Korean Journal of Polar Research
Vol.1, No.1, p. 27-46, June 1990

Oceanographic Conditions of Maxwell Bay, King George Island, Antarctica (Austral Summer 1989)

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南極 맥스웰灣의 海況(1989년 夏季)

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Abstract Maxwell Bay is an Antarctic fjord characterized by relatively small amount of freshwater input and deep sill Hydrographic measurements in the bay were conducted twice at an interval of a week in austral summer of 1989 Over this period water properties of Maxwell Bay range from -0.1℃ to 1.5℃ in temperature, 33.5‰ to 34.6‰ in salinity and 27.0 to 27.8 in sigma-t A pattern of estuarine circulation is shown in summer. which might be triggered by breakup of sea ice and freshwater input to the bay The freshwater input is dominated mainly by snow meltwater and meltwater from the submerged glaciers at the northeastern part of the fjord The halocline at the head of the bay occurs within the upper 5 m with steep gradient, while the halocline seaward gets deep in depth and mild in gradient due to increased mixing and entrainment As summer progresses the vertical structure of water column changes as follows : at the head the surface mixed layer becomes thin with stronger salinity gradient, while the layer becomes thick with higher salinity and reduced gradient at the mouth Vertical and horizontal distributions of water density are almost identical to those of salinity rather than temperature distributions, implying that the water density is controlled mainly by salinity At the head of the fjord the surface water temperatrue is lower than that at the depth of 5 m ~10 m due to thawing of sea ice The inflow water is characterized by subsurface temperature minimum and temperature maximum layers which can be also found in the western and northern regions of the Bransfield Strait where water of the Bellingshausen Sea is known to appear during summer Therefore, subsurface water found in Maxwell Bay during this period is believed to originate from the Bellingshausen Sea Changes of subsurface and bottom water properties during relatively short period can be only explained by advection Secondary halocline appears below the temperature minimum layer yielding stability of the water column Vertical temperture sections clearly indicate that the inflow tends to hug the left side (facing downstream) of the fjord due to the earth's rotational effect This can be supported by the geostrophic adjustment scale which is the internal radius of Rossby deformation smaller than the width of the fjord

Key words Antarctic fjord, Maxwell Bay, hydrography, austral summer, earth's rotation

요약: 1989년 南極海의 여름기간(austral summer)에 南極圈의 피요르드(fjord)인 맥스웰灣에서 일주일 간격으로 2회에 걸쳐 CTD에 의한 해양관측을 실시하였다. 맥스웰灣은 비교적 淡水流入量이 적고 깊은 실(sill)이 존재하는 것이 특징이다. 관측기간 동안의 맥스웰灣의 해수는 수온 -0.1℃~1.5℃, 염분 33.5‰

~34.6 ‰ 그리고 밀도(sigma - t) 27.0~27.8의 범위를 보였다.
맥스웰灣은 겨울철에는 얼음으로 덮여있으며 봄철이 되면서 얼음이 깨지고 淡水流入이 일어나면서 河口循環(estuarine circulation)이 시작되는 것으로 思料된다. 淡水流入은 주로 融雪水나 피요르드의 북동쪽에 잘 발달되어 있는 氷河로부터의 融解水에 의해 일어난다. 淡水流入으로 인하여 형성되는 염분躍層은 피요르드 上部에서는 표층으로부터 5 m 사이에 뚜렷이 나타나며 피요르드 入口쪽으로 갈수록 수직混合의 증가로 인하여 염분躍層이 나타나는 수심이 깊어지고 그 세기도 약해진다. 여름철로 갈수록 水層의 수직구조는 다음과 같이 변화한다 : 淡水流入이 활발한 피요르드 上部에서는 淡水流入의 증가로 인하여 표층염분이 낮아지고 수직적인 염분傾度가 증가하며 표층混合層의 두께가 얇아지는 반면에 피요르드 入口에서는 표층염분이 높아지고 수직적인 염분傾度가 감소하며 표층 混合層은 더욱 두꺼워져 피요르드 上部와는 정반대의 변화가 일어난다. 해수밀도는 수온보다 염분에 의해 주로 결정되므로 수직적인 밀도구조는 염분구조와 유사하다. 浮氷이 많이 분포하고 氷河에 의한 融解水 流入이 주로 일어나는 피요르드 上部에서는 海氷의 融解로 인하여 표층수온이 5 m ~10 m 깊이의 수온보다 더 낮다.
맥스웰灣으로 流入되는 해수는 브랜스필드(Bransfield) 해협의 북쪽과 서쪽에 분포하는 해수에서와 마찬가지로 中層에 수온最小層과 수온最大層이 나타나는 것이 특징이다. 夏季에 브랜스필드 해협의 북쪽과 서쪽에 출현하는 해수는 그 기원이 벨링스하우젠 海인 것으로 미루어 夏季에 맥스웰灣으로 流入되는 해수도 그 기원이 벨링스하우젠 海임을 알수 있다. 약 1주일사이의 中層과 底層에서의 해수특성 변화는 해수의 移流(advection)에 의해서만이 설명이 가능하다. 中層의 수온最小層 아래에서는 염분이 비교적 급격히 증가하여 수온逆轉에도 불구하고 水層은 안정되어 있다.
수직적인 수온단면 분포는 灣內로 유입되는 해수가 지구자전 효과로 인하여 流入방향의 왼편으로 偏向됨을 보여주며, 현장 관측자료를 이용하여 계산한 內部 로스비變形半徑(internal Rossby deformation radius)은 피요르드 幅보다 작아 이와같은 사실을 뒷받침한다.

주요어 : 피요르드, 맥스웰灣, CTD 관측, 담수유입, 지구자전효과

Introduction

Fjords are glacially carved coastal features found at high latitudes. They are geomorphologically described as elongated, steep - sided and deep land - locked marine enviroments, and they usually, but not inevitably, contain one or more submarine sills Many of the fjords have large rivers discharging into them, usually at the head, and all have some freshwater inflow (Pickard and Stanton, 1979) . They are a type of estuary which has free connections with the open sea. The sea water is measurably diluted with fresh water derived from land drainage, and an estuarine circulation is presumed to occur In this circulation, the freshwater from rivers ('runoff') flows seaward in the upper layer, while saline and more dense water must enter below the outflowing low salinity layer to maintain the average salt content of the fjord. The force responsible for maintaining the flow of brackish water toward the sea originates from the pressure field associated with the seaward - sloping free surface.

Many silled fjords have internal basins defined by sills. They show their distinctive physical and biochemical characteristics such as slow flushing time, which can raise some unique environmental problems. Thus understanding of the typical processes in each fjord is needed for use and management of fjords. Being semi - enclosed bodies of water, source inputs , such as freshwater discharge and nutrient input, can easily be identified in fjords. Thus fjords are natural oceanographic laboratories and allow very useful scientific experiment(Pickard and Stanton, 1979 ; Syvitski et al., 1987).

Fjords in Arctic and temperate zone have been the subject of intense study but there have been limited physical oceanographic studies of fjords in Antarctic region In Admiralty Bay, neighboring Maxwell bay to west, several oceanographic studies have been made mainly by Polish scientists (Rakusa - Suszczewski, 1980 ; Pruszak, 1980 ; Szafranski and Lipski, 1982) . However, hydrographic surveys in Maxwell Bay have been rarely documented. The purpose of this paper is to describe some physical oceanographic features observed during two cruises as a part of an interdisciplinary study in Maxwell Bay, Antarctica. This study was also attempted by the intrinsic interest of the features themselves in the bay.

Environmental Setting

Maxwell Bay is surrounded by King George and Nelson Islands which belong to South Shetland Islands, Antarctica(Fig. 1). It comprises a central basin and several tributary basins, Marian Cove, Potter Cove, Ardley Cove, Collins Bay and Edgell Bay. Cross sections of the central area in Maxwell Bay are in the shape of letter U typical for fjords (Park et al., 1989) . The fjord is approximately 14 km long and 6 km to 14 km wide, separated from the Bransfield Strait by a 430 m deep sill. Water depths increase gently from the coastline to 200 m depth, but they show steep slope from 200 m to 400 m depths. While the shallow areas (< 200m) show irregular topographic features, the central basin of the bay is relatively flat with depth ranging from 400 m to 500 m. The maximum depth in the central part of the bay is 520 m. Between King George and Nelson Islands lies Fildes Strait forming a unique channel which connects the bay with Southern Drake Passage. The strait is very narrow, 400 m to 800 m wide, and there have been no sounding data available because of inaccessibility to the strait due to glaciers and big icebergs. Active iceberg calving from a glacier snout was found in Collins Bay and Marian Cove during the cruises.

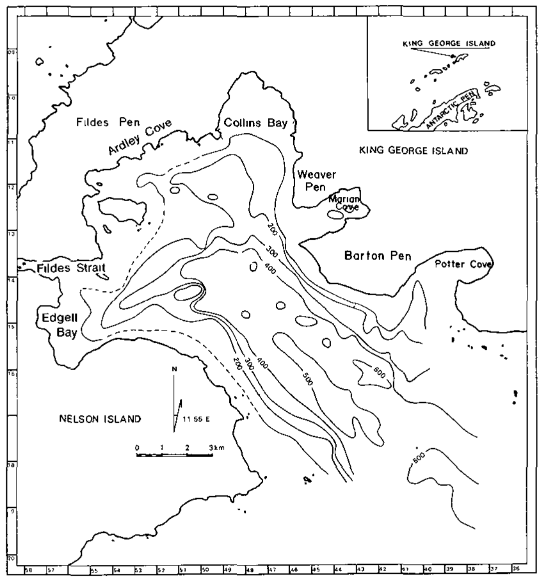


Fig. 1. Geographical location and bathymetry of Maxwell Bay Bathymetric contours are drawn from informations given by Instituto Hidrografico de la Armada de Chile.

The climate of fjords has a considerable effect on environmental conditions. From March 1988 to February 1989, monthly mean air temperature varied from -8.4℃(August) to 2.4℃(February), and annual mean air temperature was -2.2℃. The surface layer of Maxwell Bay freezed up in winter, from late July to mid - September, 1988. Maximum ice thickness reached 60 cm in Marian Cove in late August. Once free from ice cover, Maxwell Bay was soon invaded by drifting ice. During the open - water period ice floes have been always observed (KORDI, 1989) . Annual total precipitation was approximately 17 cm and precipitation during summer(from December to February) amounts to 73 % of the total annual precipitation. Annual total snow fall was approximately 460 cm, and monthly total snow fall showed its maximum value of 230 cm in June. Monthly summaries of meteorological observation are described in detail in KORDI (1989).

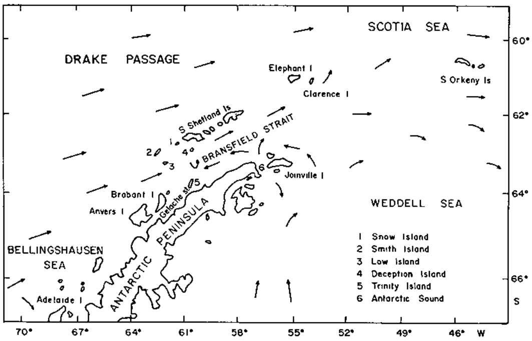
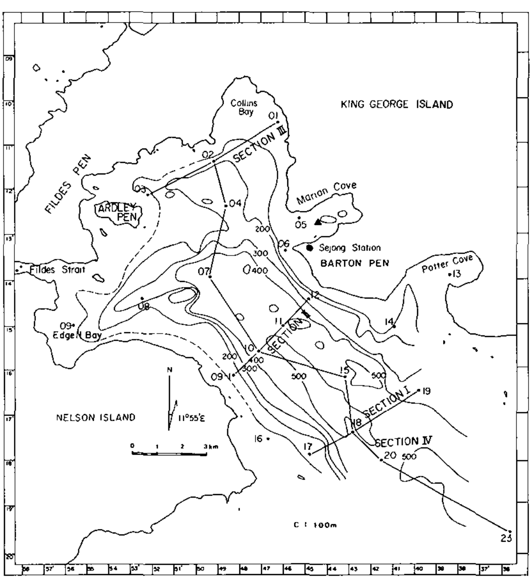


Fig. 2. Main surface currents in the Bransfield Strait and environs (after Piatkowski, 1985).

Before the hydrography of Maxwell Bay is described, some information about the Bransfield Strait must be presented. Because Maxwell Bay opens its mouth directly to the Bransfield Strait over a relatively deep sill, subsurface water exchange seems to occur easily and the water characteristics of the inner basin can be significantly affected by the open ocean conditions. The Bransfield Strait is a 112 km wide trough, trending northeast to southwest for 460 km between the South Shetland Islands and the Antarctic Peninsula (Heywood, 1985). The general hydrography of the Bransfield Strait is well understood through fairly extensive studies (Clowes, 1934; Gordon and Nowlin, 1978; Grelowski and Tokarczyk, 1985, Heywood, 1985; Grelowski et al., 1986; Tokarczyk, 1987). At the surface layer two distinctive water masses appear in the strait: water masses originating from the Bellingshausen and the Weddell Seas. Relatively warm, less saline water of the Bellingshausen Sea is known to appear in the western and northern Bransfield Strait particularly in summer. Meanwhile colder, more saline water of the Weddell Sea is reported to exist in the southeastern part of the strait (Clowes, 1934). Water of the Bellinshausen Sea enters the strait between Low, Smith and Snow Islands and splits into two near Deception Island. The southern tongue of this water spreads across the strait until it meets the water of the Weddell Sea in the vicinity of Trinity Island, where it is deflected back to join the other tongue passing along the southern coast of South Shetland Islands (Heywood, 1985; Grelowski and Tokarczyk, 1985). Charts of the relative dynamic topography at the surface indicate that the main surface current in the Bransfield Strait associated with the water of the Bellingshausen Sea flows along the southern coast of South Shetland Islands in a northeasterly direction as shown in Fig. 2 (Piatkowski, 1985; Heywood, 1985; Grelowski et al., 1986). Water of the Weddell Sea enters the Bransfield Strait around Joinville and d'Urville Islands, and passes through the Antarctic Sound, spreading northward across the strait and also southwestward along the coast of Antarctic Peninsula. Often it reaches to Trinity Island where it converges with water entering the strait via the Gerlache Strait (Clowes, 1934; Gordon and Nowlin, 1978). Another major water mass that may be considered in the Bransfield Strait is Warm Deep Water (WDW), though its influence in the strait is known to be very weak due to the strait's topographic isolation (Gordon and Nowlin, 1978; Heywood, 1985). However, the presence of WDW is somewhat clear in the western and northern Bransfield Strait, while in the eastern and southern regions of the strait where the influence of the Weddell Sea water is dominant the WDW is absent from the whole water column. The WDW was able to be identified by subsurface temperature maximum on T - S diagrams and vertical temperature sections in Maxwell Bay.

Data and Method

The CTD casts, made during the austral summer of 1989, consisted of two two - and three - day cruises between January 27 and February 6 (Fig. 3) The two legs over this period allowed duplicate CTD acquisitions at some stations shown in Fig. 3. This hydrographic survey was conducted aboard Cruz de Froward. An EG & G OCEAN PRODUCTS Smart CTD (conductivity / temperature / depth) system was used for the survey. The CTD data were used only during the downcast at a lowering rate of about 1m / s. To remove extreme values the data were despiked from the continuously increasing depth, and then averaged over 1m intervals to obtain temperature and salinity, from which density was computed. The data are considered to be correct ±0. 01℃ in temperature and ±0. 01 ‰ in salinity



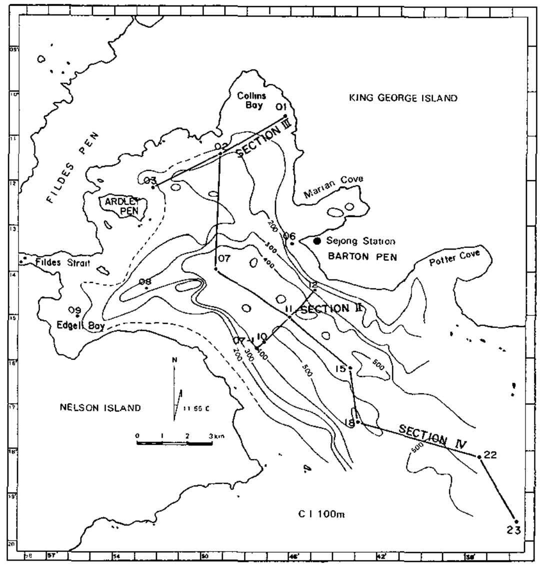


Fig. 3. Positions of CTD stations occupied during January 27-28 (left panel) and February 4-6 (right panel) in Maxwell bay. Bathymetric contours and four sections are also shown.

Results

1. T - S diagrams

In order to identify the water masses present in the survey area a correlation between temperature and salinity is employed(Fig. 4) Temperature, salinity and sigma - t of the Maxwell Bay water range from -0. 1℃ to 1. 5℃, 33. 5 ‰ to 34. 6 ‰ and 27. 0 to 27. 8 respectively Each T - S diagram can be divided into three distinct portions which are bounded by two distinctive subsurface layers: the temperature minimum layer(T_{min} layer) and the temperature maximum layer(T_{max} layer). This type of T - S relations can be found in the western and northern regions of the Bransfield Strait although the properties of the core layers in the strait are somewhat different from those of Maxwell Bay(Grelowski and

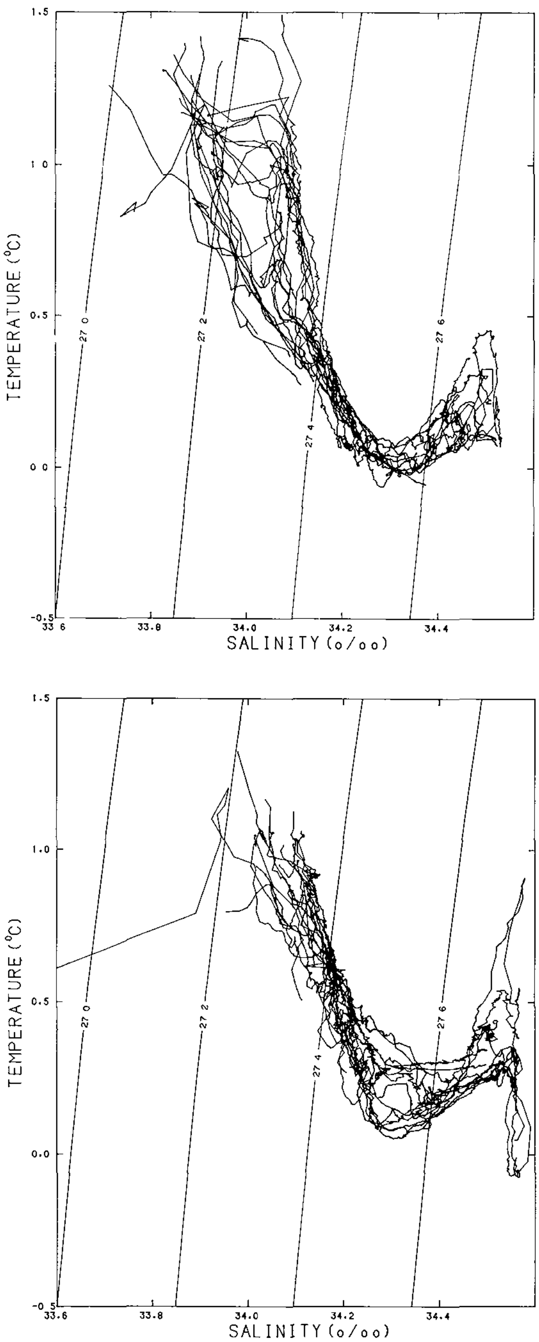


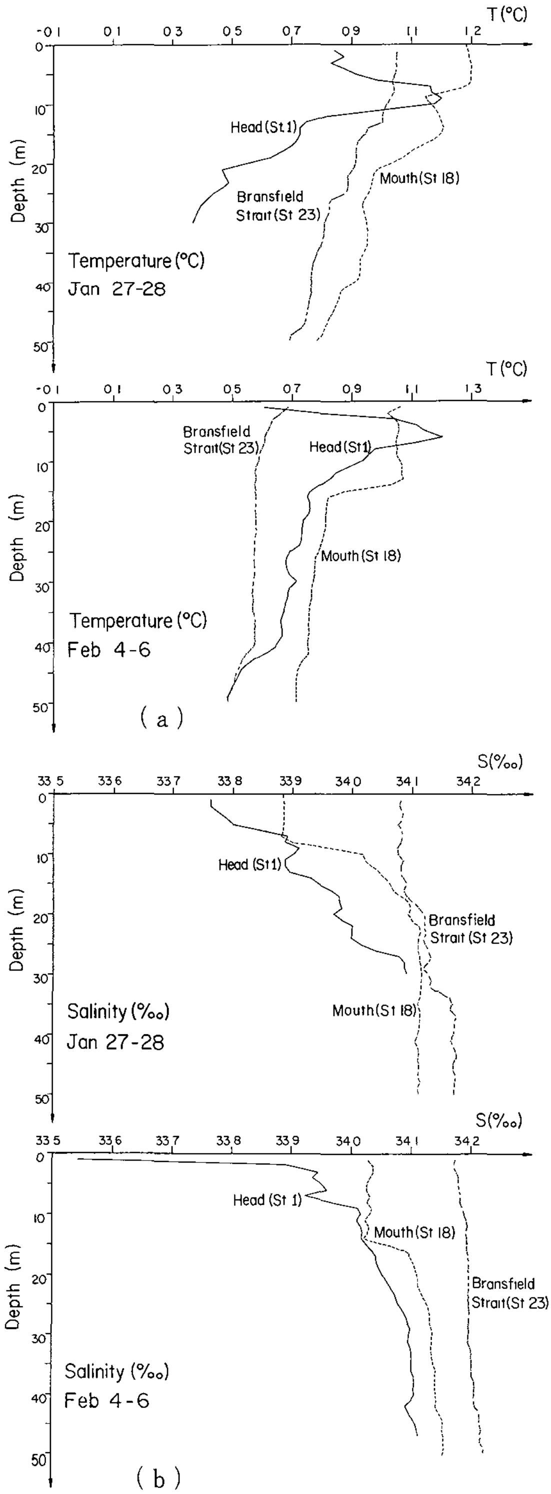
Fig. 4. Temperature and salinity diagrams for all stations occupied during January 27-28 (upper panel) and February 4-6 (lower panel)

Tokarczyk, 1985 ; Heywood, 1985 , Tokarczyk, 1987) Between the T_{min} layer and the T_{max} layer both temperature and salinity increase with depth. The subsurface temperature maximum reaches 0.9℃ at the southernmost location (station 23) but usually was in the range of 0.1℃ to 0.5℃ at the rest of the stations in Maxwell Bay. Below the T_{max} layer temperature falls and salinity remains nearly constant At the temperature range greater than 0.5℃ the T - S correlation of the first cruise reveals more variation than that of the second cruise, but below 0.5℃ the correlation is more tight in the first than in the second. The lowest salinity was found at station 1 located in the Collins Bay(Fig. 3).

2. Vertical profiles

Fig. 5 show the vertical profiles of temperature, salinity and sigma - t at stations 1 (near the head) , 18(near the mouth) and 23 (outside the fjord) in the upper 50 m within which the halocline lies Halocline is an important feature of the water structure in terms of transport and deposition of sediments and the depth of halocline is dependent on freshwater discharge and morphology of the fjord.

In the late January the surface mixed layer was 2 m thick at the head and 4 m thick at the mouth of the fjord. At the head salinity increased with depth with some irregularities. At the mouth halocline was formed between 4 m and 14 m depths, and below the halocline salinity change shows little variation. In the early February surface mixed layer becomes thin with surface salinity decreasing at the head, and stronger halocline was formed between 1 m and 3 m depths. On the other hand surface mixed layer becomes thick with surface salinity increasing at the mouth, and vertical salinity gradient is reduced. Density -



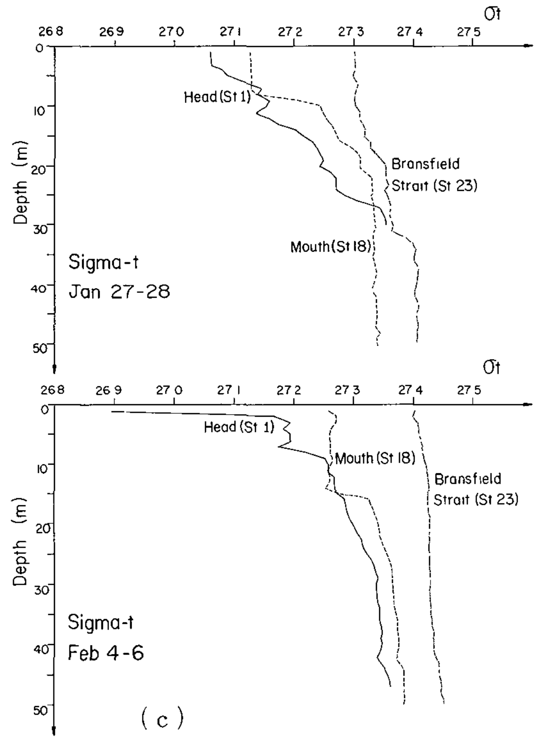


Fig. 5. Vertical profiles of (a) temperature, (b) salinity and (c) sigma-t at stations 01, 18 and 23 in the upper 50 m in the late January and early February.

depth profiles are similar to salinity profiles, which indicates that density is controlled mainly by salinity than by temperature. Vertical stability became stronger at the head in the early February due to the decrease of surface salinity caused by more meltwater input. On the other hand vertical water columns became more homogeneous at the mouth and outside the fjord in the early February. At the head of the fjord, where there are snow meltwater inflow and active iceberg calving from tidewater glaciers, vertical water temperatures show their maximum near 10 m and 5 m depths in the late January and early February respectively. Hence vertical water columns exhibit a temperature inversion from surface to 5 m or 10 m subsurface. Temperature decreased outside the fjord from surface to 50 m depth in the early February.

Vertical profiles in mid-fjord(Fig. 6) show temporal changes of vertical structure· surface mixed layer deepening and vertical stability decreasing. Water became saline and heavier in the early February. In the early February water became cooler from surface to 10 m depth, on the other hand it became warmer below 10 m depth.

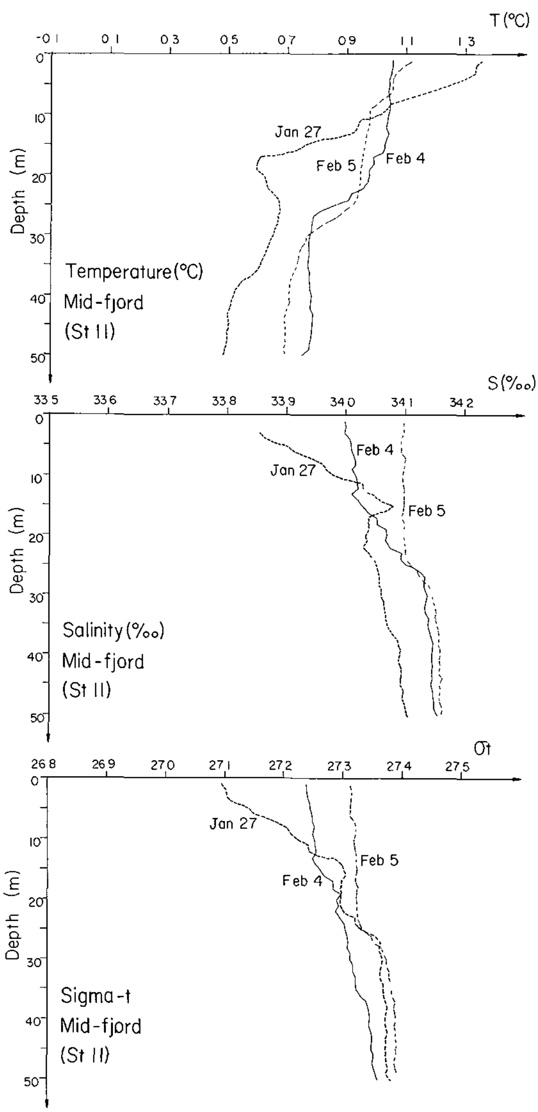


Fig. 6. Vertical profiles of temperature, salinity and sigma-t at station 11 in the upper 50 m in the late January and early February.

3. Vertical sections

1) Section I

Section I is the southernmost section which runs from southwest(left side) to northeast(right side) (Fig. 7).

Vertical temperature, salinity and sigma-t differences are about 1.2℃, 0.6‰ and 0.55 respectively. Thermocline is formed in the upper 100 m, and maximum temperature gradient is found between 50 m and 80 m. Below 100 m temperature gradually decreases towards the T_{min} layer which is found between 180 m and 280 m. The lowest temperature (<0.0℃) occurs broadly at station 18 which has the deepest water depth of this section. Below the T_{min} layer temperature increases and reaches more than 0.4℃. The T_{max} layer (>0.4℃) appears between 370 m and 430 m depths at station 18 and temperature decreases again below the T_{max} layer, reaching bottom temperature less than 0.1℃. Off Nelson Island(stations 17) and off King George Island(station 19) temperature increases from the T_{min} layer to the sea bottom, however temperature difference between the T_{min} layer and the bottom is larger at station 17(about 0.4℃) than that at station 19(less than 0.1℃).

In contrast to the vertical sections of temperature, salinity increases monotonically with depth throughout the temperature inversion layer providing the vertical stability for the water column. The vertical profile of sigma-t is almost identical with the salinity profile suggesting the main effect of salinity on density. Fresh water plume is confined within upper 10 m, and associated halocline and pycnocline, lying above the seasonal thermocline,

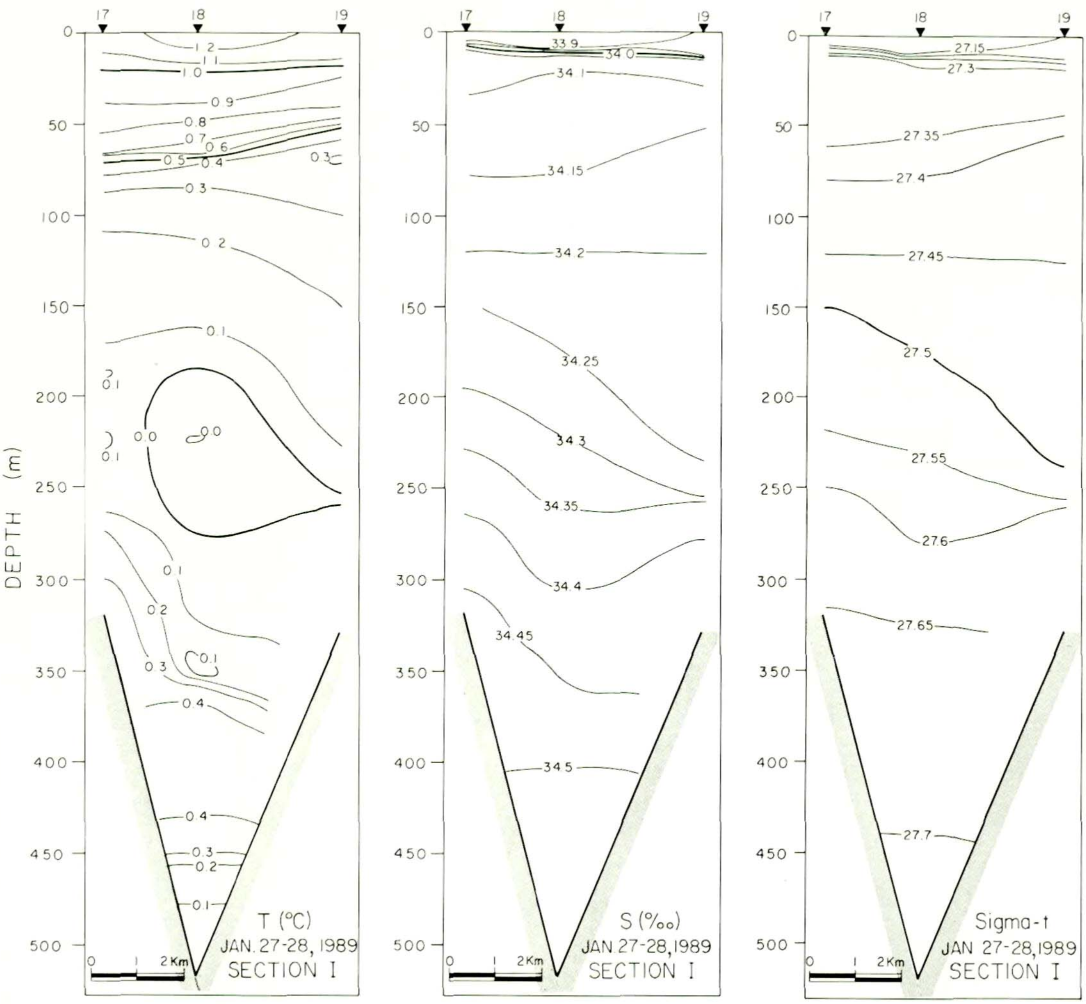


Fig. 7. Vertical sections of temperature, salinity and sigma-t along section I made during January 27-28.

are found at about 10 m. In the vicinity of the T_{mim} layer relatively sudden increase of salinity occurs.

It is interesting to note that the slope of isolines above and below 120 m is reversed in the vertical sections of salinity and sigma-t. The isohaline of 34.15 ‰ slopes up toward King George Island(station 19), but the isohaline of 34.25‰ slopes down toward King George Island. The slope of isotherms is also reversed with 80m depth in the center.

2) Section II

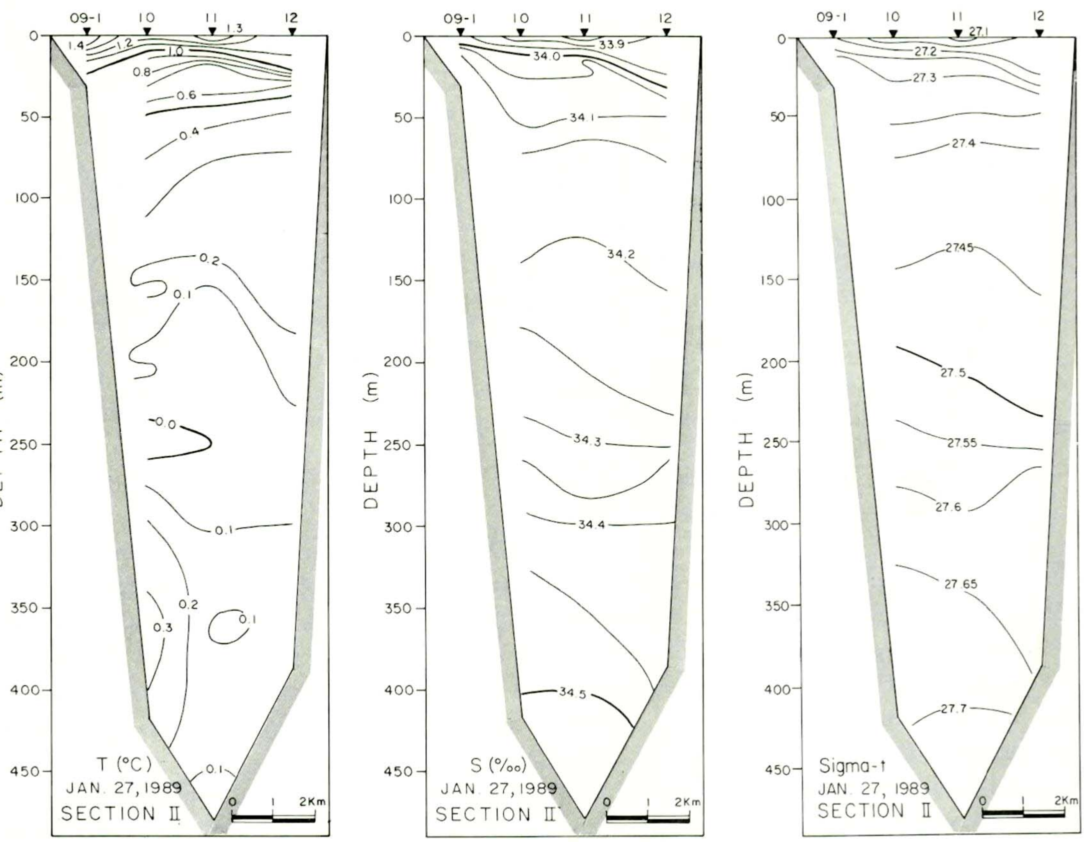
In the late January a thermocline developed in the upper 50m(Fig. 8). The layer of maximum temperature gradient is located at shallower depth than that in section I. Isotherm of 0.5℃ is at about 50m in this section, but reached 80m in the southern section(section I).

In the early February surface water becomes cooler, more saline and heavier, and their gradients are reduced. Surface mixed layer off the Barton Peninsula(station 12) is thicker than those of any other stations for two cruises. Surface temperature and salinity are higher off Nelson Island(stations 07-1 or 09-1) than those off the King George Island (station 12). The surface salinity is lower at the central part of two sections (station 11) than at the coastal stations.

The T_{min} layers lie between 200 m and 300 m. The temperature of the T_{min} layer, observed in the early February, was higher than that observed in the late January. The area surrounded by 0.1℃ isotherm is broader in the late January than that in the early February. It is also noteworthy that the T_{min} layer becomes thin in section Ⅱ compared to that in section Ⅰ. Moreover, the core of low temperature(<0.0℃) was located at the deepest central part in section Ⅰ, while in section Ⅱ it is located near Nelson Island to the west. Relatively sudden increase of salinity occurred in the T_{min} layers similar to that in section Ⅰ.

Below the T_{min} layers temperature increases due to the effect of WDW, and T_{max} layers can be found in two sections. The core of the T_{max} layer is more conspicuous off Nelson Island. Off King George Island(station 12) temperature increases by only a little lower than 0.1℃ below the T_{min} layer. On the other hand temperature difference between T_{min} and T_{max} layers reaches 0.3℃ ~ 0.4℃ off Nelson Island (station 09-1 or 07-1).

Temperature decreases with depth below the T_{max} layers. This is most pronounced at the



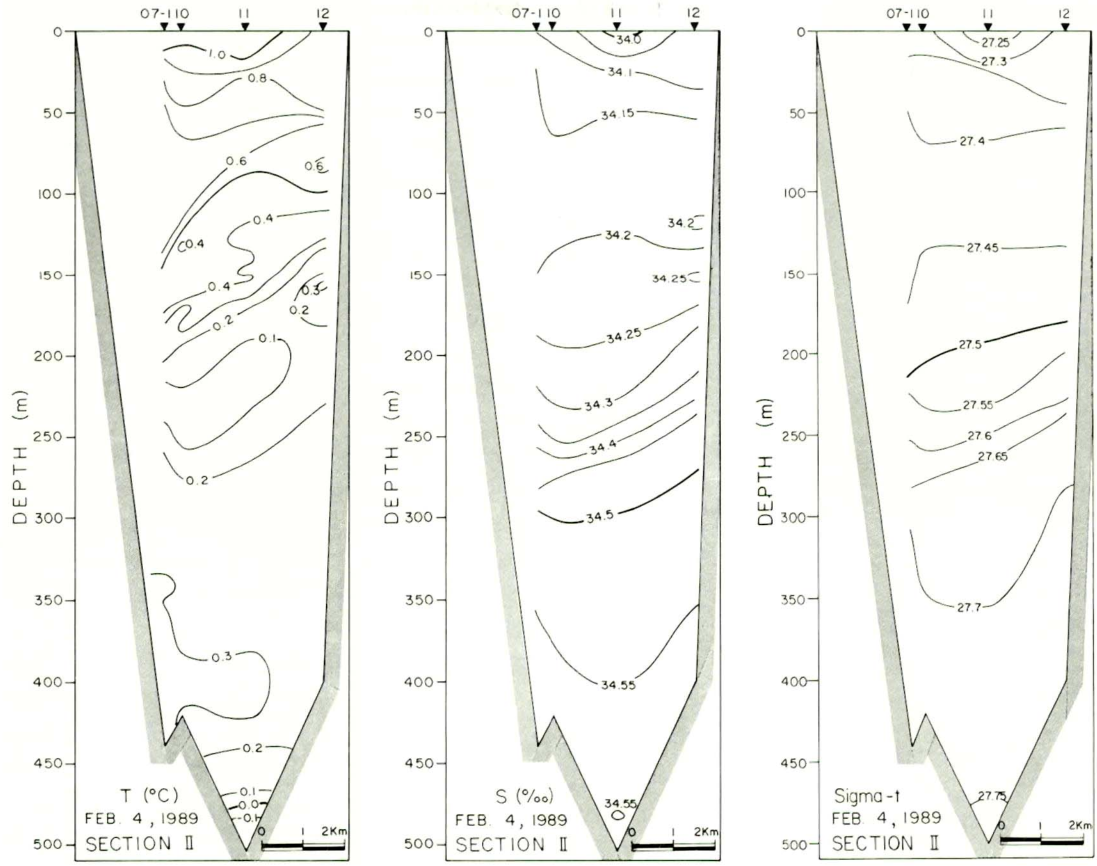


Fig. 8. Vertical sections of temperature, salinity and sigma-t along section II made on January 27 and February 4 from Nelson Island (left side) to the Barton Peninsula (right side).

deepest station 11. Compared to the first survey in the late January, the second survey in the early February reveals the following characteristics: increase in the T_{min} layer temperature with slight decrease in salinity, increase in the T_{max} layer temperature, decrease in botton temperature, increase in salinity and density of both deep and bottom waters(Fig. 9). The temperature changes of the deep and bottom waters are so large that they cannot be explained by mixing of any water masses identified in the late January shown in Fig. 4. This implies that the deep and bottom waters intrude onto Maxwell Bay from the outer region of the bay.

3) Section III

The northernmost section III runs from the Collins Bay(right side) to the Ardley Peninsula(left side)(Fig. 10).

The lowest salinity was found in the Collins Bay from both cruises with the minimum of 33.55 ‰ in the early February. Surface waters at station 1 off the Collins Bay are cooler than the underlying water. Therefore, station 1

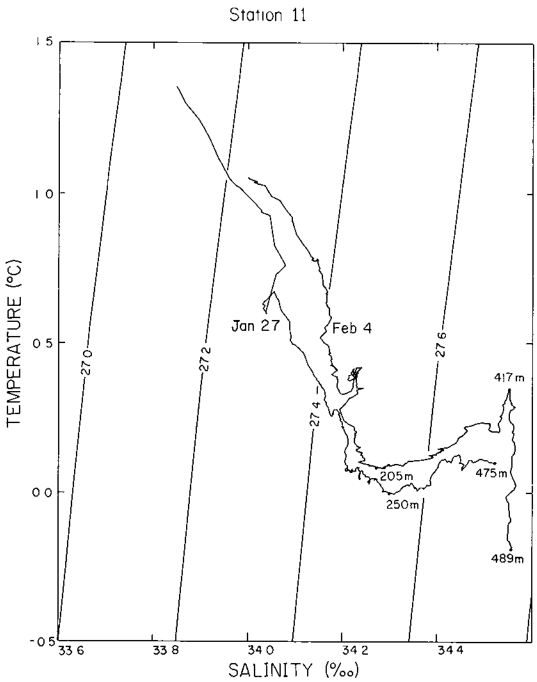


Fig. 9. Temperature and salinity diagram for station 11 located in mid-fjord occupied on January 27 and February 4. Depths of the T_{min} and T_{max} layers and the deepest measurement depths are shown for each cruise.

exhibits a subsurface temperature maximum or a temperature inversion to 10 m subsurface. Convective cooling by the atmosphere cannot account for the observed low temperature surface water, because surface waters at other stations are warmer than the underlying water. Considering the low surface salinity, the temperature inversion results from thawing of ice broken off from glaciers surrounding the bay. The effect of glacial melt does not exceed below 10m depth. Below 10 m temperature decreases and salinity increases to the bottom except the slight temperature inversion between 100 m and 140 m at stations 2 and 3 in the early February.

Surface water at station 1 became fresher in the early February, on the other hand surface water at stations 2 and 3 became more saline in the early February. Surface water became cooler in the early February but subsurface water became warmer in the early February. WDW cannot be found in this section because of relatively shallow depth.

4) Section Ⅳ

Figs. 11, 12 show the vertical sections of temperature, salinity and sigma-t in the late January and early February respectively from the Bransfield Strait(left side) to the northern end of Maxwell Bay(right side) using stations approximately in the middle of the bay. In the late January CTD cast could not be made to the bottom at station 23 due to bad weather, and CTD was lowered only to 200m(Fig. 11).

Surface water in the Bransfield Strait is more saline and heavier than the surface water within Maxwell Bay due to freshwater runoff into the bay, and surface thermohaline and density fronts are found between stations 20 or 22 and 23. The T_{min} layer having the temperature range of -0.1℃ ~ 0.0℃ lies between 180 m and 280 m in the late January. In the early February it still remains, however, temperature of the T_{min} core increases to the range of 0.0℃ ~ 0.3℃.

Below the T_{min} layers temperature increases towards the T_{max} layers. In the late January when CTD cast was not made at the Bransfield Strait the highest temperature at the T_{max} core appeared at station 18 located at the mouth of the bay. However, the temperature at the T_{max} core of station 20 was lower than that of station 18, despite that it was located farther south and only 1.7 km away from station 18. At station 20 a substantial drifting of the vessel, about 2 km off the site to the west, had occurred because exceptionally at this station sampling priority was first given

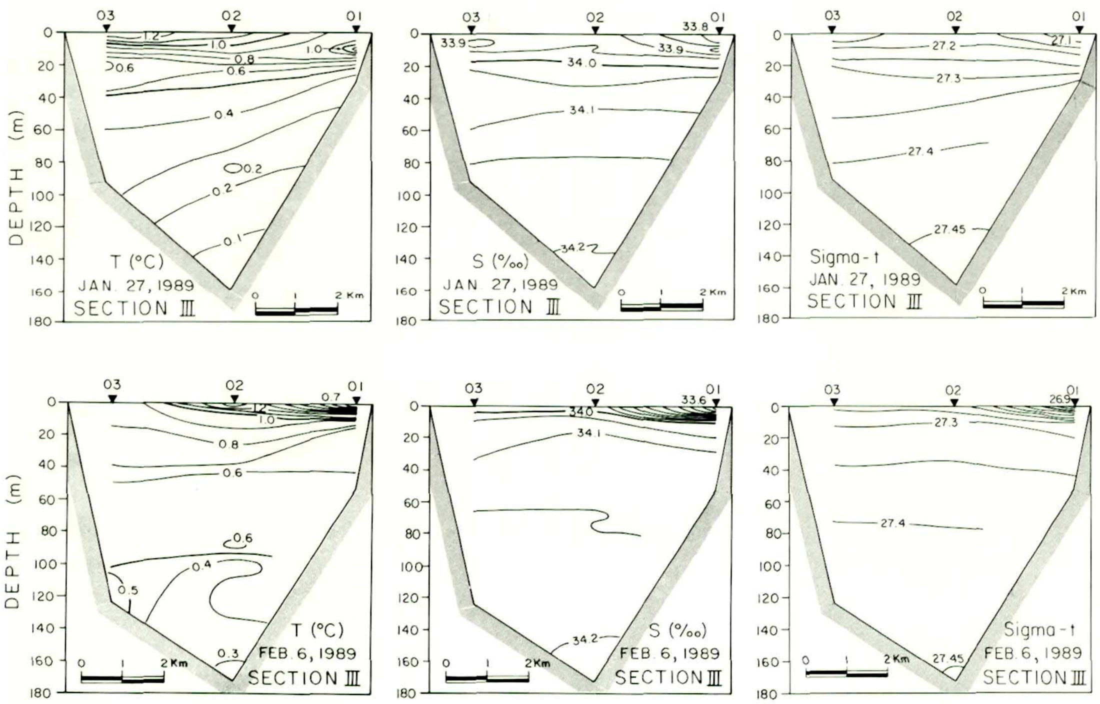
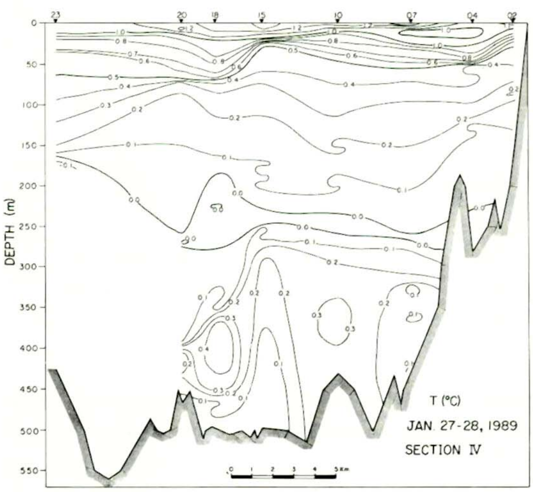


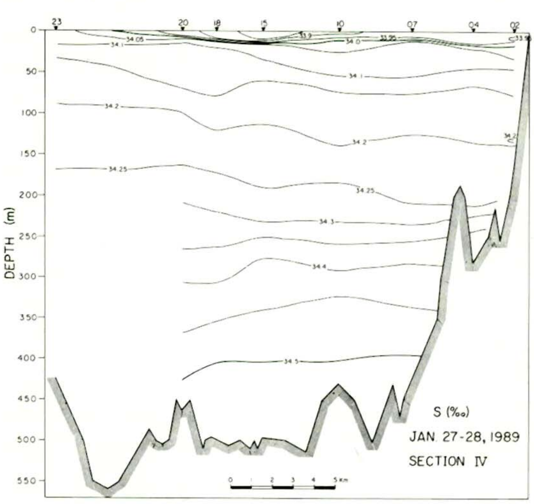
Fig. 10. Vertical sections of temperature, salinity and sigma - t along section Ⅲ made on January 27 (upper three panels) and February 6 (lower three panels) from the Ardley Peninsula (left side) to the Collins Bay (right side).

for an hour to other disciplines than CTD cast. The bottom depth at the end of the drifting showed an 100 m offset from the depth at the originally positioned site. Finally marked position of the station 20 was off 2 km southwest from station 18 deviated more to the coast of Nelson Island. For the late January section isotherm of 0.3℃ at stations 18 and 10 which represents the core of the WDW cannot be connected with each other because the temperature of the T_{max} core at station 15 is lower than that at both stations. This may be due to the fact that the main flow associated with WDW passes between station 15 and station 16 off Nelson Island. In the early February WDW core, having the slightly increased temperature range of 0.3℃~0.4℃, was found at all Maxwell Bay stations on section Ⅳ whose depth are deeper than 400 m and corresponding T_{max} layer lies between 350 m and 440 m. At the Bransfield Strait (station 23) the temperature of the T_{max} core is much warmer(about 0.6℃) than that found in Maxwell Bay. Thus the WDW seems to be greatly modified as it enters into Maxwell Bay.

Salinity and density increase monotonically with depth. Density sections are almost similar to salinity sections indicating a relatively strong influence of salinity on density. Freshwater due to the snow and glacial melts is dispersed along the entire length of the bay, and confined within upper 20 m. Subsurface halocline is approximately coincident with the temperature inversion in the lower T_{min} layer resulting in a gravitationally stable density field. It can be noted in early February section that depression of isolines below 100 m is conspicuous from the mouth(station 18) to station 22.

In the early February a cooling of surface water occurred except at station 2, and the surface cooling is prominent at station 23 located in the Bransfield Strait. Isotherm of 0.7℃ was at about 40 m at station 23 in the late January, but surfaced in the early February. Cooling effect does not penetrate into about 30 m depth within the bay, but it reachs down to about 60 m and 100 m depths at stations 18 and 23 respectively(Fig. 12). At station 2 the whole water column became warmer and more saline in the early February, but below 100 m salinity was hardly changed. At stations 7 and 10 salinity of the upper and the lower layers increased with the middle layer unchanged in the early February. Salinity change of the upper layer seems to be related with mixing(entrainment or turbulent diffusion) of more saline inflow of oceanic water at the lower layer with the upper fresh water. On the other hand salinity increase of the bottom layer is mainly due to the advection. At stations 15 and 18 bottom temperature decreased in the early February due to the advection of cold bottom water into the bay. At the mouth of the bay (station 18) middle layer salinity decreased associated with depression of isohaline in the early February (Fig. 12). At all stations the halocline was formed from surface to about 30 m depth with





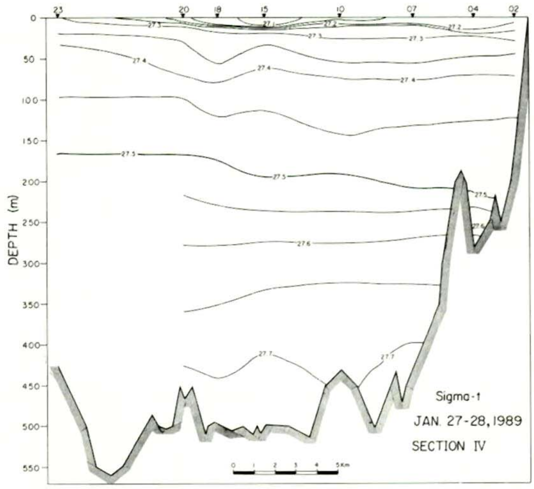


Fig. 11. Vertical sections of temperature, salinity and sigma-t along section Ⅳ made during January 27-28 from the Bransfield Strait (left side) to the northern end of Maxwell Bay (right side). At station 23 CTD was lowered only to 200 m depth due to bad weather.

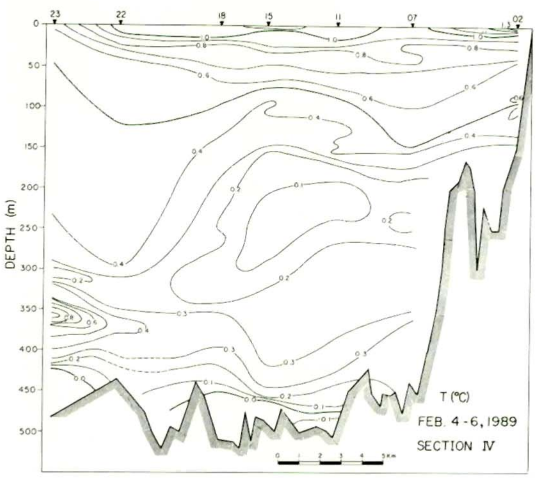
its strength reduced in the early February. Except the surface and the bottom layers the whole water column became warmer in the early February.

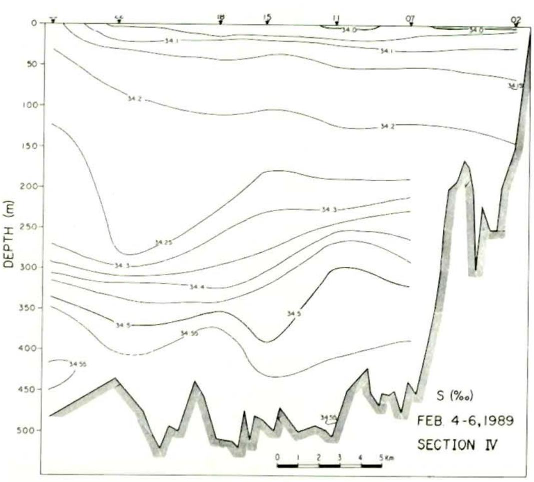
4. Horizontal distributions of water properties

Figs. 13, 14, 15 show the horizontal distributions of temperature, salinity and density (sigma - t) at 1m and 10m depths and at the bottom respectively in the late January.

Surface salinities were in the range 33.70 ‰ ~ 34.10 ‰ and the lowest surface salinity was found in the Collins Bay and the Marian Cove where the main freshwater discharge occurs from the snow and glacial melts, and the surface temperature and density were also low in these regions. The surface salinity is generally higher in the western part of the bay than in the east. Although the differnce is slight it is definite in this narrow fjord region, and the density is also high in the west due to the main dependence of density on salinity.

Horizontal distributions of water properties at the bottom show the inflow of cold and saline bottom water from the mouth of the bay following the deep central part of the bay. In this season renewal of bottom water appears to be very likely to occur due to the relatively deep sill. Bottom temperature at stations off Nelson Island is higher than that at stations off King George Island.





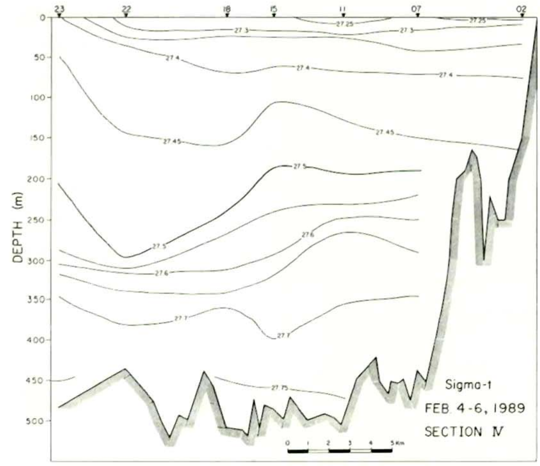
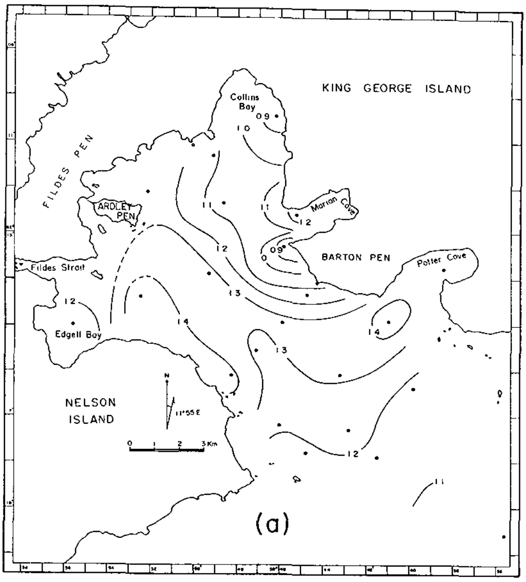
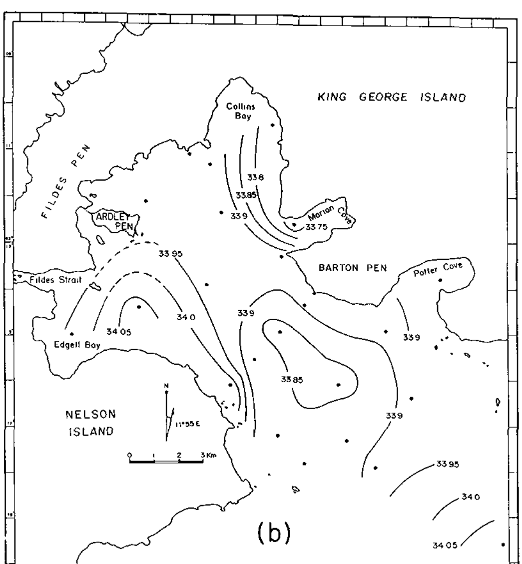


Fig. 12. Vertical sections of temperature, salinity and sigma - t along section IV made during February 4-6 from the Bransfield Strait(left side) to the northern end of Maxwell Bay (right side).

Conclusions and Discussion

Maxwall Bay is a fjord characterized by a deep sill and relatively small amount of freshwater input. The freshwater runoff is dominated by snow meltwater and meltwater from the submerged glaciers at the northeastern part of the fjord. Due to the small amount of freshwater input surface mixed layer and halocline are not so conspicuous compared with other high-runoff fjords (Pickard and Stanton, 1979), and halocline and pycnocline start nearly at the surface at the head of the fjord. The lowest salinity value (33.5‰) was observed at the surface of station 1 in the Collins Bay where active iceberg calving from a glacier snout was found, but this value is much higher than those observed in other fjords. In Admiralty Bay the lowest surface salinity of 16.40‰ was observed in an area directly adjacent to the runoff from glaciers (Szafranski and Lipski, 1982). The halocline is shallower and stronger at the head. As the mixing and entrainment increase seaward, the halocline gets deeper and weaker.





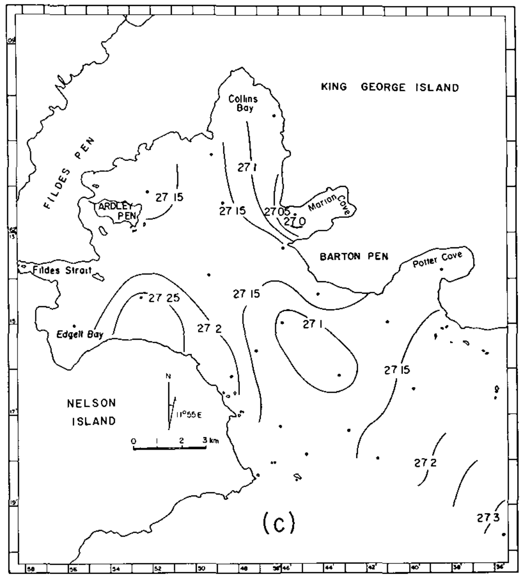
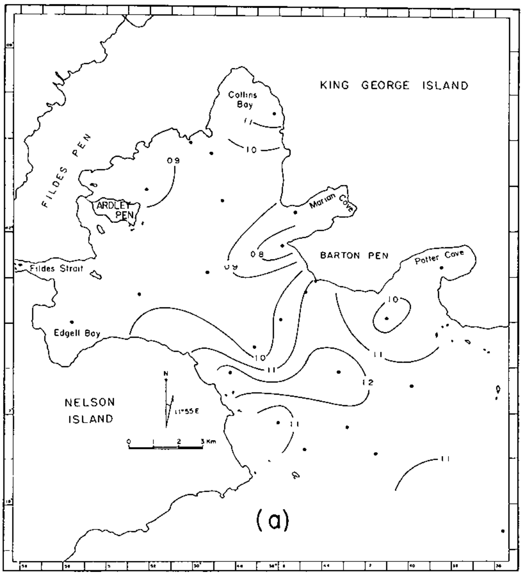
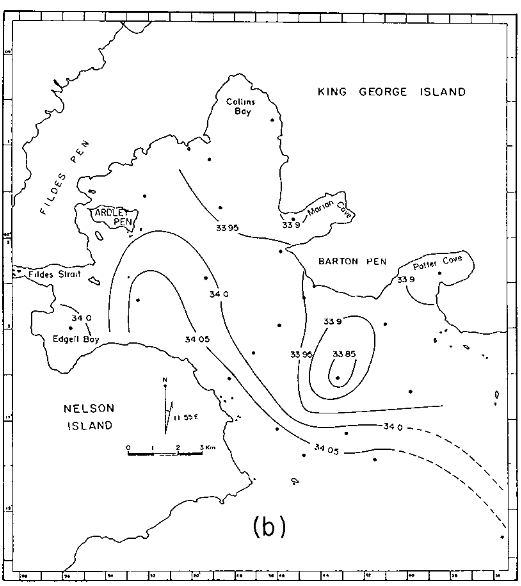


Fig. 13. Horizontal distributions of (a) temperature, (b) salinity and (c) sigma-t at 1 m depth from hydrographic stations occupied during January 27-28. Dots indicate station positions

Maxwell Bay is covered with ice in winter. As spring progresses breakup of sea ice and freshwater input occur, and they drive the estuarine circulation with runoff-laden brackish water flowing seaward at the surface and entraining salt water from the slow, landward flowing lower layer And this two - layer flow can be made more effective due to the dominant northerly wind during summer (KORDI, 1989). In Maxwell Bay precipitation falls principally as snow, so the spring melt may be the major driving force within the fjord. The spring melt predominantly occurred at the western coast of King George Island. Relatively steep slopes, absence of lakes and sparse vegetation make storage nearly non - existent during the summer months. Glaciers and drifting icebergs, by melting below the waterline also can inject significant amounts of freshwater.





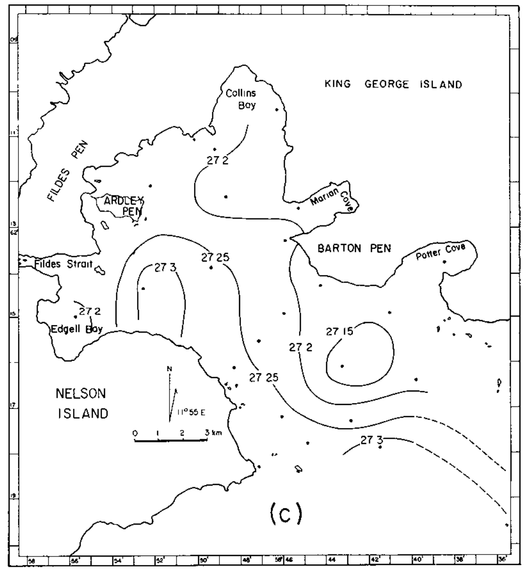
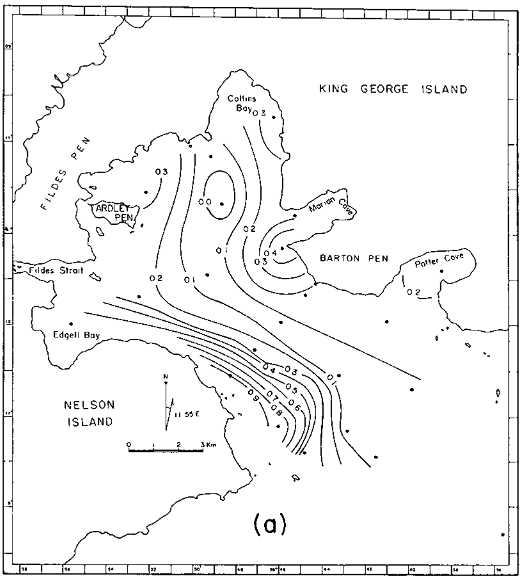
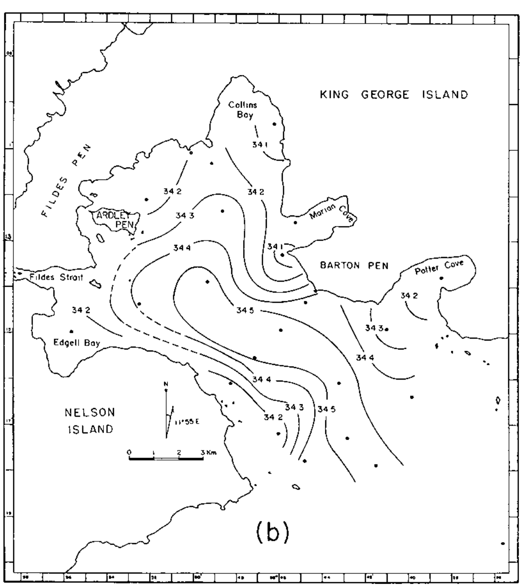


Fig. 14. Horizontal distributions of (a) temperature, (b) salinity and (c) sigma - t at 10 m depth from hydrographic stations occupied during January 27-28. Dots indicate station positions.

Vertical sections of temperature can be of great use for identifying circulation features in Maxwell Bay because the water characteristics of inflow is characterized by subsurface T_{min} and T_{max} layers, which can be also found in the western and northern regions of the Bransfield Strait where water of the Bellingshausen Sea is known to appear during summer. Therefore, subsurface water found in Maxwell Bay during summer originates from the Bellingshausen Sea. The T_{min} core layer is thought to be a remnant of the deep winter mixed layer which becomes capped by surface heating and precipitation in summer, and is commonly called Winter Water (Toole, 1981 ; Carmack, 1986) Below the T_{min} layer salinity and temperature increases due to the effect of WDW, and below the T_{max} layer temperature decreases again Salinity increase throughout the temperature inversion layer providing vertical stability for the water column because vertical stability is controlled mainly by salinity distribution. Temperature of WDW increased and bottom water temperature decreased in the second cruise, and these changes in properties of the deep and bottom waters in Maxwell Bay can be only explained by advection of these waters which have been already modified in the outer region. In summer bottom water exchange seems to occur easily due to the relatively deep sill. But bottom sediment and benthos data suggest the anoxic environment of deep central part of the bay (KORDI, 1989). In Maxwell Bay where runoff is limited to a few months, the fjord lacks estuarine circulation for a large portion of each year And when there is a little runoff and therefore only a weak estuarine circulation, the basin water is not exchanged rapidly and oxygen depletion may occur Further study is needed for the study of bottom water replenishment and oxygen measurement is





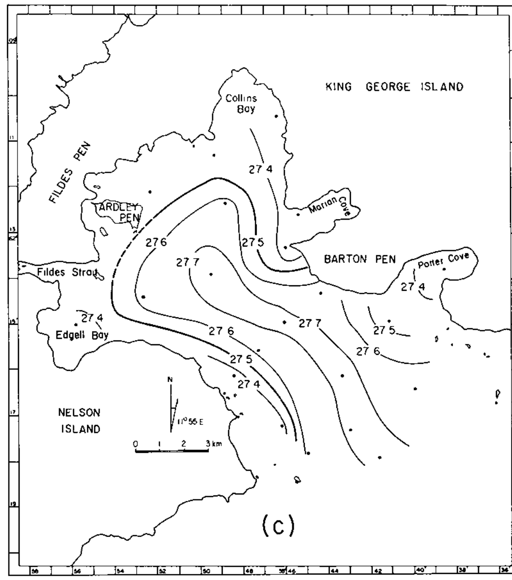


Fig. 15. Horizontal distributions of (a) temperature, (b) salinity and (c) sigma - t at the bottom from hydrographic stations occupied during January 27-28. Dots indicate station positions

necessary for this purpose

Horizontal distributions of water properties show that surface salinity and density are generally higher in the western part of the fjord than in the east and surface temperature is lower in the eastern part than in the west. This feature may be related to greater freshwater input from the northeastern part of the fjord. The freshwater input due to snow and glacial melts not only dilutes but also cools the surface water. But the influence of the earth's rotation may not be ignored.

Vertical sections clearly indicate that there is a tendency for the inflow to hug the left side (facing downstream) of the fjord. When the geometrically imposed scale (for example, the width of the fjord) becomes comparable to or larger than the Rossby radius of deformation, earth's rotational effect will be important and a significant deflection of water may be expected (Huppert, 1980) . Internal Rossby radius of deformation scale can be given by

$$R = [g h_1 h_2 (\rho_2 - \rho_1) / (h_1 + h_2) \rho_2 f^2]^{\frac{1}{2}}$$

for a two - layer flow with upper / lower layer densities and depths ρ_1, ρ_2, h_1, h_2 respectively; g is the gravitational acceleration and f the Coriolis parameter (Huthnance,1981). Calculations of R were made with changing h_1 and h_2 values based on the observed hydrographic data and they never exceed the width of the fjord, therefore, earth's rotational effect will be important. At present any quantitative data cannot be available to assure the circulation features in Maxwell Bay. But big icebergs, entered into the bay from the Bransfield Strait, were frequently observed to move northward along the eastern coast of Nelson Island during the weak wind periods by second wintering party of KORDI. And this can be a evidence of the existence of inflow mainly along the western part of the fjord due to the effect of earth's rotation Direct current measurements and assessment of freshwater discharge would be inevitable for the dynamical approach of circulation features in Maxwell Bay.

Acknowledgement

We thank to Dr. M.W Han for moral support. We also thank to Y K. Lee, Y.S Kang, H.Y. Kim and J.S. Kim for their support in laboratory. Acknowledgement was also made to members of the second Korean Antarctic Research Team and crews of M / V Cruz de Froward, Chile. This work was supported by Ministry of Science and Technology.

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