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Coastal and Inshore Water Interaction, Mixing and Primary Productivity in the Bransfield Strait, Antarctica During Austral Summer 1989/90

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Abstract : Nutrients and chlorophyll *a* were collected along CTD data in the Bransfield Strait proper and inshore waters of Maxwell Bay during 29 December 1989−9 January 1990. South East Pacific Basin originated Bransfield Strait water is well communicated with inshore waters of Maxwell Bay and Maxwell Bay water is also well communicated with Marian Cove, since the low sills in the mouths of Maxwell Bay and Marian Cove apparently does not allow the development of the characteristic basin water. Inshore waters of Maxwell Bay and Marian Cove is simply diluted with freshwater input provided by the nutrient depleted glacial melting and surface runoff. Nutrients and organic matter appears to be imported from the Bransfield Strait to the inshore waters *via* tidal activity.

Phytoplankton biomass (chl *a*) and water column stability (the surface mixed layer depth) were positively correlated in the South East Pacific Basin water mass. Our results are one of the first to present clear evidence that phytoplankton growth in the Antarctic Ocean may be hindered by the water column instability since water column hydrography in the Bransfield Strait shows that the well defined surface mixed layer is not fully developed but rather continuously stratified. This may partly answer the unresolved enigma of Antarctic marine ecosystems of relatively poor productivity despite high nutrient level.

Key words : mixing, primary productivity, Bransfield Strait

Introduction

The global temperature of surface air increased by 0.4−0.5℃ from 1880 to 1980, while temperatures of Arctic regions instead rose as much as 1.2−1.5℃ (Hansen et al., 1983). Since 1980, six of the warmest years in the past century have been observed. Polar enhancement of a temperature rise, possibly induced by anthropogenic release of green house gases to the atmosphere, results in melting of sea ice. A 5% decline of sea ice extent in the Arctic and Antarctic from 1979 to 1987 (Gloersen and Campbell, 1988) have resulted in increased light availability within previously ice-covered polar regions (Walsh, 1990). According to Walsh (1990), the total amount of increased subsurface light availability within the two polar ecosystems over the last decade may be equivalent, however, based on a multi-year satellite survey of Coastal Zone Color Scanner (G. Feldman, 1989), phytoplankton pigment concentrations are much larger in the Arctic. Extensive regions of >3 μg chl $a\,\ell^{-1}$ are found in the Arctic mediterranean seas, while such apparent bloom of Antarctica are restricted to the melt-water regions of the Weddell and Ross Seas. Since the ice-edge blooms may constitute 67−74 % of the annual coastal production of the Weddell and Ross Seas, in contrast to <10% of the Beaufort and Chukchi Seas, removal of the freshwater source of stratification may actually lead to a decline of carbon fixation in the Antarctic and an increase in the Arctic.

In order to evaluate the response of the Antarctic marine ecosystem to the recent global warming phenomenon, the Korea Antarctic Research Program has progressively expanded research area from Marian Cove (KORDI, 1988), Maxwell Bay (KORDI, 1989) to Bransfield Strait (KORDI, 1990). In this study, nutrients and chl *a* were determined in the Bransfield Strait, Maxwell Bay and Marian Cove during 29 December 1989 – 9 January 1990.

Maxwell Bay is a glacially-eroded embayment located of the south-west coast of King George Island, South Shetland Islands. The Bay has a central basin and several side arms, Marian Cove, Potter Cove, Ardley Cove, Collins Bay and Edgell Bay. The Bay is approximately 14 km long and 6 to 14 km wide with maximum depth of 520 m, separated from the Bransfield Strait by a 430 m deep sill. The Bransfield Strait is a 112 km wide trough with maximum depth of over 2000 m, trending northeast to southwest for 460 km between South Shetlands and the Antarctic Peninsula (Fig. 1).

Characteristics of water masses in the Bransfield Strait is well described by Heywood (1985). Waters in the Bransfield are the product of an interaction between two distinctive surface waters, and local influences. Weddell Sea water enters round Joinville and D'Urville Islands to spread northwards across the Strait and southwards along the coast of the Peninsula. Water from the South East Pacific Basin enters between Low, Smith and Snow Islands and passes north and south of Deception Island. The southern tongue meets Weddell Sea Water and is deflected back to join the tongue passing along the northernside of the strait. Entry of Warm Deep Water is restricted by shallow sills that stretch across the entrance to the strait. The cold Bottom Water of the deep

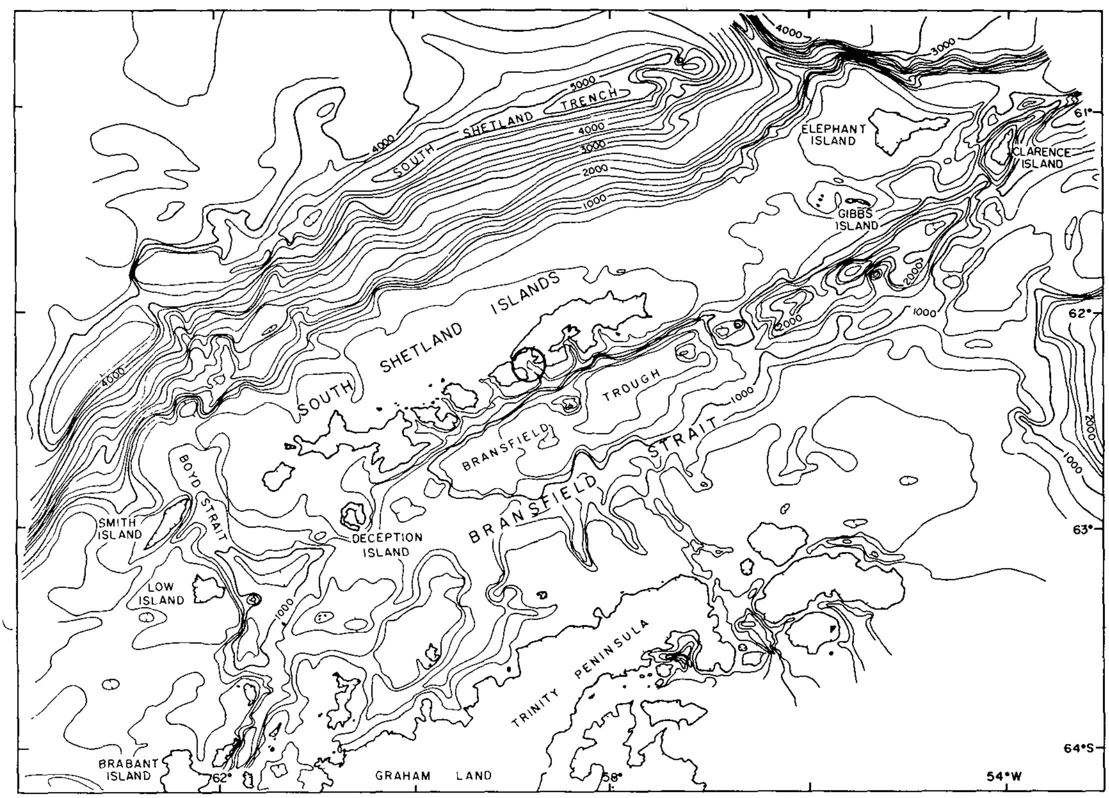


Fig. 1. Physiographic map of the Bransfield Strait with the location of Maxwell Bay (circled area, after Choi et al., 1990).

basins within the strait is formed *in situ* during the formation of ice from waters lying over shallow coastal shelf areas in winter (Heywood, 1985).

Materials and Methods

Hydrographic survey and water samples were taken in the Bransfield Strait, Maxwell Bay and Marian Cove over the relatively short period of time during 29 December 1989 to 9 January 1990 in the austral summer (Fig. 2). Water samples were collected using a 12 bottle rosette mounted with Niskin samplers at the standard oceanographic water sampling depths along the CTD measurements (EG&G Ocean Products

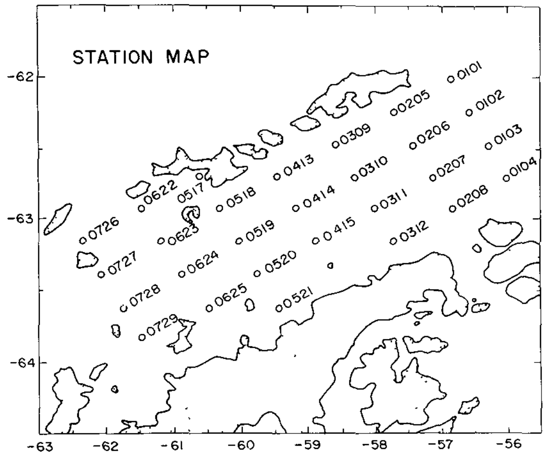


Fig. 2. Sampling stations in the Bransfield Strait.

Table 1. Reported values of nutrients and chlorophyll *a* around Bransfield Strait.

Site	PO_4(μM)	NO_3(μM)	$Si(OH)_4$(μM)	Chl *a*(μg/ℓ)	Source
Weddell−Scotia	1.9−2.2	27−32	80−100	3−4	1
				1−8	2
Antarctic Ocean			70−100		3
Weddell	2.0	25−30	50		4
				~1	5
Drake Passaage				0.1	6
Anvers Is.	0.01−1.5	2−25	56	3−22	7
				12−25	8
Admiralty Bay	2.2−2.4	20−25			9
			77−84	0.2−4.4	10
Bransfield Strait				0.4−9	8
				2	6
				<1	This study
Marain Cove	1.9−2.8	21−24	71−80	1−2	Hong(1989)
	1.8−2.1	31−34			Yang(1990)
	2.4−2.5	4−6*	36−42*	0.2	This study
Maxwell Bay	1.9−2.1	27−33*			Yang(1990)
	2.5−2.9	16−19*	38−45*	0.4	This study

* These data are out of normally reported values.

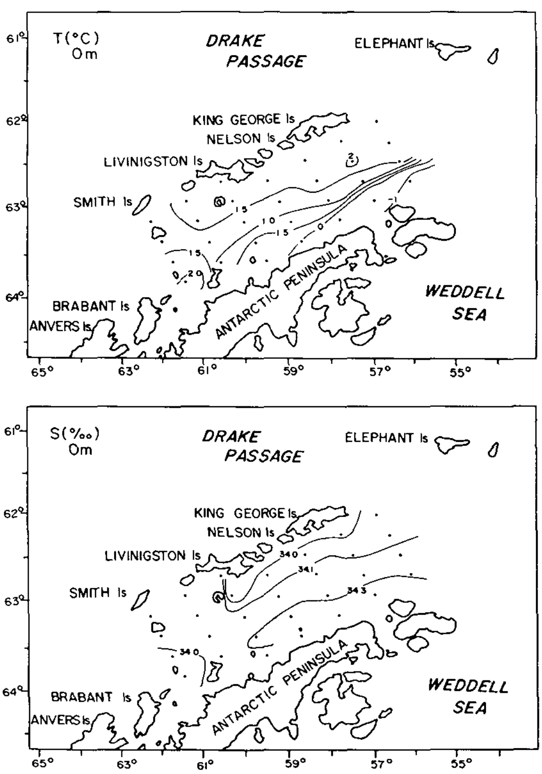
Sources : 1. Nelson et al.(1987)
2. Yang(1989)
3. Sakshaug and Holm-Hansen(1986)
4. El-Sayed and Taguchi(1981)
5. El-Sayed and Mandelli(1965)
6. Mullins and Priddle(1987)
7. Holm-Hansen et al.(1989)
8. Lipski(1985)
9. Samp(1980)
10. Rakusa-Suszewski(1980)

Smart CTD). Accuracy of temperature and salinity are ±0.01℃ and ±0.01‰, respectively. Nutrients were analyzed using a UV-VIS spectrophotometer, according to Parsons et al. (1984), on board without filtration of seawater samples. *In vivo* fluorescence was also determined with Turner Design field fluorometer (Model 10-005R), and later calibrated to the chl *a* (aceton extracts, Parsons et al., 1984) in the laboratory (Seoul, Korea) using a limited number of frozen samples.

Results

1. Quality of data

Unfortunately, analytical errors in determining nutrient contents in seawater are apparent (Table 1) due to limited working conditions : water samples were not filtered before analysis, some samples stored improperly for some time. Therefore, special consideration should be given. Hydrographic features, nutrients, and chlorophyll *a* contents of the Bransfield Strait, Maxwell Bay, and Marian Cove are shows in Figures. 3−8.



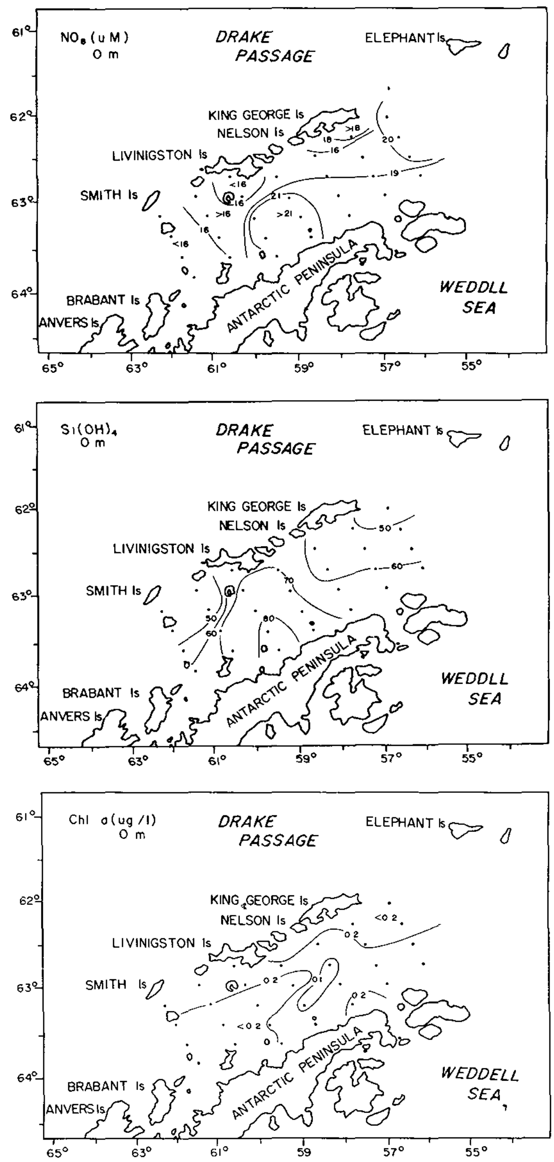


Fig. 3. Horizontal distribution of T (℃), S (ppt), NO_3 (μM), $Si(OH)_4$ (μM) and Chl *a* at 0 m isobath in Bransfield Strait during 28 December −9 January 1990.

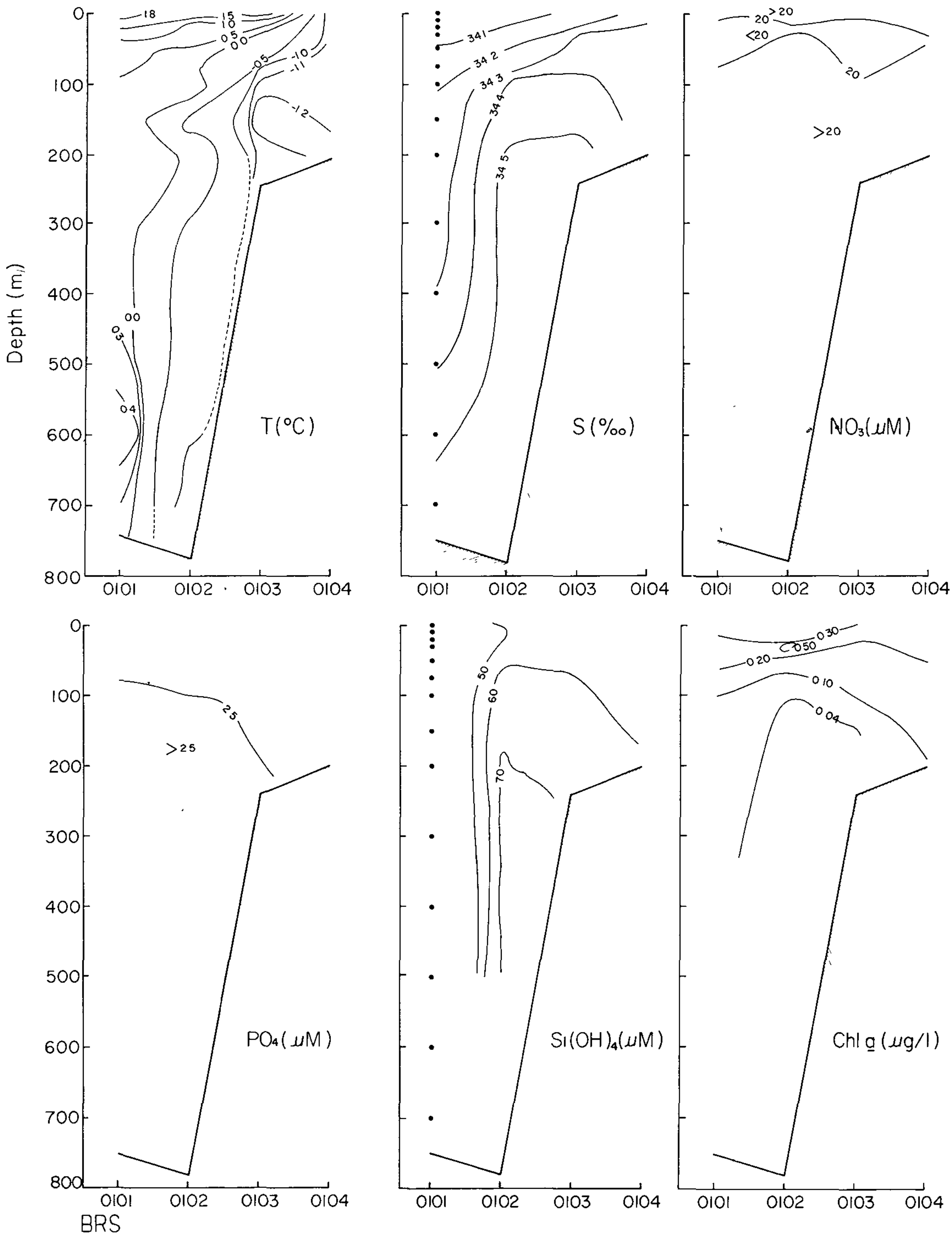


Fig. 4. T, S, nutrients and chl *a* across Bransfield Strait of section BRS01 during 28 December – 9 January 1990.

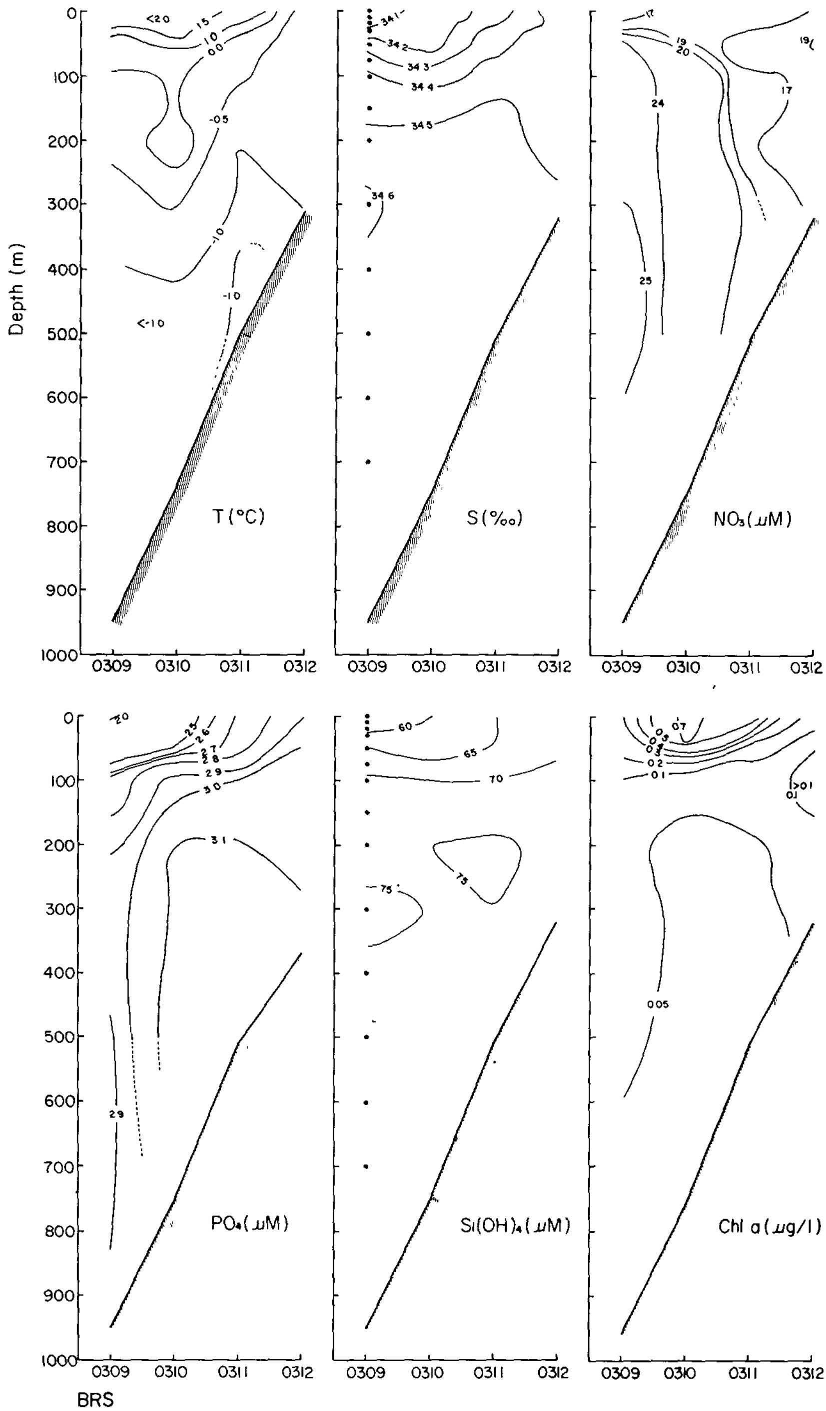


Fig. 5. T, S, nutrients and chl *a* across Bransfield Strait of section BRS03 during 28 December – 9 January 1990.

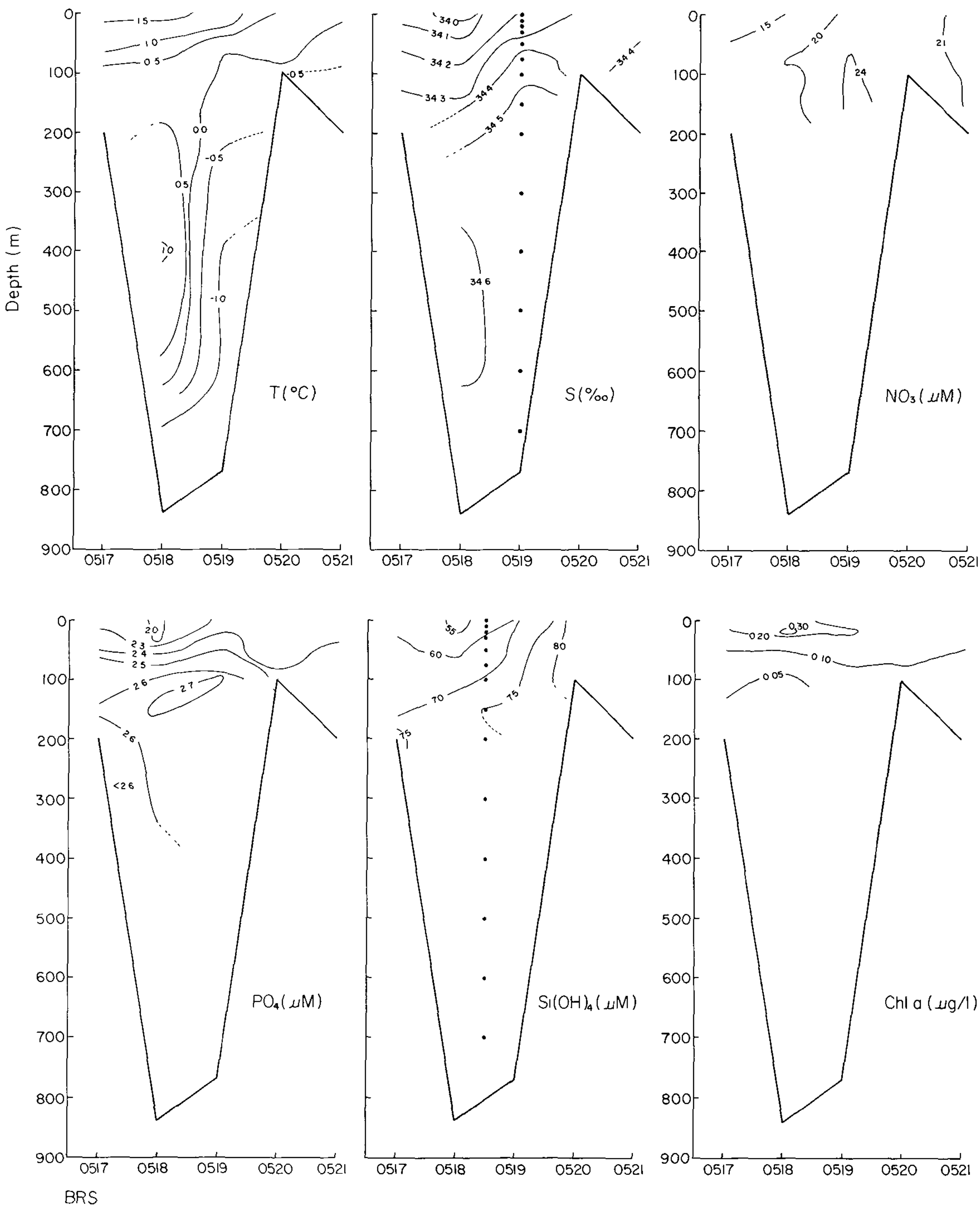


Fig. 6. T, S, nutrients and chl *a* across Bransfield Strait of section BRS05 during 28 December – 9 January 1990.

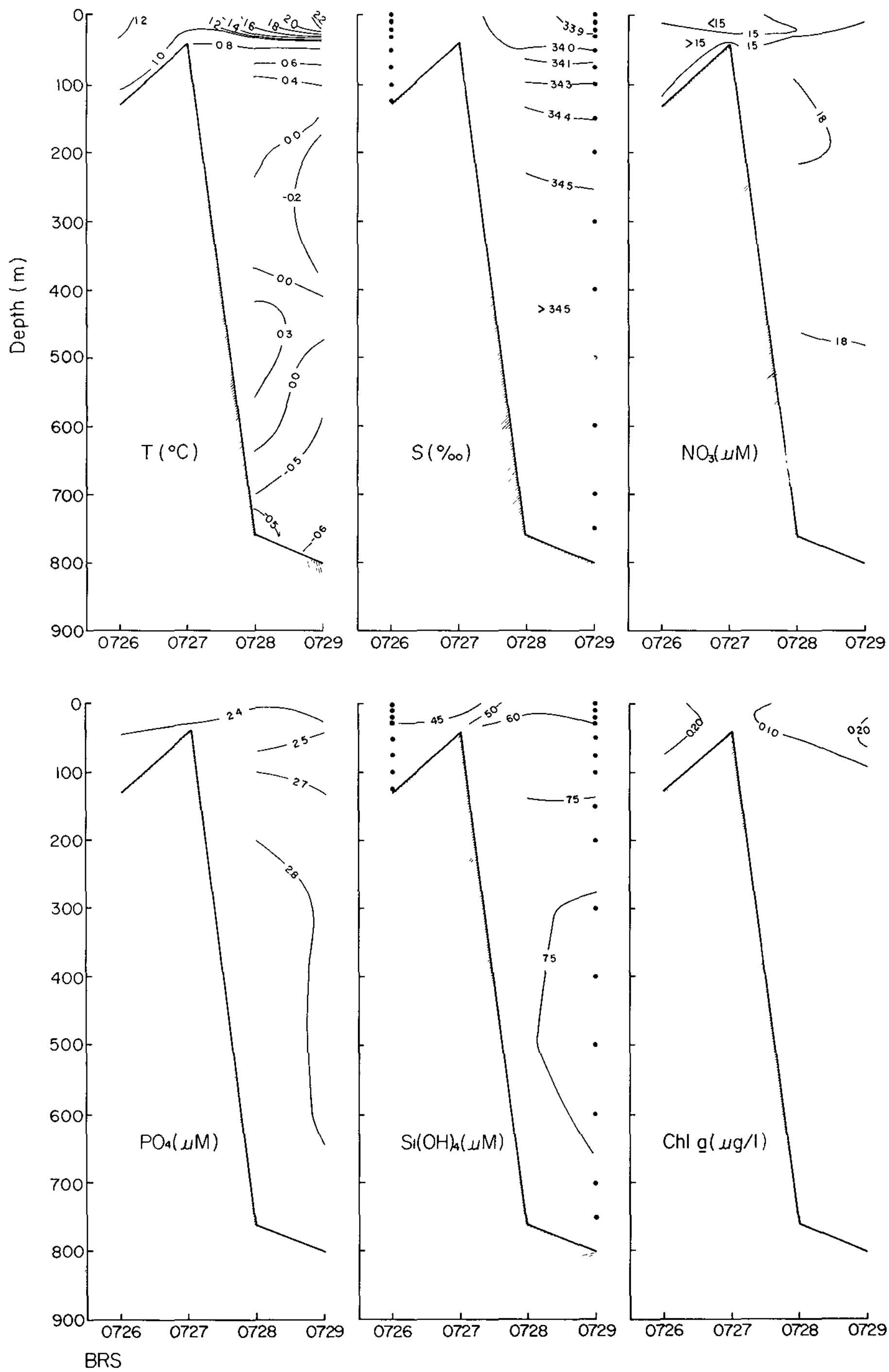


Fig. 7. T, S, nutrients and chl *a* across Bransfield Strait of section BRS07 during 28 December – 9 January 1990.

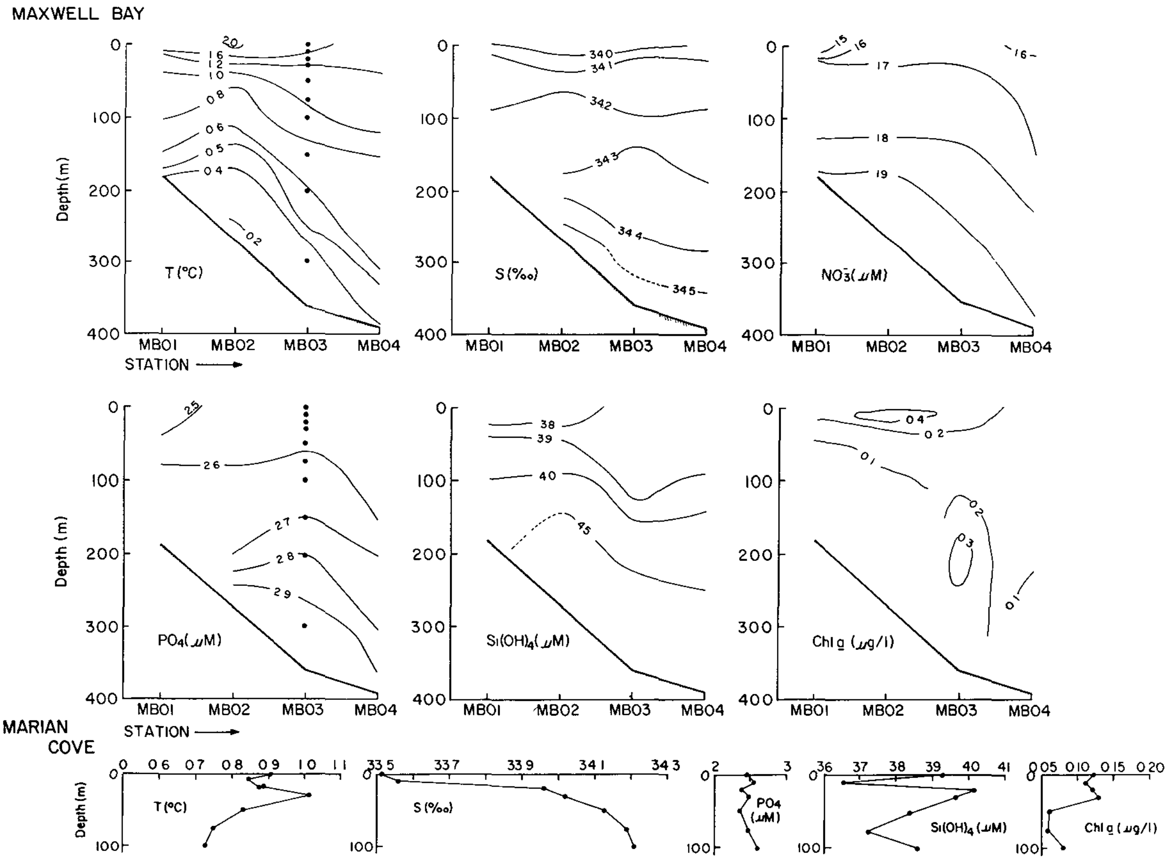


Fig. 8. T, S, nutrients and chl *a* across Maxwell Bay during 28 December – 9 January 1990.

2. Hydrographic features

The Bransfield Strait : Warm(>0℃) and less saline (<34.3 ‰) water is predominant towards the South Shetland Islands, and cold (<0℃) and more saline (>34.3 ‰) water is hugging the Antarctic Peninsula. The former originates from the South East Pacific Basin and the latter from the Weddell Sea. Salinity is lower towards the South Shetland Islands due to the increased freshwater supplied from the melting of glaciers and rainfall. In general, temperature decreases with depth, while, salinity and nutrients increase with depth. However, a warm (maximum >1℃) and more saline (maximum >34.6 ‰) Warm Deep Water (originated from the North Atlantic) intrudes around 400–600 m along the slope of the South Shetland Islands (Sts. BRS 0101–BRS 0517).

Maxwell Bay : Temperature is generally higher at the head than in the mouth. Highest temperature and lowest salinity were observed in the middle of Bay (MB02) probably due to the freshwater input from the adjacent land. In the surface temperature varies from 2.05 to 1.44℃ and salinity varies from 33.77 to 34.03 ‰. Temperature decreases to 0.2℃ and salinity increase to 34.5 ‰ in the bottom.

Marian Cove : Surface temperature (0.9℃) and salinity (33.5 ‰) is much lower than in Maxwell bay. Temperature inversion occurs at 30 m depth from thawing of ice broken off from glaciers surrounding the bay. The effect of glacial melt does not exceed below 30 m depth. Below 30 m depth temperature decreases with depth.

3. Nutrients and chlorophyll *a*

In the Bransfield Strait, nutrients of nitrate, phosphate and silicate appear to be high in the waters originates from the Weddell Sea than the South East Pacific Basin. Chlorophyll *a* content varies from 0.2 to 0.7 $\mu g\ \ell^{-1}$. In Maxwell Bay and Marian Cove, chlorophyll *a* content varies from 0.2–0.4 $\mu g\ \ell^{-1}$ and 0.1 $\mu g\ \ell^{-1}$, respectively. In general, nutrients concentrations are higher in Maxwell Bay than in Marian Cove.

Discussion

1. Coastal and inshore interaction

In order to identify the water masses present in the survey area a correlation between temperature and salinity is employed (Fig. 9). A tight T–S correlation shows that Bransfield

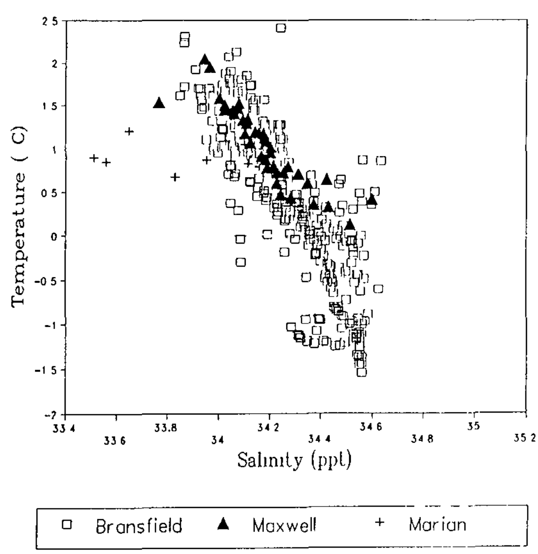


Fig. 9. Plot of salinity versus temperature for Bransfield Strait and Maxwell Bay and Marian Cove during 28 December – 9 January 1990.

Strait waters may be represented by the two end member mixing ; one is the warm and less saline South East Pacific Basin Water and the other is the cold and more saline Weddell Sea Water. These are already fairly well known (Heywood, 1985). The tongue of the Weddell Sea Water hugging the Antarctic Peninsula receives much reduced melt water (J. Anderson, Rice Univ., U.S.A. 1990, personal communication). The entire water of Maxwell Bay is warm (>0.5℃) and less saline (<34.6 ‰), and lies exactly on the upper part of the T–S curve (Fig. 10), which indicates that Maxwell Bay water is identical to the South East Pacific Basin originated Bransfield Strait water. Figure 10 also shows that Marian Cove water is originated from the Bransfield Strait with local modification by the melt water from snow melt inflow and active iceberg calving from tide water glaciers. Since the middle of Maxwell Bay (MB02) is most fresh, Marian Cove may be the largest source of freshwater in Maxwell Bay. The addition of freshwater in Marian Cove is estimated to be about 2.3 % of Maxwell Bay water using the two-end member mixing model. Estuarine circulation pattern was observed in the surface layer of Maxwell Bay during austral summer (Chang et al., 1990).

Waters in Maxwell Bay and Marian Cove appear to be well communicated with the Bransfield Strait water. Since characteristic basin water can not be identifiable from the hydrographic and nutrients data, the relatively deep sills at the mouths of Maxwell Bay and Marian Cove apparently can not hinder the water circulation (Fig. 8). Comparison of temperature, salinity, and sigma-t, phosphate, and chl *a* among the Bransfield Strait (BRS0309, off the mouth of Maxwell Bay), middle of Maxwell Bay (MB02, off the mouth of Marian Cove), and the middle of Marian Cove (MC01) are made in Figure. 10. Salinity decreases in the order of Bransfield Strait, Maxwell Bay, and Marian Cove along the isobaths. Therefore density of seawater increases from Marian Cove,

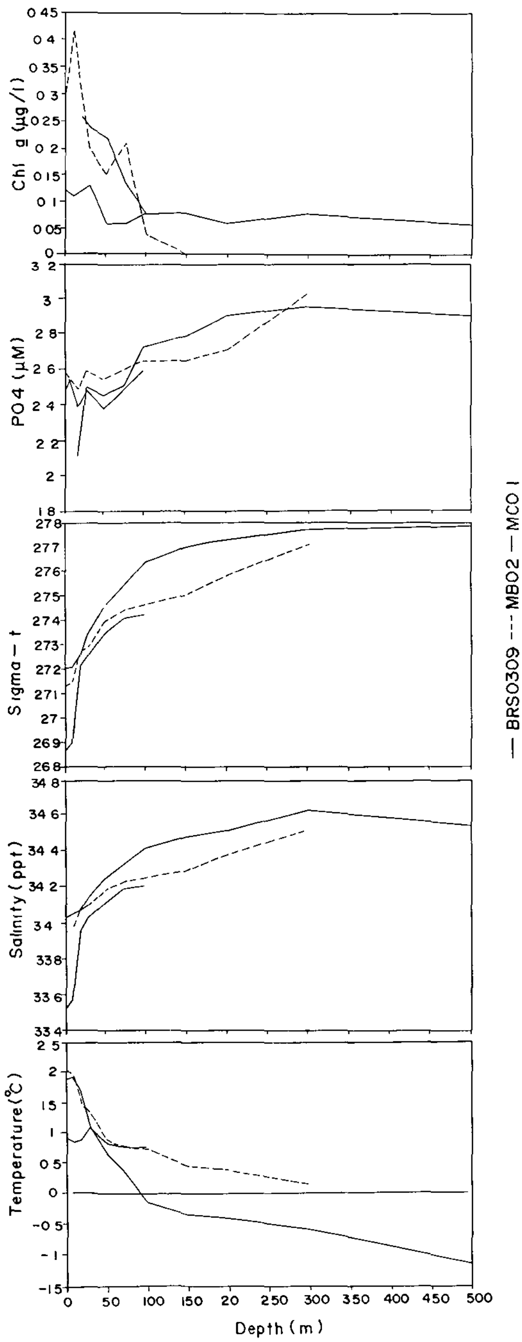


Fig.10. Depth profiles of temperature, salinity, sigma-t, PO_4 (μM) and Chl *a* (μg/ℓ) at BRS0309, MB02, MC01 during 28 December − 9 January 1990.

Maxwell Bay, and the Bransfield Strait since the strong dependence of density on salinity in the cold water. Thus, water can enter easily Maxwell Bay and Marian Cove from the Bransfield Strait. Although our nutrient data have large uncertainty, nutrient and chlorophyll *a* contents in Maxwell Bay are lower than the Bransfield Strait, and very little nutrient concentration in the surface runoff in the adjacent land (KORDI, 1990). Yang (1990) reported the primary productivity is also higher in Maxwell Bay than in Marian Cove. Therefore, it seems that salt, nutrients and organic matter is being imported into the inshore waters from the coastal ocean, and freshwater is being exported to the Bransfield Strait.

Exchange mechanism of coastal and inshore water is believed to be provided by the tidal motion. In Marian Cove, chemical compostion of bottom water (below 50 m depth) appears to vary according to tide (Hong, 1989). Although the contribution of temperature to density is negligible in cold waters, temperature is still useful to trace the water masses. Temperature versus nutrients plots show that the colder water is more enriched with nutrients except waters of higher temperature (>0.8℃)(Fig. 11). This indicates that nutrient-rich cold water is being intruded from Maxwell Bay into Marian Cove.

Water column in the Bransfield Strait, Maxwell Bay and Marian Cove are weakly continuously stratified rather than have a well developed surface mixed layer (Figs. 4−8), which is a characteristic feature of the Antarctic Ocean (Sakshaug and Holm-Hansen, 1986).

2. Mixing and primary productivity

The unresolved enigma in the Antarctic marine ecosystems is the fact that these waters are relatively less productive (0.4 μg chl *a* ℓ^{-1}; Holm-Hansen et al., 1989) despite high nutrient levels. However, there are many reports demonstrating that phytoplankton biomass and primary production are often higher (>10 μg ch *a*

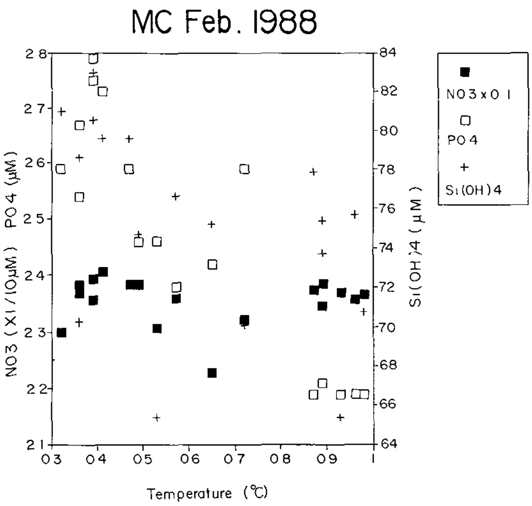


Fig.11. Plot of temperature versus NO_3, PO_4 and $Si(OH)_4$ for Marian Cove during 18 – 19 February 1988.

ℓ^{-1}; Table 1) over areas of continental shelf in Antarctica (Burkholder and Sieburth, 1961). The major hypothesis to explain the comparative richness of waters close to land in the Antarctic usually are (1) the profile of water column stability (2) differential grazing pressure (3) the possibility of a limitation of essential micro-nutrients such as iron.

Phytoplankton biomass of the Bransfield Strait is relatively low (2 μg chl *a* ℓ^{-1}; Mullins and Priddle, 1987). This study shows that the maximam value is 0.8 μg ℓ^{-1}, however, it is still higher than in the Drake Passage (<0.5 μg ℓ^{-1}; Mullins and Priddle, 1987). Unlike the coastal waters adjacent to the Anvers Isalnd (>10 μg ℓ^{-1}; Holm-Hansen et al., 1989) and Arthur Harbor (12–27 μg chl *a* ℓ^{-1}; Krebs, 1983), Maxwell Bay and Marian Cove is quite infertile (0.2–0.4 μg ℓ^{-1}). Although Maxwell Bay and the coastal waters off Anvers Island are both weakly stratified hydrographically, Maxwell Bay is much deeper than waters off Anvers Isalnd. Water column of Arthur Harbor is well stratified due to melt water of ice. Although the grazing pressure is higher in deeper waters due to a greater abundance of zooplankton, zooplankton biomass is very low (Kim et al., this volume), and the limitation of iron (Martin and Fitzwater, 1988) in the Bransfield Strait is highly unlikely due to the proximity of land, therefore, depletion of micronutrients may be ruled out. Therefore we will discuss the dependence of primary productivity upon water column stability.

Vertical distribution patterns of temperature and chl *a* content is strikingly similar in the Bransfield Strait proper and its inshore waters (Fig. 12). The steeper the temperature gradient is, the higher the chl a concentration is. This indicates that the presence of the surface mixed layer is needed to support the phytoplankton growth. Similar features were also observed in the Bransfield Strait (Mandelli and Burkholder, 1966).

With a paradox of high nutrient content and low primary production (Holm-Hansen, 1985) over the same potential growing period as the Arctic, the low annual carbon fixation of the Southern Ocean is apparently attributed to deep mixing. Growth parameters (Sakshaugh and Holm-Hansen, 1984) suggest that 50 m may be the depth limit of a surface mixed layer over which Antarctic blooms can develop. Many previous studies have attempted to relate phytoplankton biomass and distribution to the depth of the surface mixed layer. However, according to Holm-Hansen et al. (1989), those attempts failed due to the fact that lack of synoptic data and the presence of a lag period between stabilization of the surface mixed layer and the ensuing development of phytoplankton biomass. However, our sampling was done in the relatively short period (10 days), we have attempted to correlate the depth integrated chl *a* content and the surface mixed layer depth (Fig. 13) in the well characterized single water mass : warm and less saline South East Pacific Basin water mass. At the time of sampling, there was no pronounced surface mixed layer which usually observed near the ice-edge zone

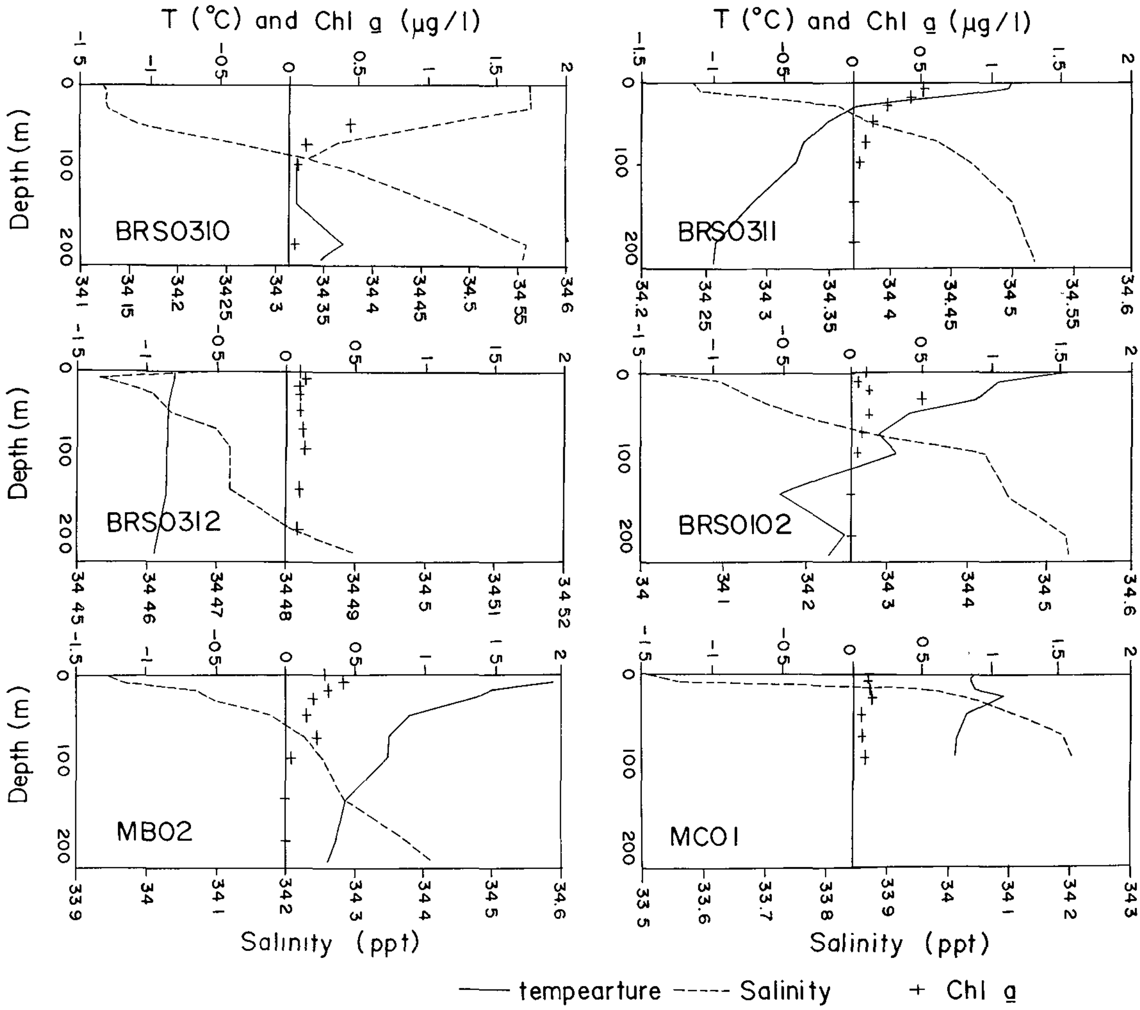


Fig.12. Depth profiles of temperature, salinity, chl *a* for the selected stations from Bransfield Strait, Maxwell Bay and Marian Cove during 28 December 1989 — 9 January 1990.

(Nelson et al., 1987), rather continuously stratified. This fact may represent the ice-free Antarctic oceanic water.

Among the surface mixed layer depth (SMLD) criteria, we choose the variable sigma-t approach to include nonlinear effects instead using a priori Δ T criterion (Glover and Brewer, 1987 ; Marra et al., 1990). Due to the nonlinear response of density to temperature and salinity, different $\Delta\ \sigma_t$ values are created depending on the surface water temperature and salinity. Especially, in the cold Antarctic waters, salinity is the main factor determining seawater density, and vertical variation of temperature is very narrow (the maximum temperature difference between surface and bottom water is about 2℃). Therefore, we calculated SMLD by taking the surface values of temperature and salinity as starting values, and a $\Delta\ \sigma_t$ due to a lowering of the temperature of

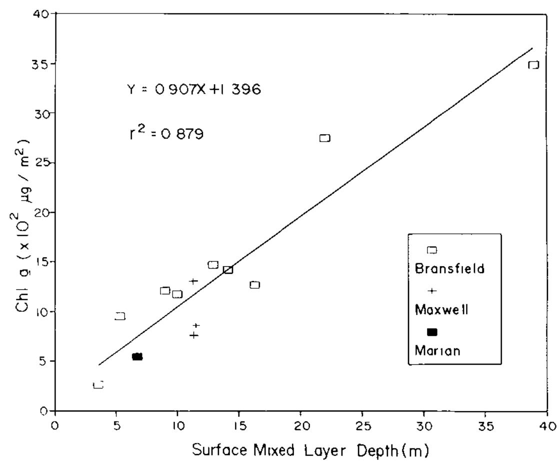


Fig.13. Plot of surface mixed layer depth and the depth integrated chl *a* for the selected stations from Bransfield Strait, Maxwell Bay and Marian Cove during 28 December 1989 – 9 January 1990.

this parcel of water by 0.5℃ was calculated. The SMLD is defined as the depth at which the difference from surface σ_t is equivalent to the calculated $\triangle \sigma_t$. SMLD varies from 4 to 40 m in the South East Pacific Basin originated Bransfield Strait and inshore waters.

Chl *a* concentration was integrated from surface to 50 m depth where light is usually attenuated to 1% of the surface irradiance in the Antarctic Ocean (Table 2), although substantial amount of phytoplankton biomass is often observed below the 1% light level in the shallow coastal waters (Holm-Hansen et al., 1989).

In the Bransfield Strait region, monthly mean wind speed is about 7 m s^{-1} with maximum speed of 43 m s^{-1} in the austral summer at the King Sejong Station in the Barton Peninsula of the King George Island (KORDI, 1989). Therefore, mean wind mixed layer (Ekman depth) is estimated to be 30–50 m with maximum over 150 m. However, mean SMLD is believed to be much deeper than 30–50 m due to the high wind, since the number of days which greatest temporal wind speed exceeding 10ms^{-1} is more than 300 days of the year. If the depth of SMLD is shallower than the euphotic depth, then bloom will occur. In the Norwegian Sea, bloom forms when the pycnocline is not deeper than 40–50 m (Sakshaug and Holm-Hansen, 1984). Since nutrients are not limited in the Antarctic Ocean, the thicker the SMLD is the bigger the phytoplankton biomass as long as SMLD is shallower than euphotic depth (Fig. 13). The duration of the maximum allowable SMLD may not be long enough to induce phytoplankton blooms due to severe and highly variable wind condition. Thus, primary productivity in the Antarctic Ocean is quite susceptible to the wind condition due to the inherent weak water column stability by the nature of cold surface temperature, lack of freshwater input like the northern counterpart, and deep and narrow continental shelf.

Table 2. Euphotic zone depth around the Bransfield Strait

Place	1% light level	Method	Source
Antarctic Sound	55m	Secchi	1
Anvers Is.	12m	MER Spectral Radiometer	2
Gerlache Strait	10m	Eppley 50 Pyranometer	3
Bransfield Strait	30m	Eppley 50 Pyranometer	3
Oceanic Area	60m	Eppley 50 Pyranometer	3

Sources : 1. El-Sayed and Taguchi(1981)
2. Holm-Hansen et al.(1989)
3. Mandelli and Burkholder(1966)

3. Antarctic response to the global warming

Growing period of phytoplankton in the Antarctic Ocean is believed to be from November to April, however, recent sediment trap study in the Bransfield Strait indicates growing intervals of just 30−60 days (Wefer et al., 1988). Similarly, ice-edge blooms of phytoplankton within locally stratified melt-waters may last about 60 days (Comiso et al., 1990). Therefore the annual primary productiviy may be 3−54 g C m^{-2} yr^{-1}, since average daily productivities in Antarctic coastal waters of 0.1−0.4 gC m^{-2} day^{-1} in the Weddell Sea (El-Sayed and Taguchi, 1981), 0.2−0.9 gC m^{-2} day^{-1} in the Ross Sea (El-Sayed et al., 1983).

Therefore, a more likely response to a doubling of atmospheric CO_2 and concomitant polar enhancement of >10℃ temperature rises by the year of 2035 would be melting of polar pack ice (Hansen et al., 1984). After the removal of ice, that is, the removal of the freshwater source of stratification may actually lead to a decline of carbon fixation in the Antarctic Ocean (Walsh, 1990).

Conclusions

The major findings of this work are :

1. Surface temperature varies from −1.0 to +2.3℃, and surface salinity varies from 33.8 to 34.5‰.

2. A warm and less saline South East Pacific Basin Water is predominant in the Bransfield Strait, while a cold and more saline Weddell Sea Water is hugging the Antarctic Peninsula. Inshore waters of Maxwell Bay and Marian Cove is diluted with fresh water supplied by ice melt and surface runoff from the adjacent land.

3. Water column is generally weakly stratified without pronounced surface well mixed layer.

4. Primary productivity in the Bransfield Strait and its inshore waters of Maxwell Bay and Marian Cove appears to depend on the depth of the surface mixed layer. The depth integrated chl *a* and surface mixed layer depth show a positive correlation.

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