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PHYSICAL AND CHEMICAL PROPERTIES OF SURFACE WATER IN THE SOUTHERN OCEAN IN SUMMER 1991/92

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Abstract: Surface water temperature and salinity were continuously recorded using the Surface Water Monitoring System in the Australasian sector of the Southern Ocean during the JARE-33 cruise in summer 1991/92. Moreover, concentrations of nitrate-N plus nitrite-N and silicate-Si were determined. Three oceanographic fronts were recognized based on the physical variables: the Subtropical Convergence, which divided the Subtropical Zone and the Subantarctic Zone, the Subantarctic Front, which divided the Subantarctic Zone and the Polar Frontal Zone, and the Antarctic Polar Front, which divided the Polar Frontal Zone and the Antarctic Zone. The positions of the fronts were consistent with previous results. Large meridional gradients of nutrient concentrations were observed in the fronts. The nutrient conditions are summarized as follows. Subtropical Zone: both nutrient concentrations are less than the detectable limits. Subantarctic Zone: nitrate plus nitrite is several μM but silicate is still less than the detectable limit. Polar Frontal Zone: the former reaches *ca.* 20 μM and the latter increases several μM. Antarctic Zone: the former is *ca.* 20 μM and the latter is also over 20 μM. These different behaviors of two different nutrients seem to be important environmental conditions for geographical distribution of phytoplankton in the Southern Ocean.

1. Introduction

Environmental properties of the Southern Ocean have been investigated by many oceanographers. These results show that there are prominent oceanographic fronts in the Southern Ocean, that is, the Subtropical Convergence, the Subantarctic Front, the Antarctic Polar Front, and the Antarctic Divergence (LUTJEHARMS *et al.*, 1985; ISHINO, 1989; TOMCZAK and GODFREY, 1994). Along the cruise track of the Japanese Antarctic Research Expedition (JARE), measurement of water temperature and salinity and determination of nutrient concentrations have been routinely conducted (*e.g.*, KURAMOTO and KOYAMA, 1982). Since the spatial resolution of the routine observation is very sparse, some attempts have been made to improve the resolution (FUKUCHI and TAMURA, 1982; FUKUCHI *et al.*, 1986; FUKUCHI and HATTORI, 1987). In addition, a Surface Water Monitoring System (SWMS) has been installed on the icebreaker SHIRASE since 1985 (FUKUCHI and HATTORI, 1987). The system is able to automatically collect data on not only physical parameters but chemical and biological information every five minutes during a cruise. By the former observations, however, either nitrate-N plus nitrite-N (nitrate plus nitrite) or silicate-Si concentration, usually the former only, was determined, since the previous SWMS had one calorimeter. The latter nutrient is important for growth of diatoms in the Southern Ocean (JACQUES, 1983). JARE-33 used two calorimeters to determine silicate as well as nitrate plus nitrite at the same time. This paper represents fine scale distributions of water temperature, salinity, and nutrient concentrations (nitrate plus nitrite and silicate) during the southward and northward legs of the JARE-33 cruise in the Australasian sector of the Southern Ocean.

2. Materials and Methods

The main structure of the SWMS employed by the JARE-33 was the same as that used on previous JAREs (see FUKUCHI and HATTORI, 1987). In the present study the nutrient analysis sampling tube was divided into two lines. One was connected to a line for analysis of nitrate plus nitrite, the other was connected to a line for analysis of silicate. Determinations of nitrate plus nitrite and silicate

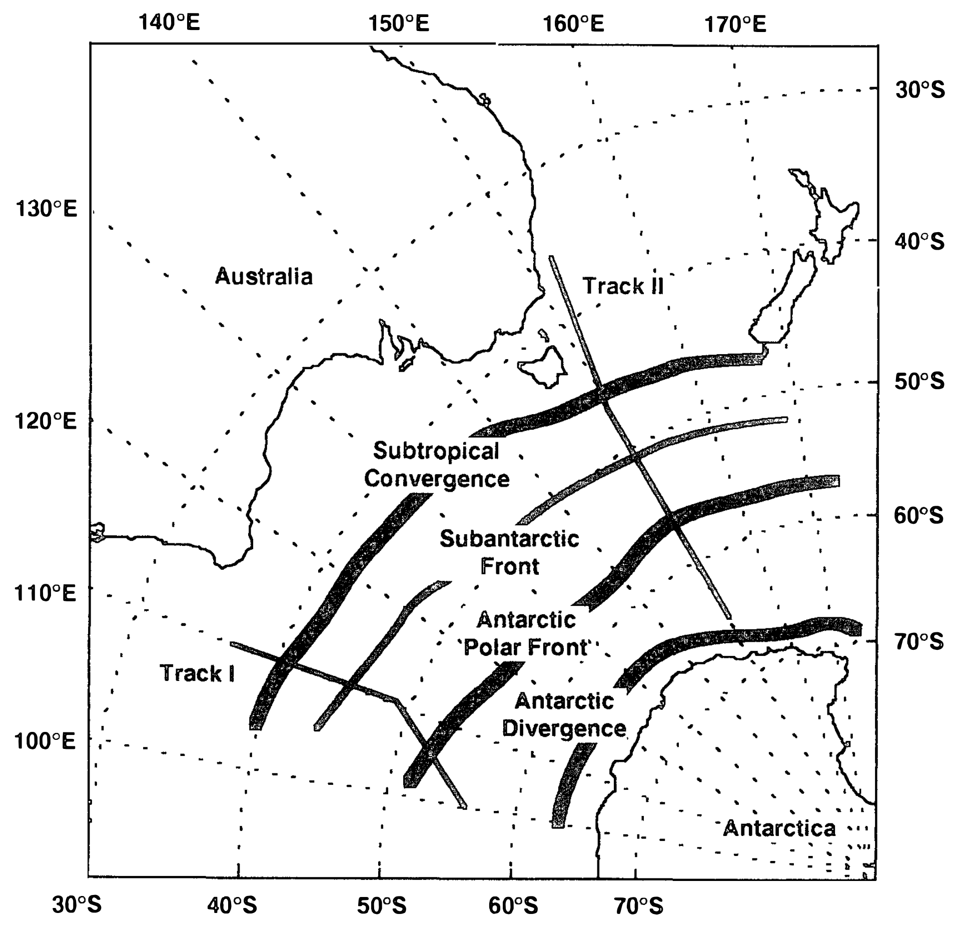

Fig. 1. Cruise tracks of the icebreaker SHIRASE (JARE-33). Cruise tracks I and II are southward and northward legs, respectively. The three fronts, which are commonly observed in the Australasian sector of the Southern Ocean, are drawn after ISHINO (1989).

were conducted using the AutoAnalyzer II (Technicon Industrial Systems) (STRICKLAND and PARSONS, 1972).

Cruise tracks of the icebreaker SHIRASE during JARE-33 are shown in Fig. 1, with three major fronts, which are commonly observed in the Australasian sector of the Southern Ocean (ISHINO, 1989). Cruise tracks I and II are southward and northward legs, respectively. Data on nutrient concentrations were collected from 11 : 00 on December 4 (36°58.4′S, 110°02.7′E) to 01 : 45 on December 9, 1991 (GMT) (56°41.3′S, 101°35.3′E) (track I) and from 02 : 15 on March 13 (59°50.0′S, 150°00.1′E) to 15 : 10 on March 18, 1992 (GMT) (35°00.7′S, 151°49.3′E) (track II). Data on the other variables were collected throughout the cruise, although salinity was not available during the northward leg. Since the mean ship speed was 15.5 knots and the data were collected every five minutes during the period, the spatial interval was estimated as *ca.* 2.4 km.

3. Results

Surface distributions of temperature and salinity along approximately 110°E

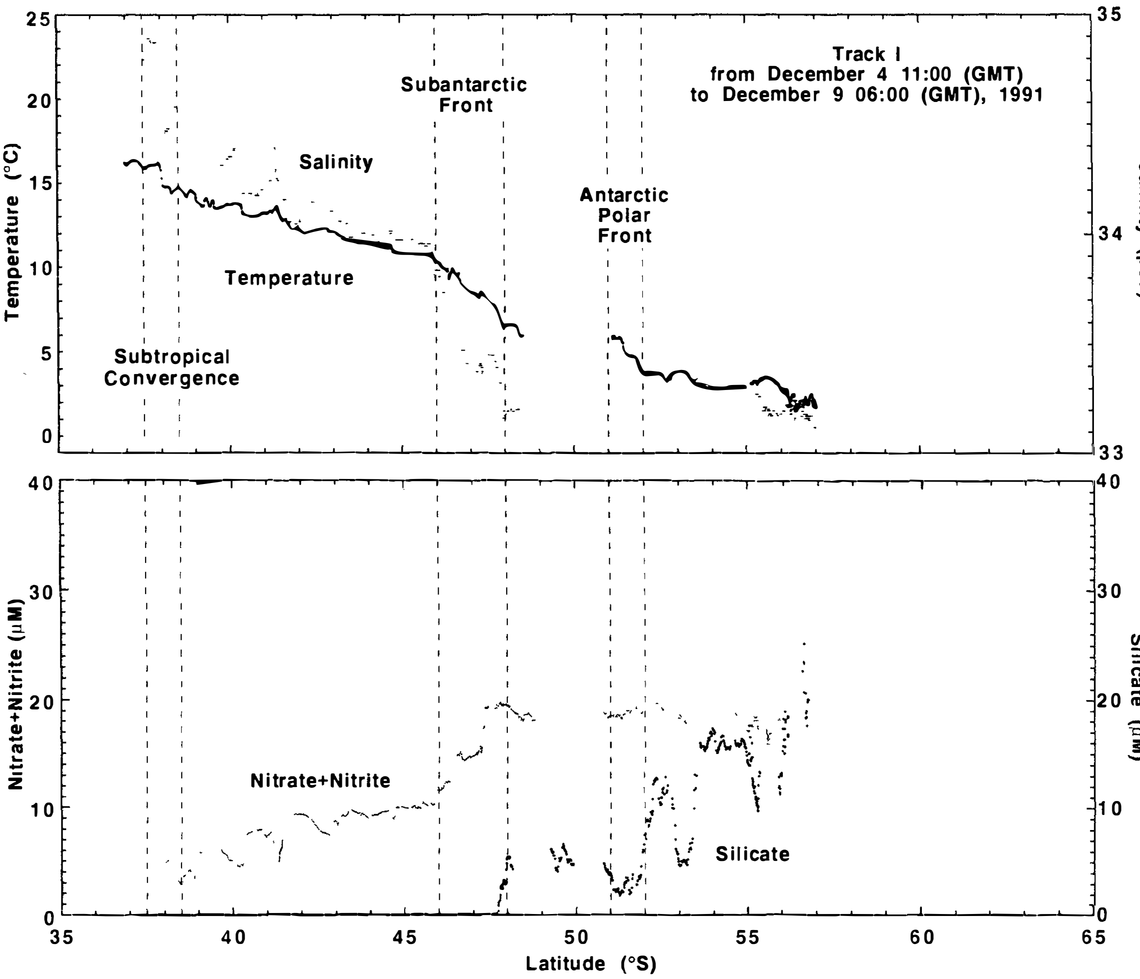

Fig. 2. Surface distributions of temperature, salinity, and concentrations of nitrate plus nitrite and silicate along cruise track I (southward leg) in the early austral summer.

during cruise track I (southward leg) in the early austral summer are shown in Fig. 2. At 38°S temperature and salinity rapidly decreased from north to south. Between 38°30′S and 46°S they gradually decreased along the cruise track. Large decreases of temperature and salinity were observed again from 46°S to 48°S. Although data are not available between 48°30′ and 51°S, almost the same temperature and salinity were recorded at 48–48°30′S and 51°S, suggesting that the water mass was the same. Temperature rapidly decreased between 51 and 52°S, where salinity did not change. As during cruise track I, large meridional discontinuities of temperature occurred between 41°30′–42°30′, 47°30′–48°30′, and 56°–57° along approximately 150°E during cruise track II (northward leg) in the late austral summer (Fig. 3). These surface discontinuities of temperature and salinity seem to correspond to the oceanographic fronts, that is, the Subtropical Convergence, the Subantarctic Front, and the Antarctic Polar Front, from north to south (ISHINO, 1989; TOMCZAK and GODFREY, 1994).

Zonation of the Southern Ocean can be conducted based on these three oceanographic fronts: the Subtropical Zone (north of the Subtropical Convergence), the Subantarctic Zone (between the Subtropical Convergence and the Sub-

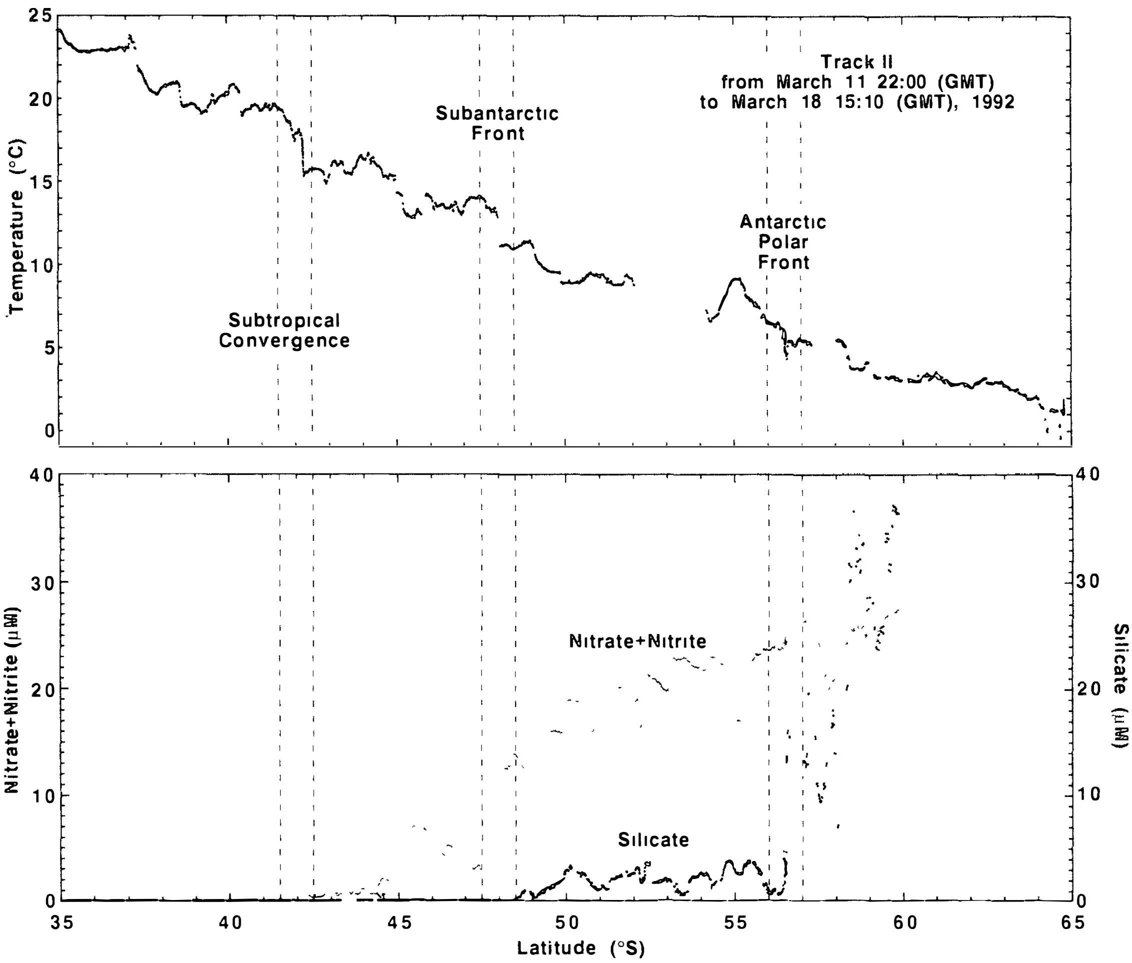

Fig. 3. Surface distributions of temperature and concentrations of nitrate plus nitrite and silicate along cruise track II (northward leg) in the late austral summer.

antarctic Front), the Polar Frontal Zone (between the Subantarctic Front and the Antarctic Polar Front), and the Antarctic Zone (south of the Antarctic Polar Front). Although the Antarctic Divergence is located south of the Antarctic Polar Front, the present observations did not cover the Divergence area. Positions of the fronts and physical properties during the southward and northward legs are summarized in Tables 1 and 2, respectively. The difference of mean water temperature between the Subtropical Zone and the Subantarctic Zone was 6.6 deg in early summer (110°E) and 3.8 deg in late summer (150°E), although the temperature of the former was higher than that of the latter. A difference of 0.7 psu was observed in salinity between the two zones. The position of the Subtropical Convergence along 110°E was more northward than that along 150°E. The Subantarctic Front was observed at almost the same latitude along both meridians. The difference of mean water temperature between the Subantarctic Zone and the Polar Frontal Zone was 6.0°C (110°E) and 5.8°C (150°E), although the temperature in the former was higher than that in the latter. The salinity difference between the two zones reached *ca.* 1.0 psu. The position of the Antarctic Polar Front, like that of the Subtropical Convergence, along 110°E occurred more northward than that along 150°E. A difference of water temperature was also noted between the Polar Frontal Zone and the Antarctic Zone (3.5 deg and 6.0 deg, respectively), but the salinity was almost the same.

The water massses and the oceanographic fronts are also clearly characterized by the amount of nutrients (Figs. 2 and 3). In the Subtropical Zone, nitrate plus nitrite and silicate were under the detectable limits (see also Tables 1 and 2). The former can be detected, but the latter was under the detectable limit in the Subtropical Convergence along 110°E and 150°E. A rapid increase to 5 μM was

Table 1. Summary of physical and chemical variables of surface water along the southward leg (cruise track I) of icebreaker Shirase *(JARE-33) in the early austral summer, 1991. Data are mean ±1 SD (number of samples). Positions of the oceanographic fronts and water masses are also shown.*

Zone	Position (°S)	Temperature (°C)	Salinity (psu)	Nitrate + Nitrite (μM)	Silicate (μM)
Subtropical Zone	<37°30′	16.2±0.12 (26)	34.87±0.03 (26)	undetectable (15)	undetectable (15)
Subtropical Convergence	37°30′–38°30′	15.4±0.68 (50)	34.69±0.18 (50)	2.2±2.12 (40)	undetectable (40)
Subantarctic Zone	38°30′–46°00′	12.4±1.15 (425)	34.14±0.16 (425)	7.8±1.33 (369)	undetectable (369)
Subantarctic Front	46°00′–48°00′	8.5±0.98 (181)	33.48±0.17 (181)	16.2±2.69 (169)	0.4±1.1 (169)
Polar Frontal Zone	48°00′–51°00′	6.4±0.24 (37)	33.20±0.02 (37)	18.6±0.36 (73)	5.1±0.7 (63)
Antarctic Polar Front	51°00′–52°00′	5.0±0.70 (48)	33.29±0.04 (48)	18.8±0.43 (51)	3.3±1.4 (50)
Antarctic Zone	>52°00′	2.9±0.60 (438)	33.24±0.07 (438)	18.2±1.17 (183)	13.4±4.3 (247)

Table 2. Summary of physical and chemical variables of surface water along the northward leg (cruise track II) of icebreaker SHIRASE *(JARE-33) in the late austral summer, 1992. Data are mean ±1 SD (number of samples). Positions of the oceanographic fronts and water masses are also shown.*

Zone	Position (°S)	Temperature (°C)	Nitrate + Nitrite (μM)	Silicate (μM)
Subtropical Zone	<41°30′	21.3±1.59 (422)	undetectable (382)	undetectable (382)
Subtropical Convergence	41°30′–42°30′	17.5±1.31 (74)	trace (65)	undetectable (65)
Subantarctic Zone	42°30′–47°30′	14.7±1.18 (248)	3.0±2.22 (232)	undetectable (232)
Subantarctic Front	47°30′–48°30′	12.4±1.20 (50)	9.2±4.03 (47)	trace (47)
Polar Frontal Zone	48°30′–56°00′	8.9±1.21 (291)	19.2±3.04 (415)	2.1±0.9 (413)
Antarctic Polar Front	56°00′–57°00′	5.7±0.58 (132)	24.2±0.36 (77)	4.6±5.1 (93)
Antarctic Zone	>57°00′	2.9±1.23 (451)	24.7±2.20 (186)	23.2±9.9 (190)

observed along 110°E. The concentration of nitrate plus nitrite gradually increased from north (several μM) to south (*ca.* 10 μM) in the Subantarctic Zone, where silicate was still under the detectable limit. Silicate became detectable in the Subantarctic Front, where nitrate plus nitrite rapidly increased to 20 μM (110°E) and 14 μM (150°E). Both the concentrations seem to be the same through the Polar Frontal Zone. In the Antarctic Polar Front the concentration of silicate increased considerably from several μM to *ca.* 10 μM (110°E) and to 20 μM (150°E), but that of nitrate plus nitrite did not change along either meridian. In the Antarctic Zone the concentration of silicate increased from north to south, reaching almost 40 μM south of 58°S along 150°E, although the concentration of nitrate plus nitrite did not change. The concentration of nitrate plus nitrite was almost the same in the Polar Frontal Zone and the Antarctic Polar Front (*ca.* 20 μM along 110°E, *ca.* 25 μM along 150°E).

4. Discussion

Three oceanographic fronts are recognized in the present study using the SWMS. The northernmost front is the Subtropical Convergence, which is a boundary between the Subtropical Zone and the Subantarctic Zone. The former is warmer and more saline than the latter, the differences of surface temperature and salinity are 4–5 deg and 0.5 psu, respectively. Our results are consistent with the description of DEACON (1982). FUKUCHI (1980) summarized the middle position and temperature of the Subtropical Convergence using data collected by JAREs-7 to 18. He found the average position and temperature (average ±1 SD) of the Subtropical Convergence to be 39°49′±1°32′S and 13.9±1.17°C (n=12) for the southward legs conducted in early austral summer in the eastern Indian sector and 42°17′±1°29′S and 14.0±1.99°C for the northward legs conducted in late austral summer in the western Indian sector. The former leg covered the almost the same sea area as the present study (see FUKUCHI, 1980). The position and temperature of the Subtropical Convergence revealed in the southward leg of the present study (37°30′–38°30′S and 15.4°C, Table 1) are comparable with the averages based on the results of FUKUCHI (1980). Although the coverage of the northward leg of JAREs-7 to 18 and the JARE-33 cruise is different, the average position and temperature summarized by FUKUCHI (1980) are consistent with the present results (41°30′–42°30′S and 17.5°C, Table 2). On the other hand, the position shifted southward and the temperature of the Subtropical Convergence increased in late austral summer. This suggests that the position of the Subtropical Convergence varies seasonally.

BURLING (1961) found a surface temperature discontinuity approximately halfway across the Subantarctic zone south of Australia and New Zealand. Although he called it the Australasian Subantarctic front, now we call it the Subantarctic Front (ISHINO, 1989). This front borders warm and saline subsurface water in the Subantarctic water mass (BURLING, 1961; ZILLMANN, 1970; DEACON, 1982). The meridional gradients of temperature and salinity in the Subantarctic Front are comparable to those in the Subtropical Convergence as described by DEACON (1982).

The southernmost front detected in the present study is the Antarctic Polar Front. Since cold Antarctic water slips below and mixes with warmer water, a steep meridional gradient of temperature is observed at the surface (DEACON, 1982). We also encountered a discontinuity of surface water temperature between 51° and 52°S during the southward leg along 110° and between 56° and 57°S during the northward leg along 150°E (Tables 1 and 2), which are consistent with the position of the Antarctic Polar Front shown by DEACON (1982) (51°30′S and 56°30′S, respective meridians). The averaged middle position and temperature of FUKUCHI (1980) during southward legs in the eastern Indian sector (51°26′±0°56′S and 4.2±0.84°C, respectively) are almost the same as those observed during the present southward leg. The position, however, is further south during the northward leg along 150°E, compared with the average position of FUKUCHI (1980) (50°09′±0°23′S), of which data were collected in the western Indian sector.

High nutrient concentrations of surface water are a striking feature of the Southern Ocean. In particular, the waters south of the Antarctic Polar Front, the Antarctic Zone, comprise by far the greatest geographic extent of nutrient-rich surface water on earth. The enrichment of the surface layer results from an oceanic divergence that brings the deep waters to the surface (JONES *et al.*, 1990). The oceanographic fronts of the Southern Ocean correspond not only to well-marked hydrographic structures but also to major boundaries in nutrient distribution (DEACON, 1982; LE JEHAN and TRÉGUER, 1983; LUTJEHARMS *et al.*, 1985; FUKUCHI and HATTORI 1987; JONES *et al.*, 1990). The present study revealed that nitrate plus nitrite and silicate behave differently in the fronts. Only the former changes rapidly in the Subtropical Convergence, while the latter did not change. In the Subantarctic Front both concentrations (nitrate plus nitrite and silicate) varied considerably. The concentration of silicate rapidly increases in the Antarctic Polar Front, reaching almost 40 μM, although that of nitrate plus nitrite does not change. LE JEHAN and TRÉGUER (1983) and LUTJEHARMS *et al.* (1985) also demonstrated the different behaviors of nitrate and silicate in the Indian and the Atlantic sectors of the Southern Ocean, respectively. These different behaviors of both nutrients may result in or from the difference of species composition of phytoplankton community.

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