

## Nutrient Matters in the Indian Sector of the Antarctic Ocean

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南極海インド洋区における栄養塩

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**要旨：**1979年12月から1980年3月にわたって実施された水産庁「開洋丸」によるインド洋南極海の調査航海において、オーストラリアと南極間の表面観測および東経100°~120°南緯61°以南に設定された調査海域の各層観測を行い、栄養塩の分布を明らかにするため、溶存酸素、リン酸塩、ケイ酸塩、亜硝酸塩および硝酸塩を測定した。

表面観測の結果、亜熱帯収束線および南極収束線にて急激なる栄養塩の変動が明らかとなった。

各層観測の結果は以下の通りであった。(1)硝酸塩、リン酸塩の鉛直変化は100~150 m 以深では非常に均一である。(2)100  $\mu\text{g-at/L}$  以上のケイ酸塩および5.0 ml/L 以下の酸素を示す等濃度線が63°~64°Sの表層へ向かい100~200 m 付近にまで分布している。これらの分布パターンは南極発散域における湧昇現象を示唆していると思われる。(3)硝酸塩とリン酸塩の比は $15.2 \pm 0.6 : 1$ と南極海以外の海域に比較し高目の値を示した。

**Abstract:** During the cruise of the R. V. KAIYO MARU (Fisheries Agency of Japan) in the Indian Sector of the Antarctic Ocean from December 1979 to March 1980, the surface observation between Australia and Antarctica and serial observation in the area bounded by 100°-120° E and 61°-65°S off the Budd Coast of Wilkes Land were carried out on board, in order to determine contents of dissolved oxygen, phosphate-phosphorus, silicate-silicon, nitrite-nitrogen and nitrate-nitrogen.

Surface observation revealed marked longitudinal changes of nutrient matters related to the existence of the Subtropical Convergence and the Antarctic Convergence.

Serial observation showed that distributions of nitrate and phosphate were quite homogeneous below the depth of 100-150 m. Relatively low

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dissolved oxygen content and high silicate content were found up to 100 m in the region of about 63°–64°S. This phenomenon may be attributed to the upwelling of water in the region of the Antarctic Divergence.

The ratio of nitrate to phosphate in the sea off the Budd Coast was  $15.2 \pm 0.6 : 1$ . This ratio was relatively higher than those in other oceans.

## 1. Introduction

For the hydrographic observations in the Antarctic Ocean, extensive cruises by R. R. S. DISCOVERY II were made between 1929 and 1935 (CLOWES, 1938). In the Indian Sector of the Antarctic Ocean, the routine oceanographical observations have been continued by the members of the Japanese Antarctic Research Expedition (JARE) since 1958. Nutrient matters in sea waters between Cape Town and Lützow-Holm Bay have been examined by many investigators (TORII *et al.*, 1959; FUKASE, 1962; ISHINO *et al.*, 1958, 1963; KUGA and WATANUKI, 1963; SHIOZAKI, 1966; AKIYAMA, 1968). However, information is scarce on the behavior of nutrient matters in the waters near the Antarctic Continent.

The present investigation was carried out intensively in the Indian Sector of the Antarctic Ocean near the Budd Coast of Wilkes Land from 12 December 1979 to 8 March 1980, during the cruise of the R. V. KAIYO MARU. The serial observations on the contents of oxygen, phosphate, silicate, nitrite and nitrate were done. Moreover, the surface observations between Australia and Antarctica were performed.

## 2. Materials and Method

Surface water sampling on the southward (from Fremantle) and northward (to Melbourne) legs was performed four times a day at 2:00, 8:00, 14:00 and 20:00 by local time. Positions of the Subtropical Convergence (STC) and the Antarctic Convergence (AC) on the two legs were determined on the basis of the data of thermosalinograph and bathythermograph as described in detail in the KAIYO MARU Cruise Report (SUISAN-CHO, 1980). On the southward leg, location of STC and AC was 40°06'S and 55°42'S, respectively. On the northward leg, location of STC was 44°07'S and that of AC was 58°47'S.

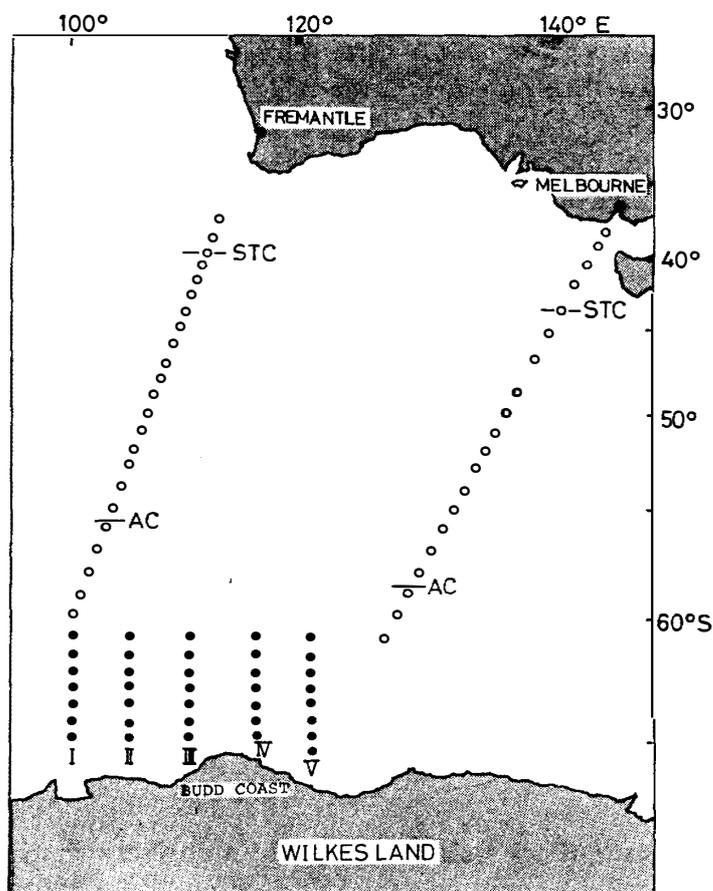


Fig. 1 Stations of surface (○) and serial (●) observations during the cruise of the R. V. KAIYO MARU in 1979-1980. STC and AC denote Subtropical Convergence and Antarctic Convergence, respectively. Roman numerals indicate serial number of sections.

Serial observations were carried out at 36 stations off the Budd Coast as shown in Fig. 1. Water samples were collected from 19 different depths down to 2000 m. These stations were arranged in five sections: I, along 100°E (61°-65°S); II, along 105°E (61°-65°S); III, along 110°E (61°-65°S); IV, along 115°E (61°-65°S); V, along 120°E (65°-66°S).

The methods of the chemical analysis are as follows:

Dissolved oxygen, WINKLER's method.

Phosphate-P, MURPHY and RILEY's method (1962).

Silicate-Si, MÜLLIN and RILEY's method (1955).

Nitrite-N, BENDSCHNEIDER and ROBINSON's method (1952).

Nitrate-N, GRASSHOFF's method (1976).

Standard solutions of nutrient matters (Sagami Chemical Research Center) were used for the standardization of the shipboard analysis. The colorimetric

analysis was done on board using a HIRAMA model 6-B (flow cell type) spectrophotometer.

### 3. Results and Discussion

#### 3.1. Surface observation along the cruise track

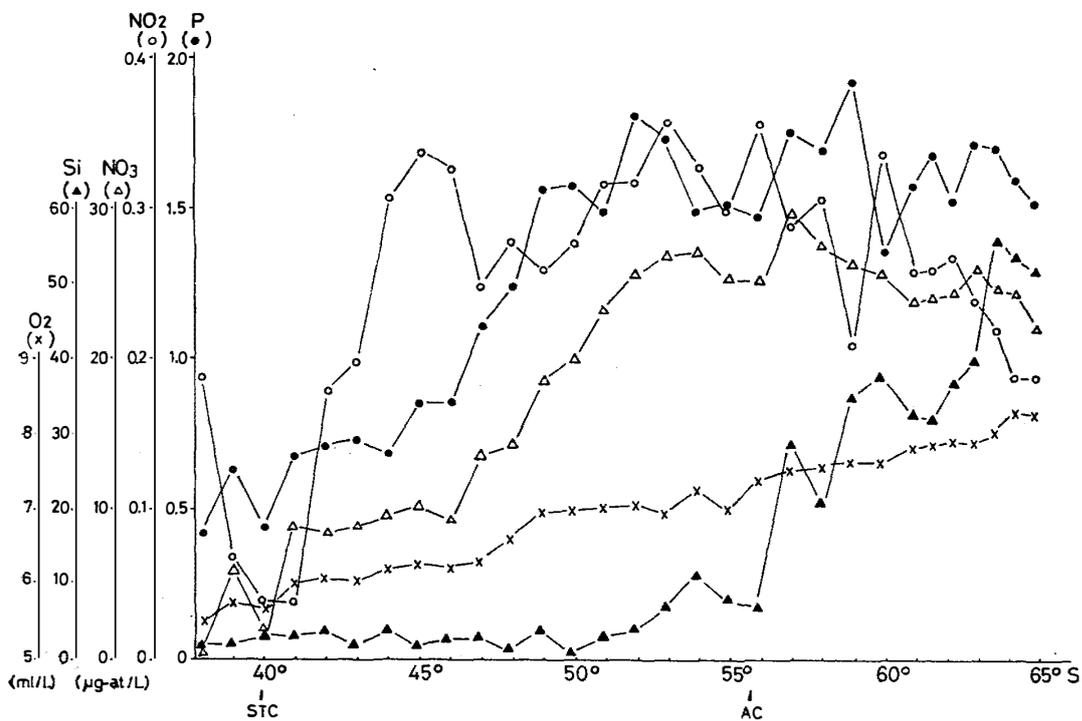
##### 3.1.1. Southward leg from Fremantle to Section I

Changes in the contents of dissolved oxygen, phosphate, silicate, nitrite and nitrate in surface water during the period from 7 to 15 January are shown in Fig. 2a. The dissolved oxygen content was 5.56 ml/L near 38°S, and it increased gradually to 8.0 ml/L at the northern edge of the pack ice region (65°S) near the Continent. Crossing AC and STC, no marked change was observed in the content of dissolved oxygen. This result is the same as that reported by TORII *et al.* (1959). The content of phosphate was as low as 0.42  $\mu\text{g-at/L}$  on the north side of STC and it increased to 1.8  $\mu\text{g-at/L}$  in the Subantarctic water. On the other hand, little change was observed from AC to the south side of the Convergence (1.84  $\mu\text{g-at/L}$ ). Relatively lower value was observed in the pack ice region near the Continent. As to the silicate, the content is nearly constant in the Subantarctic water from 40° to 56°S, but it increased abruptly to 29  $\mu\text{g-at/L}$  at AC. The content increased gradually from AC to 63°S but it decreased to 52  $\mu\text{g-at/L}$  in the pack ice region. The highest value of silicate was 56  $\mu\text{g-at/L}$  at 63°S. The content of nitrite increased from 0.04 to 0.18  $\mu\text{g-at/L}$  near STC. Further south, its content exceeded 0.30  $\mu\text{g-at/L}$  near AC, but in the pack ice region it decreased to 0.19  $\mu\text{g-at/L}$ . As to the nitrate content, 1.4  $\mu\text{g-at/L}$  was observed at 40°S and it increased gradually toward 54°S. The highest value, 29.8  $\mu\text{g-at/L}$ , was observed near AC. However, further south the nitrate content decreased to 22.3  $\mu\text{g-at/L}$  near Antarctica.

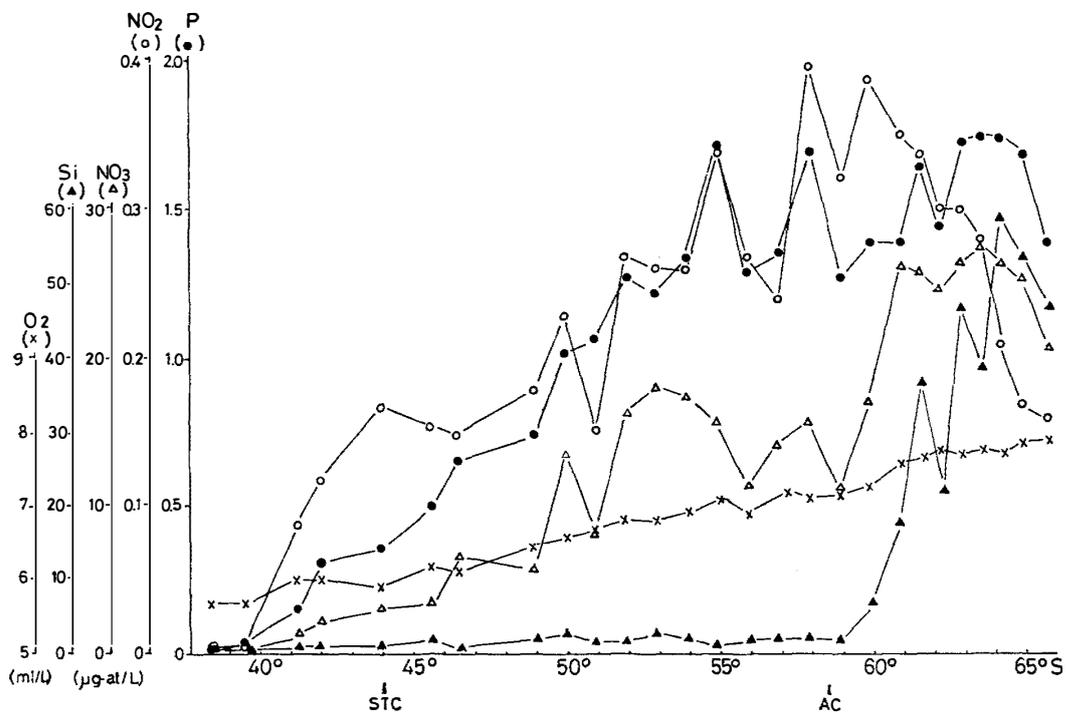
It is clear that abrupt increases in the content of nutrient matters occur at AC and STC.

##### 3.1.2. Northward leg from Section V to Melbourne

The longitudinal changes in the content of dissolved oxygen and nutrient matters in surface water during the period from 27 January to 8 February are shown in Fig. 2b. The highest content of dissolved oxygen was observed as 8.04 ml/L at 66°S near the Continent and it gradually decreased to 5.72 ml/L at 39°S. Longitudinal changes in the dissolved oxygen content on the northward leg are similar to those on the south leg. The highest content of phos-



a. Southward leg



b. Northward leg

Fig. 2. Longitudinal changes in oxygen, phosphate, silicate, nitrite and nitrate contents on the southward leg (a) and northward leg (b). STC and AC as in Fig. 1.

phate along the northward leg was  $1.73 \mu\text{g-at/L}$  at  $55^\circ\text{S}$ , which is located in the middle part of the Subantarctic zone, and a much lower value of  $0.73 \mu\text{g-at/L}$  was observed near STC. The distribution of phosphate on this leg shows the same pattern as that seen on the southward leg, but a little lower value was observed on the northward leg than that on the southward one. Higher content of silicate was observed as high as  $37 \mu\text{g-at/L}$  near  $61^\circ\text{S}$  and it rapidly decreased to  $2 \mu\text{g-at/L}$  at AC. Relatively high values of silicate ( $22\text{--}59 \mu\text{g-at/L}$ ) were found in the Antarctic Ocean. As to nitrite, the highest value of  $0.40 \mu\text{g-at/L}$  was observed near AC and it gradually decreased to  $0.15 \mu\text{g-at/L}$  at STC. Further north of STC, the nitrite content decreased and the value of  $0.03 \mu\text{g-at/L}$  was observed at  $38^\circ 20'\text{S}$ . Nitrate values ranged from 17.1 to 27.6  $\mu\text{g-at/L}$  in the Antarctic region. The nitrate content abruptly decreased to  $11.3 \mu\text{g-at/L}$  at AC and increased to  $18.1 \mu\text{g-at/L}$  in the Subantarctic zone at  $53^\circ\text{S}$ . However, the content decreased to  $3.2 \mu\text{g-at/L}$  at STC.

Longitudinal changes of nutrient matters on this leg are similar to those on the southward leg.

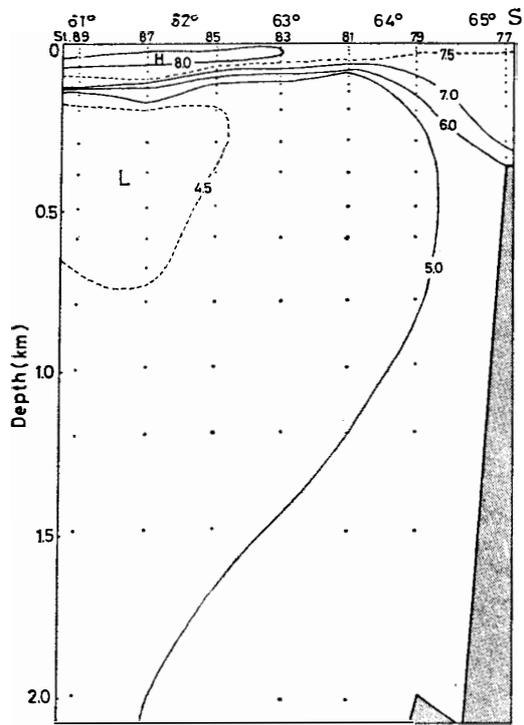
### 3.2. Vertical observation off the Budd Coast

The profiles of dissolved oxygen and nutrient matters along the five sections were generally alike. Examples of the profiles of oxygen and nutrient matters obtained along Section IV, in which an upwelling is observed clearly as discussed in the later part of this report, are dealt with here.

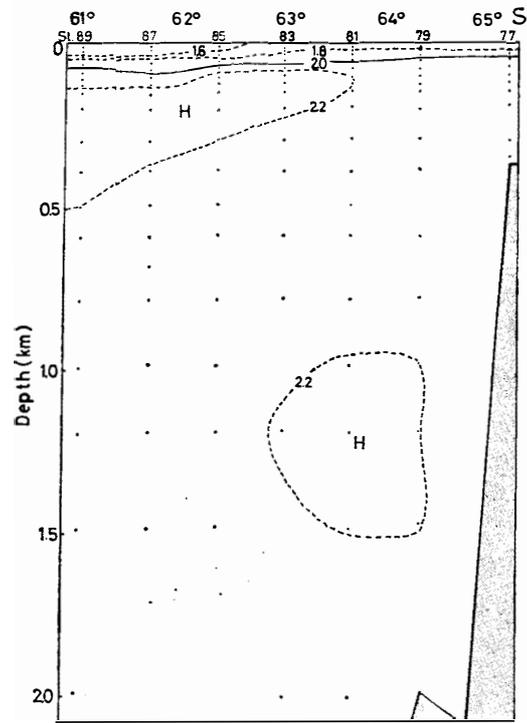
#### 3.2.1. Dissolved oxygen (Fig. 3a)

The water with dissolved oxygen content more than  $7.5 \text{ ml/L}$  was observed from the surface to the depth of 100–150 m, and this layer corresponded to the Antarctic Surface Water. In this layer, the water with more than  $8.0 \text{ ml/L}$  of oxygen content was located between 30 m and 50 m in depth around  $61^\circ\text{--}63^\circ\text{S}$ . The water layer may be formed by the effect of combined processes, such as surface warming during the Antarctic summer and subsurface activity of photosynthetic organisms. The Antarctic Circumpolar Water can be designated by the oxygen content lower than  $5.0 \text{ ml/L}$  distributed between 200 m and 2000 m depth. Southern boundary of this water may be located at  $64^\circ 30'\text{S}$ . The Antarctic Circumpolar Water may upwell around  $64^\circ 30'\text{S}$  corresponding to the Antarctic Divergence. The Antarctic Bottom Water can be designated by the oxygen content higher than  $5.0 \text{ ml/L}$  and it is clearly found along the Continental slope.

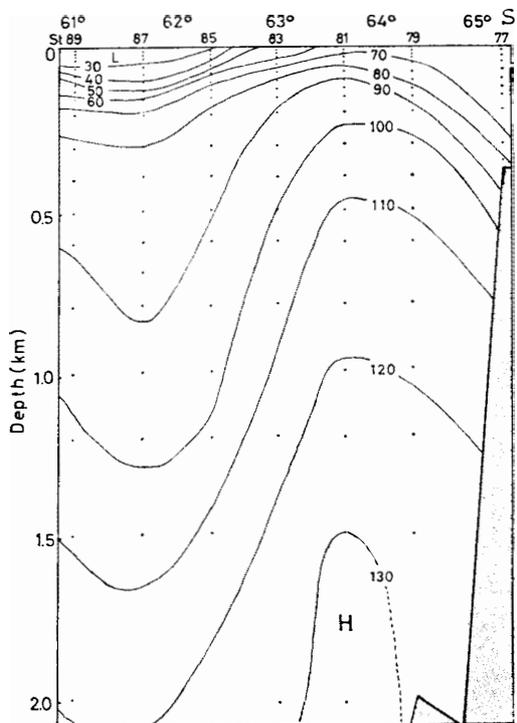
#### 3.2.2. Phosphate (Fig. 3b)



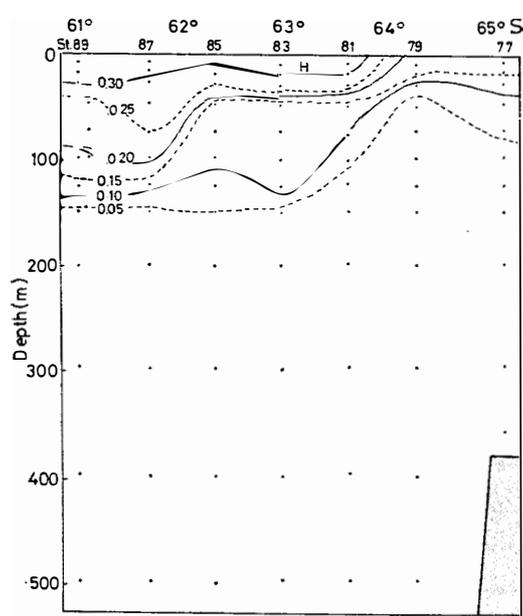
a. Oxygen (ml/L).



b. Phosphate ( $\mu\text{g-at/L}$ ).



c. Silicate ( $\mu\text{g-at/L}$ ).



d. Nitrite ( $\mu\text{g-at/L}$ ).

Fig. 3.

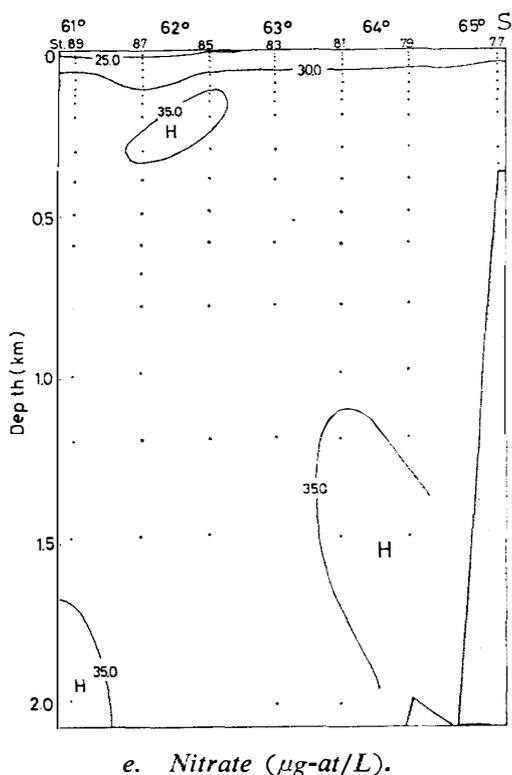


Fig. 3. Profiles of dissolved oxygen (a), phosphate (b), silicate (c), nitrite (d) and nitrate (e) along the Section IV.

The phosphate content lower than  $2.0 \mu\text{g-at/L}$  was observed uniformly from the surface to the depth of about 100 m. This layer corresponded to the Antarctic Surface Water. Little change was found below the depth of about 100 m, the value ranging from  $2.0$ – $2.3 \mu\text{g-at/L}$ . In the area north of  $63^\circ\text{S}$ , a phosphate maximum was discernible between 200 m and 500 m.

The expansion of the Antarctic Circumpolar Water cannot be traced by phosphate distribution. However, in other section, the water mass with the phosphate content between  $2.0$  and  $2.2 \mu\text{g-at/L}$  was distributed corresponding to the Antarctic Circumpolar Water. The phosphate content in the Antarctic Circumpolar Water in the Indian sector was consistently lower than that of the deep water in the Pacific Ocean. As to the low content of phosphate, SHIOZAKI (1966) reported that the Circumpolar Water of this region originates from the Antarctic Deep Water of low phosphate content. The phosphate content of the Antarctic Bottom Water was a little higher than  $2.2 \mu\text{g-at/L}$ .

### 3.2.3. Silicate (Fig. 3c)

The silicate content of  $30$ – $70 \mu\text{g-at/L}$  was observed in the surface layer down to about 150 m, corresponding to the Antarctic Surface Water. These values were generally higher than those in the surface layer of the other oceans.

The silicate content in the Antarctic Circumpolar Water ranged from 80 to 120  $\mu\text{g-at/L}$ . In the deeper part of the Antarctic Circumpolar Water which may be characterized by salinity maximum, the silicate content was about 100  $\mu\text{g-at/L}$ . However, the depth of water with 100  $\mu\text{g-at/L}$  was seen in a shallow layer around  $64^\circ\text{S}$  in five sections, the depth of 100  $\mu\text{g-at/L}$  water in Sections I, II, III, IV and V being 340 m, 400 m, 320 m, 240 m and 400 m, respectively. According to silicate distribution, it is considered that the region of the Antarctic Divergence is located around  $64^\circ\text{S}$ .

From the silicate content, the presence of the Antarctic Bottom Water was not clearly found in Section IV.

#### 3.2.4. Nitrite (Fig. 3d)

The nitrite content of 0.18–0.35  $\mu\text{g-at/L}$  was found in the surface water, and it decreased to a trace amount below 150 m. The nitrite was not detected in the water of the Antarctic Circumpolar Water. The depth of water with the same concentration of nitrite became gradually shallow from  $62^\circ$  to  $65^\circ\text{S}$ . The subsurface maximum of nitrite was not found.

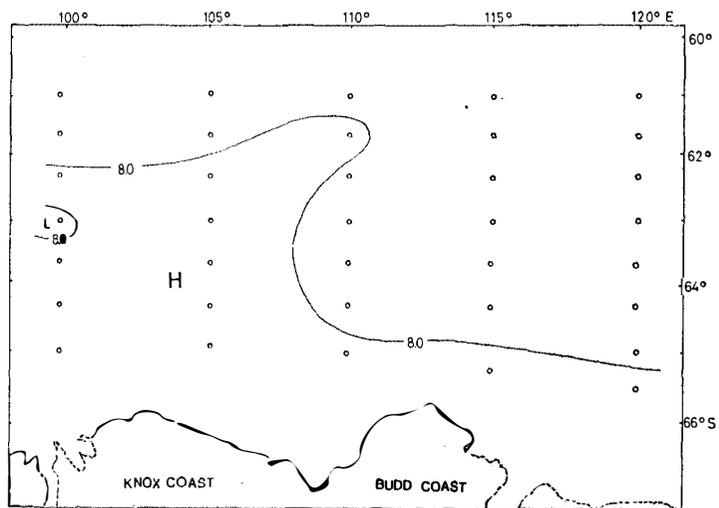
#### 3.2.5. Nitrate (Fig. 3e)

The content of nitrate in the surface water was below 30  $\mu\text{g-at/L}$  and water with lower nitrate content than 25  $\mu\text{g-at/L}$  was found in the northern part of  $63^\circ\text{S}$ . This nitrate level in the surface water was generally higher than that in the surface water of other oceans. The nitrate content below about 100 m was quite homogeneous ranging from 30–37  $\mu\text{g-at/L}$ . In the region of  $62^\circ\text{S}$ , water with the nitrate content more than 35  $\mu\text{g-at/L}$  was found between 100 m and 300 m. These depths may coincide with those of oxygen minimum and phosphate maximum. Then, the depth of this layer corresponded to that of the upper part of the Antarctic Circumpolar Water.

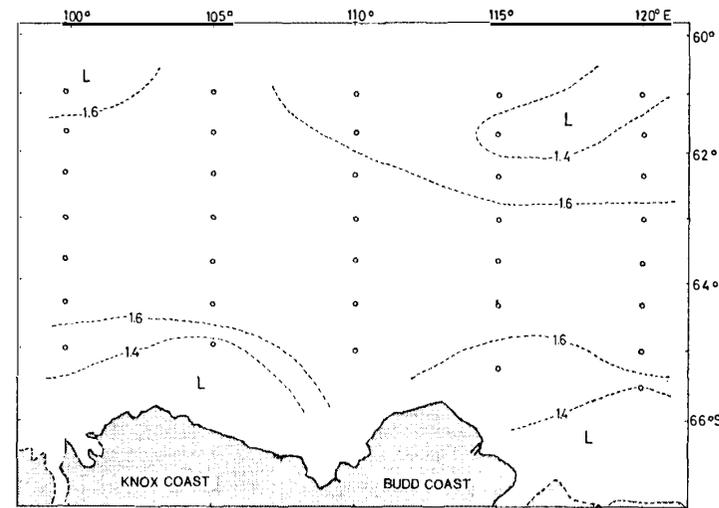
Higher contents over 35  $\mu\text{g-at/L}$  were present between the depths of 1000 m and 2000 m around  $64^\circ\text{S}$ , which corresponds to the value of the Antarctic Bottom Water.

### 3.3. Horizontal distributions of dissolved oxygen, phosphate and silicate in subsurface water

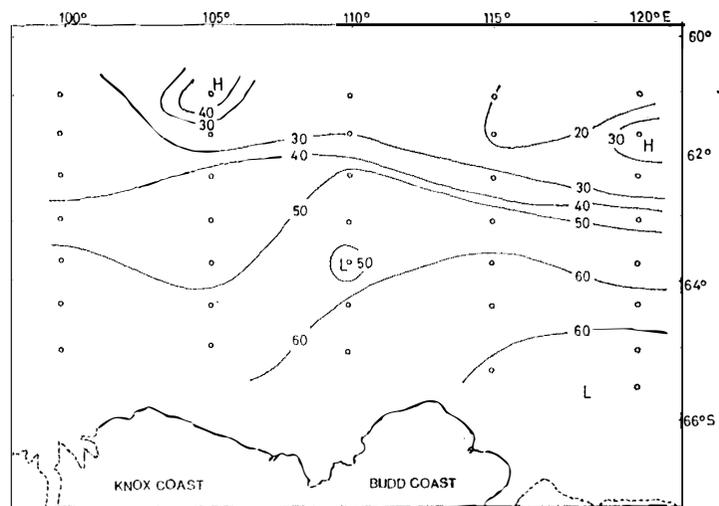
Horizontal distributions of dissolved oxygen, phosphate and silicate at a depth of 10 m are shown in Fig. 4a–c. Water with the dissolved oxygen content of 7.5–8.0 ml/L is distributed relatively uniformly. The phosphate content of 1.6  $\mu\text{g-at/L}$  was distributed in most part of this region, while the water of less than 1.4  $\mu\text{g-at/L}$  near the Continent may have resulted from the



a. Oxygen (ml/L)

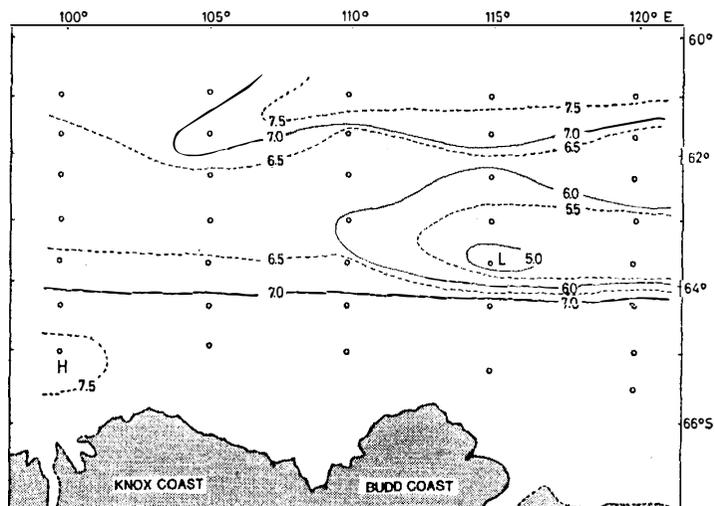


b. Phosphate ( $\mu\text{g-at/L}$ )



c. Silicate ( $\mu\text{g-at/L}$ )

Fig. 4. Horizontal distributions of dissolved oxygen (a), phosphate (b) and silicate (c) in the layer of 10 m.



a. Oxygen (ml/L)

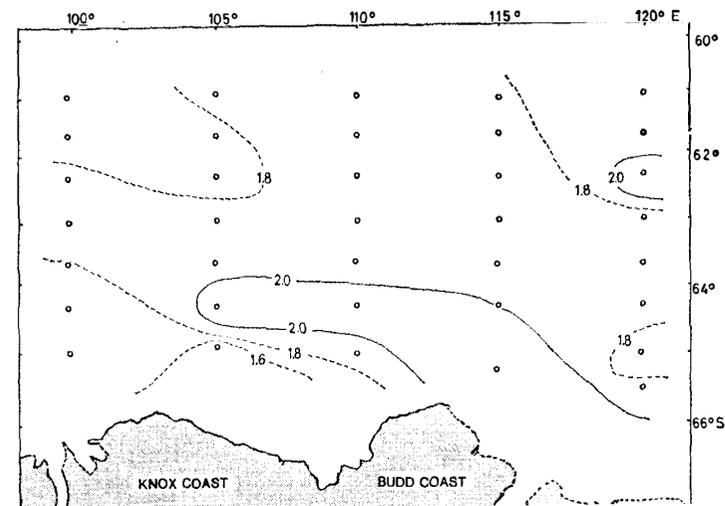
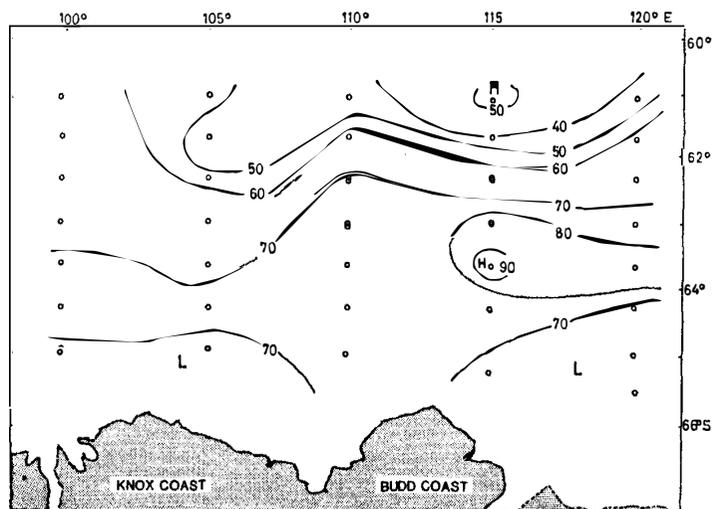
b. Phosphate ( $\mu\text{g-at/L}$ )c. Silicate ( $\mu\text{g-at/L}$ )

Fig. 5. Horizontal distributions of dissolved oxygen (a), phosphate (b) and silicate (c) in the layer of 100 m.

melting pack ice. The silicate content in the region of higher latitudes was higher than that in the region of lower latitudes.

Horizontal distributions of dissolved oxygen, phosphate and silicate in the layer of 100 m depth are shown in Fig. 5 a-c. Water with the dissolved oxygen content of less than 5.0 ml/L was clearly found around 63°30'S along 115°E. Such low values originated from the deep water. Therefore, it is clearly indicated that the Antarctic Circumpolar Water upwells up to 100 m. The phosphate content ranged from 2.0–2.2  $\mu\text{g-at/L}$  at the depth of 100 m, but upwelling of the Antarctic Circumpolar Water cannot be clearly found. The maximum silicate content higher than 90  $\mu\text{g-at/L}$  was seen around 63°30'S along 115°E, while the silicate content higher than 70  $\mu\text{g-at/L}$  was found south of 63°–64°S. The area of highest silicate corresponds to that of oxygen minimum. From these results, it can be presumed that the region of the Antarctic Divergence is located around 63°–64°S.

### 3.4. The ratio of nitrate to phosphate

REDFIELD (1934) found that the ratio of nitrate to phosphate in the sea water was generally close to 15:1 by atoms. COOPER (1938) pointed out that the ratio varied from area to area. According to an extensive study by SAGI (1970, 1975, 1979, 1980), the ratio is 13.6:1 in the deep water along 130°E in the western North Pacific, 12–13:1 in the deep water of the northern part of 10°N in the Pacific Ocean, 16:1 in the western Pacific Sector of the Ant-

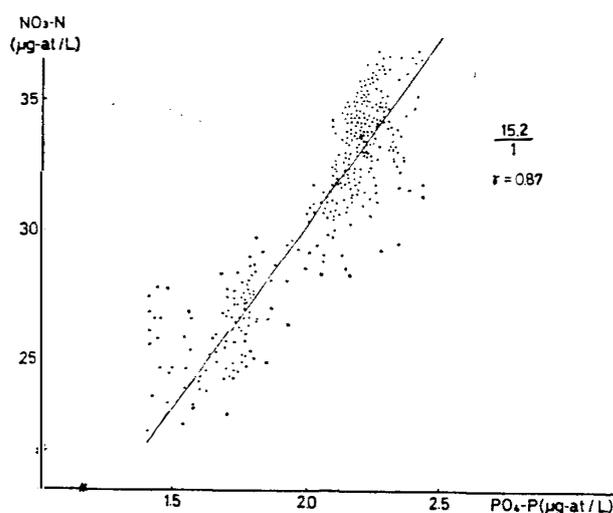


Fig. 6. Relationship between nitrate and phosphate obtained from serial observations.

arctic Ocean and 10 : 1 in the intermediate water off Mexico, respectively. In the Antarctic region between Australia and Antarctica, FUSHIMI *et al.* (1979) found that the ratio was 15-16 : 1. The mean ratio in the present observation was calculated for the water near the Continent. The relationship between nitrate and phosphate is shown in Fig. 6. As a whole, the mean ratio with the standard deviation was  $15.2 \pm 0.6 : 1$  and this value coincides with that observed by FUSHIMI *et al.* (1979). From these results, it may be considered that the ratio in the Antarctic Ocean was relatively higher than those in other oceans.

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