which, together with *E. lucens* and *E. similis*, was the most abundant euphausiid.
Isopoda	
Euridyce pulchra	Occurred sparsely at five stations.
Tunicata	There is nothing singular about the tunicate distribution and they were relatively sparse.
Appendiculata	
Oikopleura sp.	
Frittilaria sp.	
Thaliacea	
Salpa sp.	

(Appendix 2 continued)

IDENTIFICATIONS AND RATIFICATIONS

Chaetognatha	A. Alverino U.S.M.F.S., La Jolla, California. U.S.A.
Copepoda	P. van der Byl S.F R.I., Cape Town, R.S.A.
Amphipoda	T. Bowman Smithsonian Institute, Washington D.C., U.S.A.
Euphausiacea	B. Boden Rhodes University, Grahamstown, R.S.A.

13. PUBLICATIONS

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