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# Some Oceanographic Observations in the Polynya and along a section in the Southwest Indian/Antarctic Ocean

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## ABSTRACT

Hydrographical and hydrochemical observations have been made at a shelf station off Princess Astrid Coast Dronning Maud Land Antarctica and at 11 other stations along a transect from Antarctica to about 30°S latitude. The shelf station located in a trough has been occupied at 1-month interval in January and February. Significant vertical and temporal variations in temperature and salinity are restricted to the upper 200 m the water is more or less homogeneous below this depth probably trapped in the trough and renewed by the winter convection. There is some near surface thermohaline stratification especially pronounced in January. Substantial warming of surface waters occurs from January to February resulting in the melting of ice which reduces the surface salinity. A sub surface oxygen maximum is observed in January associated with a maximum in primary production. Oxygen concentrations at all depths exhibit decreases from January to February in conjunction with increases in nutrients except phosphate probably resulting from the oxidation of organic matter following high primary production in January.

Vertical sections of temperature salinity potential density dissolved oxygen apparent oxygen utilization phosphate nitrate silicate pH and alkalinity through Antarctic subantarctic and subtropical zones are presented and discussed. The Antarctic Divergence is observed appreciably to the south of its previously reported positions around 20°E longitude indicating some variability in its position. No large gradients in the sea surface temperatures are observed in the Polar Front Zone supporting the view that the transition from Antarctic to subantarctic waters is less sharp in the area around Crozet island. Most striking changes in all properties are observed in the transition zone between waters of subantarc tic and subtropical types. An oxygen minimum occurs within the upper deep water in conjunction with the temperature maximum. The layer is also characterized by high nutrient (phosphate and nitrate) concentrations and low pH. The lower deep water identified by a salinity maximum is characterized by low nutrients. The salinity minimum corresponding to the Antarctic Intermediate. Water is occasionally associated with an oxygen maximum. An oxygen maximum and a pronounced thermostad corresponding to the Subantarctic Mode Water however are not observed at any station probably due to a weakly-developed subantarctic zone south of the subtropical convergence in the area of study.

The ratio between the changes in nitrate and phosphate is deduced as N P = 13 6 1 (by atoms) in conformity with some recent data from the Indian sector of the Southern Ocean suggest ing a lower N P ratio in the biomass than the corresponding oceanic average value (16 1)

## INTRODUCTION

The oceanographic processes that occur in Antarctic waters are essential to (1) maintenance of aerobic conditions in the intermediate deep and bottom waters of the world oceans (2) the removal of heat and addition of fresh water necessary for a steady state character of deep water (3) the re newal of warm water sphere and (4) the equalization of water characteristics of the three major oceans (Gordon 1971). The importance of these processes had been realized by early workers which lead to a spurt in research activities in the southern ocean in the second quarter of this century. The coverage of the oceanic regime around Antarctica for this purpose however has not been uniform and perhaps the Indian sector has been studied least extensively. Some reports on the hydrography and hydro chemistry of this region have appeared from time to time (Ivanenkov and Gubin 1960 Jacobs and

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Georgi, 1977 Sen Gupta and Qasim, 1983 Rama Raju and Somayajulu 1983, Le Jehan and Treguer 1983). The present study was undertaken to provide additional information on the variations in some hydrographical and chemical parameters based on observations along a transect in the Southwest Indian/Antarctic Ocean as a component of the Third Indian Scientific Expedition to Antarctica.

## MATERIALS AND METHODS

11 hydrographic stations were occupied on a transect running from 68°30 S 19°55 E to 29° 43 S, 54°34 E during the return voyage of *MS Finnpolaris* from 3 to 16 March, 1984. Unfortunately due to some mechanical problems with the hydrographic winch the sampling was restricted to the upper 2 000 m of the water column.

Some oceanographic work was also carried out within a polynya when the ship was alongside or near the ice shelf. A station was selected in a trough off Lazarev, the abandoned Soviet station (69°59 20 S 12°42 15 E) where depths exceeding 700 m were encountered on the shelf otherwise 100-200 m deep (Gupta, 1984 - Fig 2). The station was occupied twice on 11 January and 7 February, 1984. By late February, just before the vessel sailed on her return voyage attempts to occupy the same station again were unsuccessful due to hostile weather.

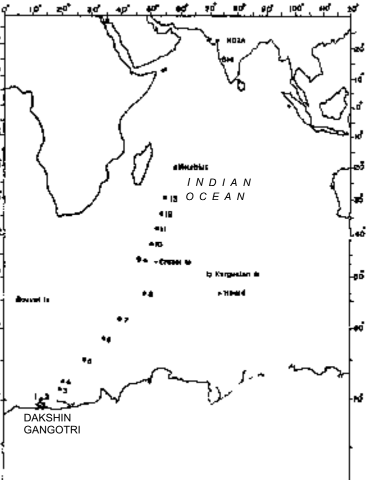


Fig 1 Location of sampling stations

Water samples from standard depths at the stations shown in Fig 1 were collected using PVC Niskin samplers equipped with reversing thermometers. These were analysed onboard the ship shortly after the collection for nutrients (phosphate-phospho rus, nitrate-nitrogen, nitrite-nitrogen and silicate-silicon), dissolved oxygen, alkalinity pH and salinity. Inorganic micronutrients and dissolved oxygen were estimated following standard procedures(Grasshoff,1976). The pH was measured with the ORION Research Model 701 A/digital IONALYZER, calibrated with NBS buffers. The pH was corrected for *in situ* temperature according to Gieskes (1969). The pressure effect was incorporated with the data of Culberson and Pytkowicz (1968). Alkalinity was estimated by the pH method of Culberson *et al* (1970) and salinity was determined with Autosal model 8400 salinometer.

RESULTS AND DISCUSSION

**Characteristics of Shelf Waters off Lazarev**

Profiles of salinity, potential temperature ( $\theta$ ), potential density ( $\sigma_\theta$ ) silicate-silicon dissolved oxygen apparent oxygen utilization (AOU) phosphate-phosphorus and nitrate-nitrogen at a station along the ice-shelf off Lazarev, occupied in January and repeated in February are given in Figs 2a and 2b Marked variations in all the properties are observed with depth and there are appreciable differences between the two sets of observations especially pronounced in the upper 200 m of the water

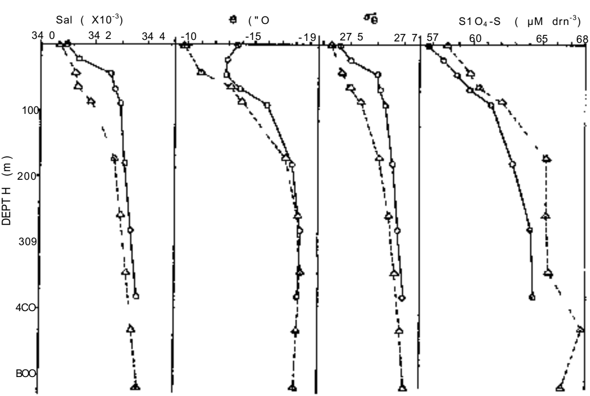


Fig 2a Vertical profiles of salinity potential temperature ($\theta$) potential density ($\sigma_\theta$) and silicate silicon at the shelf station occupied on 11th January (circles) and 7th February (triangles)

column. Below this level, the water is almost isothermal, with the two sets of observations yielding remarkably similar temperature data. Variations in salinity are also relatively small below 200 m than those observed in the overlying water column. There is an evidence for shallow thermohaline stratification more pronounced in January as compared to February and a thick-well-mixed surface layer does not appear to exist during either month. A pronounced temperature minimum, characteristic of waters south of the Polar Front Zone (PFZ), was not observed at this station. This is not surprising considering that the temperature minimum sinks to depths greater than 200 m near Antarctica, and may even be absent at some locations (Wyrtki, 1971). A weakly-developed temperature maximum was observed at 45 min January (Fig 2a), posssibly due to a decrease in sea surface temperature through contact with pack ice, however, it eroded in February with considerable warming of the surface layer (the mean temperature in the upper 100 m increased from -1 38 in January to -1 19°C in February) The increase in surface temperatures was accompanied by a decrease in salinity from 34 212 to 34 130 x $10^{-3}$, evidently resulting from the melting of ice. Although the entire water column appears to be fresher in February as compared to January, the difference in the deeper layers (depth > 200 m) are not very large, and could well be due to a slight offset in salinity data. In view of the relatively small variations in thermohaline characteristics of waters below ca 200 m it seems reasonable to assume that this layer is renewed by thermal convection only in winter and is topographically isolated during the summer. Consequently, it should reflect the hydrographic conditions prevailing during the winter months. If this is true then the salinity of shelf waters during winter should not exceed 34 4 x $10^{-3}$ , and the temperature should range from -1 80 to 1 85°C, corresponding to $\sigma_t$ < 27 80. Thus, it can be inferred that the ice formation during the winter does not seem to increase the density adequately for this part of the shelf to be a source of bottom water production.

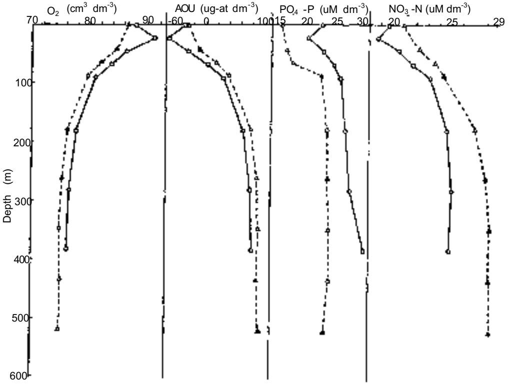


Fig 2b Vertical profiles of dissolved oxygen apparent dissolved oxygen utilization phosphate phosphorus and nitrate nitrogen at the shelf station occupied on 11th January (circles) and 7th February (triangles)

The oxygen profiles for January and February are quite similar, but there are two important differences between the two sets of observations (Fig 2b) (1) a pronounced oxygen maximum observed at 23 m in January was absent in February and (2) the oxygen concentrations at all levels were consistently lower during the latter observations, the difference ( ~ 0 1 cm$^3$ dm$^{-3}$) being larger than the estimated analytical error (< 0 05 cm$^3$ dm$^{-3}$). The oxygen maximum observed in January was associated with pronounced minima in AOU, nitrate and phosphate (Fig 2b). These features probably result from the inhibition of photosynthesis at the surface during January which shifts the depth of maximum production a few metres below the surface. Measurements of phytoplankton biomass and the primary production support this view with the values being maximal between 10 and 20 m (Pant, 1985). The phytoplankton biomass was at maximum around mid-January (about the time the first station was worked), after which the values decreased until the end of the month, increased slightly in early February, and decreased again thereafter until the early March (Pant, 1985). The lower oxygen concentrations observed in February merely reflect the biochemical consumption of oxygen for the oxidation of organic matter following high primary production in the preceding month. Qualitatively consistent with this interpretation are increases in nitrate and silicate at all levels. Surprisingly, the phosphate concentrations apparently decreased during the same period, a discrepancy that is difficult to account for. It is possible that the phosphate values for January are in error and hence the phosphate data are excluded from the following discussion.

The increases in nutrient concentrations appear to be larger than predicted from the Redfield-Ketchum-Richards (RKR) model (Redfield *et al* 1963). The increase at six depths between 40 and 400 m ranged between 8 4 and 18 9 (mean 12 9 µg-at $dm^{-3}$) for AOU, 1 2 and 3 4 (mean 2 18 µM $dm^{-3}$ for nitrate and 0 6 and 2 4 (mean 1 15 µM $dm^{-3}$) for silicate. If the regeneration ratios C N P Si = 106 16 1 15 are assumed to hold good (Richards, 1958 Redfield *et al* 1963). The average biogenic additions of nitrate and silicate between the two sets of observations could be calculated to be 0 70 and 0 75 µM $dm^{-3}$ corresponding to 60 and 34% of the observed increases in silicate and nitrate, respectively. The $NO_3/SIO_4$ ratio varied from 0 3 to 1 0, with an average of 0 47, considerably lower than the value reported by Le Jehan and Treguer (1983) from the Indian sector of the southern ocean. The discrepancy could result from different modes of calculation of the regeneration ratios.

### Oceanographic section in the southwest Indian/Antarctic Ocean

The distributions of the hydrographical and chemical properties measured along the transect running from 68°30 S 19°55 E to 29°43 S 54°34 E are illustrated in Figs 3-12. The section is neither meridional nor latitudinal however latitudinal variations in the properties are likely to be much smaller than the meridional changes considering that the flow in the southern ocean is mostly zonal (Gordon 1971).

The most dramatic changes in the properties are observed between Stas 10 and 11, the transi tion zone between waters of subantarctic and subtropical types the so-called subtropical convergence (STC) positioned at about 42°S in this region (Deacon, 1982) South of this discontinuity the changes in all properties are gradual. Based on observations along a section at 66°30 E, west of Kerguelen, Gamberoni *et al* (1978) and Gamberoni (1979) suggested that the classical scheme of two convergences, subtropical and Antarctic, did not exist at this longitude. Instead, a single discontinuity was observed between 43°S and 46°S latitudes, leading these authors to conclude that the subantarctic zone did not exist in this region. Deacon (1983), however, doubted such a complete change of the usual scheme arguing that the Antarctic temperature minimum was observed to sink below 200 m, albeit gradually, between latitude 49°S and 48°S along the section worked by Gamberoni *et al* (1978), and the salinity minimum continued northwards between 3°C and 4°C isotherms into the Antarctic intermediate layer as in other longitudes. He concluded that the area including Marion, Crozet, Kerguelen and Heard islands seems to be one where there is more interchange and less clear gradation between Antarctic and subantarctic waters than in most latitudes" (Deacon, 1983, p 77). The observations of Rama Raju and Somayajulu (1983), along a transect slightly to the west of the present one, appear to be similar to those of Gamberoni *et al* (1978) and Gamberoni (1979) in that the discontinities in the sea-surface temperatures at the STC and PFZ are not well resolved. Although the stations occupied in the present study are not close enough (especially in the critical region between Stas 7 and 9) to determine the location of the PFZ precisely, it appears that no large gradients in the sea-surface temperatures exist between Stas 8 and 9 where the PFZ is supposed to lie based on Deacon's (1983) map (assuming that it corresponds to the location where the Antarctic temperature minimum sinks below 200 m, see Deacon, 1934). In the present study, the temperature minimum sank gradually from 97 m at Sta 7 to 178 m at Sta 8, and then rapidly to 1087 m at Sta 9. However, as pointed out by Deacon (1983), in the neighbourhood of shallow soundings and complex bottom topography, such

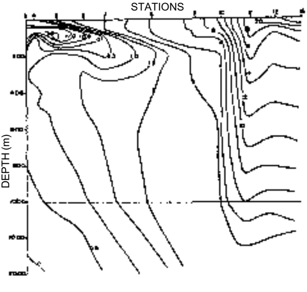


Fig. 3 Vertical section of potential temperature (°C) between 68°30'S, 19°55'E and 29°43'S, 54°34"E

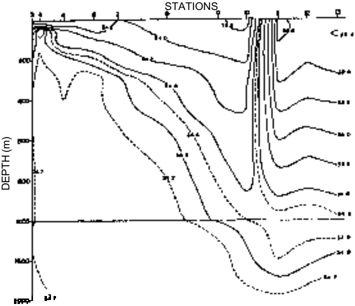


Fig 4 Vertical section of salinity (x $10^{-3}$)

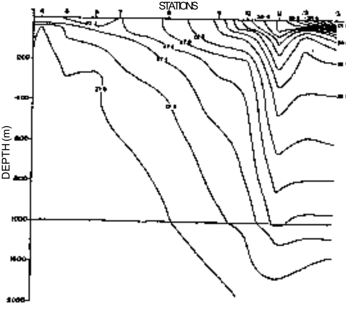


Fig. 5 Vertical section of potential density ($\sigma\theta$)

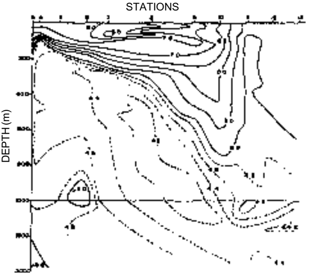


Fig 6 Vertical section of dissolved oxygen ($cm^3$ $dm^{-3}$

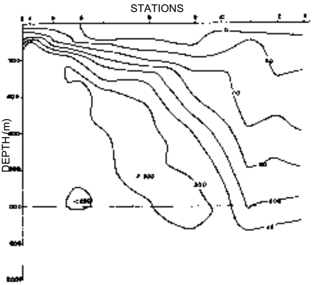


Fig 7 Vertical section of apparent oxygen utilization ($\mu$g-at dm$^{-3}$)

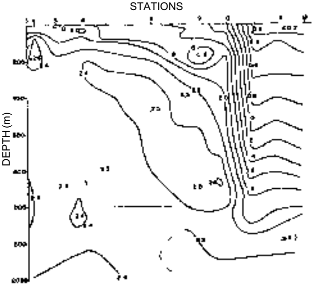


Fig 8 Vertical section of phosphate phosphorus ($\mu$M dm$^{-3}$)

as observed around Marion, Crozet, Kerguelen and Heard islands the sinking of the temperature minimum below 200 m is not as useful an indicator of the surface discontinuity as it is in the deep ocean.

The Antarctic temperature minimum, invariably observed south of Sta 9 intensified southward. It is shallowest (~ 50 m) at Sta 4. Occurrence of upwelling at this station is evident from the distribution of all properties (Figs 3-12). The presence of high salinity and phosphate cells within the upwelling water (Figs 4 and 8) implies eddies. However Sta 4 is located at least 2½ degrees to the south of the previously reported positions of the axis of the Antarctic Divergence in the region. Deacon's (1982) map shows the divergence to occur slightly north of 65°S, hence, Sta 5 instead of Sta 4 should be expected to be located closer to the zone of circumpolar upwelling. Working in the same area, Rama Raju and Somayajulu (1983) found the divergence to occur close to 63°30'S latitude. These data suggest considerable variability in the position of Antarctic Divergence around 20°E longitude.

Underlying the Antarctic surface water which comprises of waters within and above the temperature-minimum layer south of the PFZ is the Warm Deep Water (WDW) flowing southward and upward to compensate for the northward and downward components of flow of the surface and deep waters. The deep water has two components characterized by maxima in temperature and salinity respectively, the temperature maximum occurring considerably shallower (see Gordon, 1971, Jacobs and Georgi, 1977). An oxygen minimum is also observed, generally below the temperature maximum but could be near or above it in some regions (Gordon, 1967). In the present study the temperature maximum, shoaling up from 1087 m at Sta 9 to 285 m at Sta 4, cannot be observed north of Sta 9. The oxygen minimum invariably occurs at the same depths as the temperature maximum (Figs 3 and 6). The depth of the oxygen minimum increased northward, and north of the STC, the minimum being at depths exceeding 1400 m. The distributions of phosphate and nitrate (Figs 8 and 9) follows much the same pattern, with maxima in their concentrations occurring at same levels, located slightly above the temperature maximum and oxygen minimum. The lower deep water, characterized by a salinity maximum, is also characterized by relatively low concentrations of nitrate and phosphate.

A salinity minimum corresponding to the Antarctic Intermediate Water (AIW) is observed at all stations north of the STC at depths ranging between 971 and 1148 m(Fig 4). Across the STC the minimum can be traced to the surface layer in the PFZ between 3°C and 4°C isotherms. Within the core of AIW salinities are lower than 34 5 x $10^{-3}$ at all stations in conformity with the results of Warren (1974) Jacobs and Georgi (1977) and Spencer *et al* (1982) that the 34 5 isohaline associated with AIW extends well north of 37°S the boundary inferred from the previous data (Deacon 1937 Wyrtki 1971). A maximum in dissolved oxygen is associated with the AIW salinity minimum at Sta 11 but not at other stations indicating erosion of the oxygen maximum during the northerly flow (Fig 6). Surprisingly the usually more prominent shallower oxygen maximum is not observed at any station in the present study. This maximum associated with the Sub Antarctic Mode Water (SAMW) has been observed north of the STC in the Indian Ocean by several workers (Ivanenkov and Gubin 1960 Wyrtki 1971 Jacobs and Georgi 1977 Warren 1981 Spencer *et al* 1982). It extends as far to the north as the Arabian Sea (Wyrtki 1971 Sen Gupta and Naqvi 1984, Naqvi and Sen Gupta 1985) The oxygen maximum occurs in conjunc tion with a thermostad a relic of the distant late winter mixed layer in latitudes 40-50°S at progressively lower temperat ures from south Atlantic to southeast Pacific it should be expected at temperatures 12-13°C between longitudes 40-60°E north of the STC in the Indian Ocean (McCartney 1977). Indeed the thermostad and the associated pycnostad have been observed as far to the north as lat 18°S in the Indian Ocean at temperatures 9-12°C (Warren 1981). However pro nounced thermostad or pycnostad are not discernible at temperatures 12-14°C in Figs 3 and 5 con sistant with the absence of an oxygen maximum. It has been suggested that the circulation of SAMW is related to the wind driven southern hemisphere anti cyclonic gyres (McCartney 1977). Hence the SAMW in the southwest Indian Ocean would be expected to be derived from the eastern region through the anticyclonic gyre. Erosion of oxygen maximum during such flow is possible though unlikely. Alternatively if the flow is mostly meridional at these depths the possible absence of a well defined subantarctic zone as discussed earlier might explain the absence of the the thermo stad and oxygen maximum associated with SAMW.

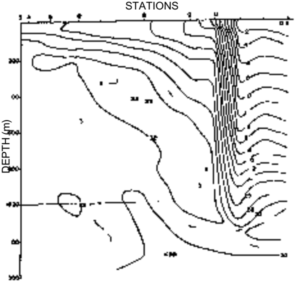

Fig 9 Vertical sect on of nitrate nitrogen (µM dm $^{3}$)

The distributions of nitrate and phosphate discussed above are in good agreement with the previously published results (Redfield 1960 Wyrtki 1971 Jacobs and Georgi 1977 Spencer *et al* 1982 Le Jehan and Treguer 1983). However the nitrate and phosphate concentrations observed in the present study are inexplicably substantially higher than reported by Sen Gupta and Qasim (1983) from the same general area. Silicate distribution is more or less similar in both studies. Unlike phos phate and nitrate surface silicate concentrations fall to low levels well south of the STC and no large gradients in its concentrations exist between Stas 10 and 11 (Fig 10). Distribution of pH (Fig 11) closely follows that of dissolved oxygen with the minimum values (pH < 8 00) associated with the oxygen minimum within the upper deep water characterized by the temperature maximum.

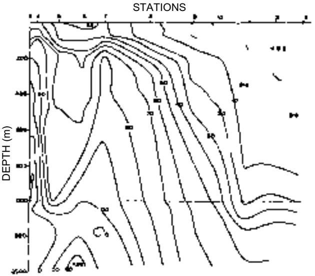


Fig 10 Vertical section of silicate silicon (µM $dm^{-3}$)

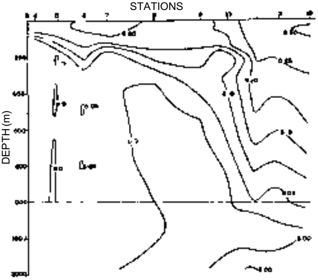


Fig 11 Vertical section of pH

The distribution of normalized alkalinity ($Alk_n$ = TA x 35/S) is illustrated in Fig 12. There are few published alkalinity profiles available from the south Indian Ocean with which to compare the present results. The subtropical front could be seen in Fig 12 as a zone of rapidly changing $Alk_n$ with the isolines being almost vertical down to a depth of about 1 km separating the zone of decreasing $Alk_n$, lying north from that of uniformly high $Alk_n$ south of the front. A tongue of low alkalinity associated with AIW observed in the alkalinity sections in the atlas of Spencer *et al* (1982) based on GEOSECS observations, is not seen in Fig 12 because of the normalization of alkalinity data.

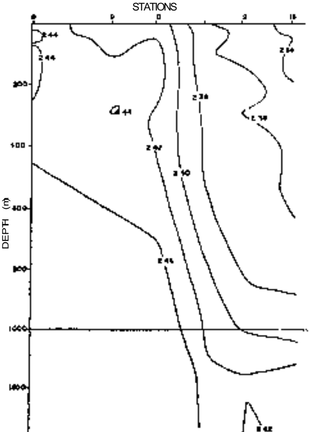


Fig 12 Vertical section of normalised alkalinity (TA X 35/5) meq $dm^{3}$-)

### Nitrate-Phosphate Relationship

Owing to the wide meridional coverage in the present study, large horizontal and vertical variations are expected in reserved nutrients. A relationship between oxygen and nutrients, as determined by Sen Gupta and Qasim (1983), suffers from poor correlation due to considerable scatter of data. The correlation between nitrate and phosphate, on the other hand, is quite good with the two-way linear least squares regression leading to the following equation

$NO_3 = 13\ 62\ PO_4 — 0\ 88$ (r = 0 95)

The $NO_3$/ $PO_4$ ratio (13 6) is close to the value (14 3) for the Arabian Sea (Naqvi *et al* 1982), but is slightly lower than the value (16 0) predicted by the RKR model as well as the ratio (19 0) deduced by Sen Gupta and Qasim (1983). Using the nutrient anomalies calculated from the values expected from simple conservative mixing relationships and the nutrient concentrations actually measured Le Jehan and Treguer (1983) estimated the uptake and regeneration ratio N/ P to range from 12 to 16 8 between latitudes 40 and 60°S along 66°30 E. Most values (mean 14 0) were however, close to the ratio deduced in the present study. Thus, the N/ P ratio in the water, and consequently the N P ratio in plankton in the south Indian/Antarctic Ocean appears to be slightly lower than predicted by the RKR model.

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