ON THE PHYSICAL OCEANOGRAPHY
OF
BURRARD INLET AND INDIAN ARM,
BRITISH COLUMBIA

by

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ABSTRACT

Measurements of the distributions of temperature, salinity and oxygen in Burrard Inlet and Indian Arm, British Columbia from May 1974 to October 1975 have been analysed to determine features of the large scale circulation in this system. Observations at roughly four-week intervals were supplemented by serial CSTD casts taken over intervals of a few hours, and by 93-day records of near-bottom currents, temperature, and salinity on the Indian Arm sill.

Short-term tidal fluctuations in property distributions have been shown to be small compared to seasonal changes.

Circulation in the Burrard Inlet - Indian Arm system is basically estuarine: relatively fresh surface waters normally flow down the inlet overlying more saline waters which enter from the Strait of Georgia. Turbulent mixing associated with estuarine and tidal flow through the shallow constrictions at both First and Second Narrows yields surface waters between the narrows which are more saline and cooler than those which would be found in a simpler estuarine environment. In a complementary sense, bottom waters are fresher and warmer.

Significant exchange and overturn of deep water in Indian Arm was recorded between October 1974 and April 1975. Intruding waters were shown to have originated west of First Narrows. In one instance exchange of at least 80% of the volume of the Arm, over an interval of 33 days, was inferred from property distributions, compared to exchange estimates of 111% and 74% deduced from the current meter record for the same event.

Exchange was shown to be intermittent, with fresh water runoff volume into Indian Arm, tidal mixing (particularly at Second Narrows) and density of Georgia Strait water being identified as some of the controlling factors.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Page

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CHAPTER 1 INTRODUCTION

1.1 General Description of Study

In the past 30 years, numerous inlets of the southern British Columbia coast have been studied and reported on, many by researchers from the Institute of Oceanography, UBC. Beyond the general overviews by Pickard (1961 and 1975), these include Alberni Inlet (Tully, 1949; and Farmer, 1972), Indian Arm (Gilmartin 1962), Bute, Jervis and Knight Inlets (Tabata and Pickard, 1957; MacNeill, 1974; and Lafond, 1975), Pendrell Sound (Buckingham, 1976) and Howe Sound, (Bell, 1973; Bell, 1974; and Buckley, 1977). Despite these many projects, relatively little attention has been paid to the waters of the Burrard Inlet - Vancouver Harbour system located so near that Institute. The description of Burrard Inlet by Tabata (1971) based upon the data report of Waldichuk et al. (1968) identifies typical summer and winter conditions for the area but does not discuss transitions between these seasons.

Motivated by this lack of information for the Vancouver area, the present project was conceived in the spring of 1974 to provide a thorough documentation and synoptic discussion of the physical oceanographic parameters of the Burrard Inlet system. In the earliest planning stages it was determined that the geographical scope of the project would include Indian Arm as well as Burrard Inlet through which the Arm is connected to the Strait of Georgia. Thus, while the portion of this study which deals explicitly with Indian Arm may be viewed as a scaled down repetition of some of Gilmartin's work, it is unique in its presentation with simultaneous measurements from Burrard Inlet and with some relevant information on currents over the sill at the mouth of Indian Arm. In relation to Tabata's work, the present study is an expansion with its investigations of tidal effects on the distribution of properties, its more thorough seasonal analysis, its consideration of surface distributions of properties and its treatment of deep water exchanges between the harbour and Indian Arm.

The goal of this project was to monitor the distribution of temperature, salinity, and dissolved oxygen concentration in the study region over a period of at least 12 months, to identify annual cyclical changes in these properties, and thereby to infer information about the large scale circulation pattern in the area. It was thought that time-series measurements such as these, at appropriately selected locations, could also yield at least some qualitative information about the mixing processes which take place in First and Second Narrows. Finally, it was also desired to determine if mid-winter exchanges of deep water occurred in Indian Arm during the period of observations and if so, to estimate the spatial and temporal scales of such exchanges.

Through a series of 27 oceanographic cruises and the analysis of a 93 day current meter record each of the above objectives was accomplished. The following chapters and sections describe the field program and present an analysis of the resultant data. A secondary project was attempted to measure currents through First Narrows using a photographic dye tracking technique. This project was not pursued to the extent of generating a significant volume of useful data to be included in the presentation of results. However, a successful technique was developed and is described in Appendix I.

1.2 Physical Description of the Study Area

Small and large scale maps of the study area are presented as Figures 1.1(a) and 1.1(b). Significant place names are noted along with positions and names of the oceanographic sampling stations. It is to be noted that dissolved oxygen concentration was monitored at approximately one half of the sample locations. These are symbolically identified on Figure 1.1(b).

The convention introduced on Canadian Hydrographic Service charts 3481 and 3484 is employed here in identifying the regions of the study area. The term "Burrard Inlet" is used to refer to the entire area (excluding Indian Arm) extending from Point Atkinson to the head of the inlet near the townsite of Port Moody. Within Burrard Inlet, subdivisions are identified as follows:

(a) Vancouver Harbour: Approaches - that region extending eastward from Point Atkinson to First Narrows, including English Bay. False Creek is considered to be a distinct body of water extending eastward from the Burrard Bridge, and is not treated in this study.

(b) Vancouver Harbour: West - that region enclosed between First and Second Narrows.

(c) Vancouver Harbour: Central - that region extending eastward from Second Narrows to Burn's Point and northward at the mouth of Indian Arm to the vicinity of station Ind 0.

(d) Vancouver Harbour: East - that remaining portion of the inlet extending eastward from Burn's Point through Port Moody.

In the following text, the designation "Vancouver Harbour" may at times be deleted and the regions referred to as "the approaches", "the western harbour", etc. Indian Arm is defined as that body of water extending northward from station Ind 0 to the delta of the Indian River. The physical characteristics of the various regions are now described.

Burrard Inlet, which extends eastward 30.6 km from Point Atkinson to Port Moody is not representative of typical British Columbia coastal fjords. Although its long narrow shape resembles that of other coastal embayments, it differs from these in many other respects. Particularly along the south shore, the steep mountain walls associated with fjords are not present. The width of the inlet varies greatly along its lengths from a mean width of 6.9 km in the approaches, through the 0.6 km wide constriction at First Narrows into the western harbour with a mean width of 1.9 km. Through a second 0.7 km wide constriction at Second Narrows opens the central harbour which has a mean width of 1.3 km. Further, beyond Burn's Point, lies the eastern harbour characterized by a 0.9 km width.

Burrard Inlet exhibits a shallow, irregular depth profile (Figure 1.2(a)) which is distinctly different from that of most British Columbia coastal inlets. Outside First Narrows, the bottom slopes quite uniformly from a maximum depth of 110 m off Point Atkinson to the 14 m outer sill at the Narrows. In the western harbour are observed the deepest hole (66 m just east of Burnaby Shoal) and the shallowest bank (Loch Katrine Bank at 16 m) inside First Narrows. Beyond the 18 m sill at Second Narrows is found another depression extending to 60 m depth. Finally, eastward from the mouth of Indian Arm, the bottom rises quite uniformly to the tidal flats at the head in Port Moody. With the exception of the area just east of Second Narrows where the shallow booming grounds extend a substantial distance across the inlet, the cross channel profiles generally exhibit a symmetrical U-shaped form. It is seen then from the above descriptions that the very shallow, narrow passages at First Narrows, Second Narrows, and Burn's Point separate Burrard Inlet into its four distinct regions.

Again in contrast to the typical British Columbia fjord, Burrard Inlet receives effectively all of its fresh water input from peripheral sources, rather than from a major source at the head. Most significant in the approaches, outside First Narrows, is the effect of Fraser River water. Water discharging primarily through the North Arm of the Fraser and sweeping north eastwards around Point Grey is a major factor in controlling surface layer property distributions in this region. Although tempered by mixing in the Narrows, the influence of this fresh water source is also identifiable in the western harbour. Apart from the Fraser, most of the streams entering Burrard Inlet do so from the north. The Capilano River which enters just west of First Narrows provides the greatest volume discharge into this area. Secondary sources entering progressively further to the west are Vinson, Lawson, Macdonald, Rodgers, Godman and Cypress Creeks. McKay and Mosquito Creeks provide a small discharge into the western harbour. Spanning Second Narrows are significant sources in Lynn Creek to the west and the

Seymour River to the east. Occasional small creeks enter between Second Narrows and the head, but do not constitute a major source. In a less direct sense, Indian Arm itself must be considered as a source of fresh water input to the Burrard Inlet system. Estimates of input rates are presented in section 4.2 with a discussion of the effects of fresh water input.

No collection or analysis of bottom sediments was performed during this survey. Tabata, however, comments from Waldichuk's data, that the general composition of the inlet floor is mud, silty clay and sand. Organic material has been observed in some locations, notably near the Brockton Point Sewer Outfall. There is a suggestion that the silt may be of Fraser River origin.

In contrast to Burrard Inlet, the physiographic structure of Indian Arm, with its long, narrow shape surrounded by steeply sloping mountain walls identifies it as a typical fjord. The Arm extends 21.5 km from the mouth at station Ind 0 to the head, with a mean width of 1.3 km. A minimum width of 0.5 km is observed off Hamber Island near the mouth, while slightly further north near Raccoon Island a maximum width of 2.2 km is noted. The depth profile along a longitudinal transect near the centre of the fjord is illustrated in Figure 1.2(b) where the significant features which appear are the very shallow sill depth of approximately 25 m near the mouth and the maximum depth of 220 m near the middle of the inlet. The horizontal constriction off Hamber Island, coupled with the presence of a shallow sill in this area suggests a probable physical impedance to circulation and exchange of waters between Burrard Inlet outside and the upper reaches of Indian

Arm towards the head. It will be shown (Chapters 5 and 6) that while such exchange is normally restricted, major large volume exchanges do in fact take place under certain conditions.

Four primary sources of fresh water input to Indian Arm are identified as follows:

(a) the Indian River which enters at the head of the fjord

(b) numerous small peripheral streams which cumulatively account for input from the remainder of the surrounding watershed

(c) the Buntzen Power Houses #1 and #2, through which controlled amounts of fresh water are discharged from Buntzen Lake

(d) direct precipitation.

As mentioned, the significance of the various sources is considered in Section 4.2.

Gilmartin deals in some detail with the distribution of bottom sediments in Indian Arm, and identifies the presence of sands, silts, clays, and some organic material.

1.3 Historical Review

1.3.1 General Review

In presenting an historical review of oceanographic work in Burrard Inlet and Indian Arm, consideration should first be given to three overview works. The first is that of Carter (1934) in which an early summary of physiographic features of British Columbia fjords is given, together with some suggestions concerning the origin of these features. Also presented is a brief description of the distribution of temperature, chlorinity, and nutrient concentration for a number of fjords (including Indian Arm) which open into the Strait of Georgia. In a later work, Pickard (1961) gives a thorough treatment of the oceanographic features of the coastal fjords of British Columbia. He categorizes the various inlets according to their fresh water input and shows how the observed distributions of properties in a given inlet are in large measure explained by the nature and volume of its fresh water input. Indian Arm is identified as a medium runoff inlet, with little or no contribution from glaciers. The physical dimensions of the Arm are slightly smaller than average for fjords of the British Columbia coast. A further paper by Pickard (1975) discusses annual and longer term variations in the properties of deep waters in various southern British Columbia inlets, passages and coastal basins, including Indian Arm. Although a generally regular annual cycle of change was identified for the Arm from a total of 13 years of data, this cycle was shown to be disrupted by occasional large changes, likely attributable to major deep water exchanges.

1.3.2 Burrard Inlet

From 1949 to 1951, a number of oceanographic surveys of the entire Fraser River Estuary were conducted by the Pacific Oceanographic Group for the Vancouver and Districts Joint Sewage and Drainage Board. Included in the resultant data report (Pacific Oceanographic Group, 1951) are temperature, salinity and dissolved oxygen data for a number of stations in Burrard Inlet. Also included in this report are current observations from various depths, and recorded tidal curves from locations surrounding the inlet.

Campbell (1954), in his investigation of lateral circulation in an inlet employed some of these data to generate his plots of average salinity distribution outside First Narrows. These he found to compare favourably with theoretically predicted distributions.

Waldichuk (1965), in his paper dealing with water exchange in Port Moody provides a reasonably thorough treatment of the physical oceanography and circulation of the head waters of Burrard Inlet. His basic emphasis is on that region east of the present station Van 39, a region which is not treated in detail in this thesis.

As noted earlier, the work of Tabata (1971) is the most complete treatment to date. The major observations and conclusions of his work are summarized as follows:

(a) Fresh Water Sources: The drainage area of Indian Arm (including discharge through the two Buntzen Power Houses), the drainage area of Burrard Inlet, and the Fraser River are identified as three significant sources of fresh water. The former two contribute to the establishment of an estuarine circulation pattern. This pattern may be weakened or disrupted by the presence of Fraser River water just outside First Narrows. The effect of direct precipitation in diluting surface salinity is estimated to be approximately 10% that of runoff.

(b) Heat Budget: The balance of physical processes associated with heat is such that "most of the heat energy stored in the inlet during the heating season is released back to the atmosphere during the cooling season".

(c) Tidal Currents: Tidal currents of speeds up to 6 knots are associated with First and Second Narrows: a system of eddies coupled with these currents is identified in the harbour. These "currents are considered as the dominant agency contributing to the mixing of waters in the inlet".

(d) Salinity, Temperature, Oxygen Distribution: The seasonal observation of relatively high surface salinity in winter and relatively low surface salinity in summer is explained in terms of fresh water input cycles. Deeper water salinity varies less over an annual cycle and is considered to be controlled somewhat by mixing processes in the Narrows. Temperature distribution is characterized by a typical summer case and a typical winter case. Distribution of dissolved oxygen is claimed to be coupled closely to biological processes in the inlet. There is a relatively high oxygen content in Burrard Inlet. Annual fluctuations are shown to be small.

(e) Turbidity and Water Quality: Waters in Burrard Inlet are typically very turbid except in early winter near the mouth of Indian Arm. Areas of the system (e.g. the western harbour) do not meet standards of water quality suitable for public bathing: other areas marginally meet these standards.

1.3.3 Indian Arm

Due to its typical fjord nature, and its proximity to Vancouver, Indian Arm has been the site of several biological and physical oceanographic surveys. The most comprehensive treatment of the physical oceanography and circulation of the Arm is given by Gilmartin (1962). His major results concerning circulation in the Arm are now summarized.

(a) Analysis of sediment distribution patterns leads to some suggestions regarding circulation:

- based on progressive sorting of sediments along the fjord in both northerly and southerly directions, two sediment sources (water sources) are identified; the Indian River entering at the head, and intruding waters from Burrard Inlet entering at the mouth.

- based on cross channel distributions, it is suggested that water entering the fjord flows inward along the eastern side while that leaving the fjord flows outward along the western side.

- non-stagnant conditions prevail, indicating a relatively frequent replenishment of deep water.

(b) A basic estuarine circulation is documented with the important controlling features being identified as the cycle of fresh water input, the sill depth and water property (particularly density) distributions outside the sill. Exchange of intermediate and deep water is evident from the property distributions. Superimposed upon the basic estuarine circulation are tidal effects. A tidal jet theory is suggested to explain the presence of narrow tongues of intruded water observed in the near surface layer between depths of about 20 m and 40 m. Tidal mixing in the narrow, shallow channel off Hamber Island is considered to be of significance in determining the circulation pattern.

A number of biological researchers besides Gilmartin, notably McHardy (1961), Shan (1962), Regan (1968), and Whitfield (1974) have also monitored physical parameters as part of their surveys. In each case, their physical data clearly show the evidence of mid-winter intrusions of dense water into the Arm. Some such changes are seen to be vertically confined within the water column, while others are evidenced even in the deepest bottom water.

The mechanism of deep water exchange has been investigated in other fjords. Lazier (1963) has suggested a tidal jet mechanism for shallow-silled fjords. The behaviour of the jet water, once across the sill is determined by its density. Deep water replenishment can occur when the intruding water is of sufficient density to displace upward the indigenous bottom water. More recently, Lafond (1975) has monitored frequent intermediate and deep water intrusions into Sutil channel and Bute Inlet over a two-year period. Intrusions occurred when water at sill depths outside the inlet became more dense than corresponding water inside. Using property budget methods, Lafond has estimated the volume of these intrusions and suggested possible magnitudes for the associated currents.

CHAPTER 2 DATA COLLECTION AND REDUCTION

2.1 The Field Program

Throughout the period May 14, 1974 to October 16, 1975 a total of 27 oceanographic cruises were undertaken to collect data for this survey. These cruises ranged in length from 7 hours to 4 days, with a typical excursion being of 1 to 2 days duration. Table 2.1 is presented as a summary of cruises. It is seen from the time information in columns 2 and 3 that apart from two 6-week gaps, the cruises were separated generally by 3 to 4 weeks. The summer sampling program was not significantly more intense than that conducted in the winter months.

Ship time was provided by the Canadian Hydrographic Service on Canadian Survey Ships VECTOR, PARIZEAU, and RICHARDSON and the Motor Vessel PANDORA II, and by the Defence Research Board on Canadian Forces Auxilliary Vessels LAYMORE and ENDEAVOUR.

The geographic distribution of sampling stations is illustrated in Figure 1.1(b). Stations Van 11, 14, 17, 24, 27, 34, 39 and Ind 0, 1, 1.5, 2 were selected as "main line" stations (station Van 14-8 was added to this group commencing with Cruise 74/31). It was attempted to occupy each of these principal stations at least once per cruise. Two supplementary sets of stations were also established: these were sampled less regularly in conjunction with the main line. The first auxilliary set, in the area outside First Narrows, included stations Van 11-8, 11-5, 11-1, 14-10, 14-5, 14-2, 17-8 and 17-5. The second set, which provided more intensive spatial coverage in Indian Arm, included stations Ind 1.3, 2.5, 2.8 and 3. A summary of stations sampled on each

TABLE 2.1

SUMMARY OF CRUISES

1	2	3	4	5	6	7
CRUISE #	DATES	DAYS SINCE LAST CRUISE	NUMBER OF STATIONS			COMMENTS
			MAIN (1) LINE	APPROACHES (2)	IND ARM (3)	STN (#=TIMES SAMPLED) (X=NOT SAMPLED)
74/17	14 May	-	11	-	-	
74/19	25 Jun	42	14	-	-	14(2), 24(2), 34(2),
74/24	17 Jul	22	18	-	-	14(2), 17(2), 24(2), 27(3), 34(3)
74/26	31 Jul - 1 Aug	14	20	9	-	11(2), 14(2), 17(2), 24(4), 27(4)
74/28	27 Aug - 29 Aug	26	23	9	2	11(2), 14(2), 17(6), 24(6)
74/29A	9 Sep	13	8	-	-	11(X), 1.5(X), 2(X)
74/29C	11 Sep	2	10	-	1	1.5(X)
74/31	26 Sep	15	12	-	-	Commenced 14-8 as main line
74/32	16 Oct	20	12	-	2	
74/34	7 Nov	22	12	-	3	
74/35	25 Nov	18	12	-	-	
74/36	5 Dec	10	11	-	2	27(X) Current meter deployed
75/01	3 Jan	29	9	-	-	27(X), 39(X), 1.5(X)
75/03	23 Jan	20	12	-	2	Current meter serviced
75/05	19 Feb	27	11	-	2	14-8(X)
75/06	22 Feb	3	4	8	-	Sampling outside First Narrows only
75/08	7 Mar	13	12	-	-	Current meter recovered
75/11	26 Mar	19	12	-	2	
75/13	29 Apr	34	12	-	2	
75/18	30 May	31	12	8	-	
75/20	13 Jun	14	12	8	-	
75/25	24 Jul - 25 Jul	41	16	8	-	11(2), 14(2), 14-8(2), 17(2)
75/27	18 Aug - 19 Aug	25	16	8	2	11(2), 14(2), 14-8(2), 17(2)
75/28	25 Aug - 28 Aug	7	61	28	-	CSTD casts only
75/29	2 Sep - 3 Sep	8	16	8		11(2), 14(2), 14-8(2), 17(2)
75/31	9 Oct - 10 Oct	37	16	8	-	11(2), 14(2), 14-8(2), 17(2)
75/32	16 Oct	7	12	-	-	

(1) Main line, includes 12 stations; 8 in Burrard Inlet, 4 in Indian Arm

(2) First auxilliary set; includes 8 stations

(3) Second auxilliary set; includes 4 stations

cruise is provided in Table 2.1, columns 4 to 7. On some cruises, particular main line stations were repeated. On others, some such stations were excluded entirely. A documentation of these anomalies in the sampling program is presented in column 7. Repeated samplings of a particular station are indicated by the station number, followed in brackets by the number of repetitions. Main line stations not sampled on a given cruise are indicated by the station number followed in brackets by the letter "x". It is observed that the only significant loss of main line station data occurred on Cruise 75/01, January 3, 1975 when 3 stations were missed. The information in columns 5 and 6 indicates the degree of secondary sampling which was conducted on each cruise.

To supplement the information gathered in the property sampling program a recording current meter was deployed on the Indian Arm sill (0.5 km southwest of Raccoon Island) on December 5, 1974 and recovered March 7, 1975. Current speed and direction for waters within 3 m of the bottom at a time of major exchange is provided by the resultant 93 day record.

A second supplementary program was undertaken on Cruise 75/28, from August 25 to 28, 1975, to monitor changes in the distribution of temperature and salinity over periods of a few hours, and thereby to assess the short term effect of tides on the property distributions. Conductivity - salinity - temperature - depth (CSTD) casts to 30 m depth were taken repetitively at various groups of 2 to 4 stations on the different days of this survey. In addition, on several regular cruises, short time-series surveys were taken at stations Van 11, 17 and 24. The time interval between casts for these assorted serial measurements varied from 15 minutes to nearly 2 hours. The analysis of these data to assess tidal influence is presented in Chapter 3.

2.2 Instruments and Methods

At each oceanographic station occupied, a series of parameters were recorded. These included:

(a) Meteorological parameters:

- wind speed and direction
- barometric pressure
- wet and dry bulb air temperature
- cloud type and cover

(b) Oceanographic parameters:

- wave height (visual estimate)
- secchi disk depth
- vertical distribution of temperature
- vertical distribution of salinity
- vertical distribution of dissolved oxygen (at selected stations).

The basic oceanographic program consisted of sampling temperature, salinity and oxygen concentration at discrete depths, as indicated in Figure 1.2. Water samples were collected in plastic N.I.O. bottles of approximately 1.3 litre capacity. Temperatures were determined to an estimated accuracy of ±0.02^{o}C using Yoshino Keike reversing thermometers mounted on the N.I.O. bottles. Salinity determination was made ashore using an Autolab (inductively coupled) Salinometer. The quoted uncertainties for this instrument are ±0.003^{o}/oo above 28.0^{o}/oo and ±0.02^{o}/oo below this level. Dissolved oxygen determination was done aboard ship by the Winkler titration method. These oxygen values are assumed to be accurate to within approximately ±0.05 ml/l. Surface temperature and salinity samples were taken from a surface bucket. No oxygen samples were taken at the surface. From the temperature and salinity data, values of σ_t were computed using the Knudsen (1901) formula.

Supplementary temperature information was collected from the commencement of the survey until Cruise 75/20, June 13, 1975, using bathythermographs to depths of 30 m (BT#13099) or 60 m (BT#10065). After this time, an InterOcean 513 CSTD profiling system was used, supplementing both temperature and salinity data to a maximum depth of 30 m.

The current meter employed was an Aanderaa RCM4, with temperature, conductivity and pressure sensors attached. Manufacturers' specifications for this instrument quote accuracies of ±1 cm/s in speed above a threshhold value of 1.5 cm/s, ±7.5^{o} in direction for extreme speeds, ±5^{o} in direction for mid-range speeds, ±0.15^{o}C in temperature, and ±1% of range in pressure. No accuracy is quoted for conductivity although a resolution of 0.1% of range is stated. This type of meter records the total revolutions of its Savonious Rotor over the sample period to generate an estimate of average speed. Direction is sampled only at one discrete time during the sample interval. For this installation, a sample period of 15 minutes was chosen. The current meter mooring consisted of a concrete anchor, an acoustic release package, the meter itself, and a subsurface flotation pontoon. With the system deployed in nearly 40 m of water, the meter was suspended approximately 3 m from the bottom.

2.3 Secondary Data Sources

Meteorological and runoff data were acquired from a number of sources. Air temperature and precipitation data from stations surrounding the study area were taken from the Monthly Record of Meteorological Observations in Canada, published by the Atmospheric Environment Service, (A.E.S.). Detailed wind data were made available by the Pacific Weather Centre of A.E.S. Runoff figures for the Fraser and Seymour Rivers were obtained from the Water Survey of Canada, Inland Waters Directorate. Outflow statistics from the Capilano reservoir plus consumption figures from the City of Vancouver were provided by the Greater Vancouver Water District. The difference in these two figures is the net discharge from the Capilano River. The British Columbia Hydro and Power Authority made available estimates of discharge through the two Buntzen power houses into Indian Arm.

Two secondary sources of temperature and salinity data are known to exist. Though these data were not extensively employed in the present study, their availability is indicated for completeness. The Pacific Environment Institute of the Department of Fisheries and the Environment, located on the North Shore between Cypress and Godman

Creeks, has in the past maintained an intermittent program of temperature and salinity sampling for its sea water intake system. Some data records exist for times concurrent with this survey. Since early 1977, a more systematic sampling program has been undertaken and should provide good quality time-series data for further Burrard Inlet Studies.

The Vancouver Public Aquarium also maintains a sea water intake system. The intake housing, which extends 3 m above the sea floor, is located in First Narrows approximately 365 m northwest of the Lumberman's Arch pool. At lowest low tide, water depth at the housing is 9.1 m, placing the intake at a depth of 6.1 m in the water column. Daily at approximately 0800 hrs the temperature and salinity of the water at the Aquarium end of the intake system are recorded. This water has passed from the intake, through a pumping station at Lumberman's Arch, and to the Aquarium. It has been in the system for approximately one hour when the measurements are made. Long time-series records of these data are available through the Aquarium's engineering reports.

2.4 Data Reduction Techniques

Much of the data reduction and plotting has been accomplished with the use of the IBM 370/168 computer and Calcomp plotter system. Associated with the use of these machines are some difficulties which do not arise with the conventional hand plotting of data.

A computerized contouring program was employed to prepare the vertical sections through Indian Arm and the time-depth sections later presented in Chapters 3 and 5. The format of these programs required that the property data which, when collected, were irregularly distributed in the vertical, be interpolated to generate values at a series of regularly spaced depths. A basic interpolation routine developed by Rattray (1962), specifically for use with oceanographic data, was employed to calculate values of the scalar properties at desired interpolation depths below the depth of the first bottle sample. This routine estimates the interpolated value by evaluating and averaging two parabolic Lagrange Polynomials, each of which uses three sample points (one above and two below, or two above and one below the interpolation depth). Error analysis performed by Rattray and amplified by Reiniger and Ross (1968) indicated the acceptability of this procedure away from regions of strong gradient.

The method demonstrated by Reiniger and Ross to improve the Rattray procedure in regions of strong gradient still demands at least three (preferably four) sample points. In the present data, the greatest changes consistently are observed between the surface and the depth of the first bottle sample (2 or 5 m). Thus, insufficient data points are available to justify the use of this modification for the near-surface interpolations. Consequently, a simple linear scheme was used to interpolate between the surface and the depth of the first bottle. Below this depth the unmodified Rattray scheme was employed.

A second phase of data reduction which required computer assistance was preparation of the CSTD data. Output from the InterOcean CSTD is in the form of analogue profiles of temperature, conductivity and salinity versus depth. The salinity is calculated internally from measured conductivity and from a compensating temperature measured by a second thermistor (additional to the primary temperature sensing thermistor).

As an initial step in analysis of the CSTD records, a comparison was made between the internally calculated salinity profile, the salinity profile calculated externally using conductivity and primary temperature, and the salinity determined from bottle samples taken approximately 15 minutes prior to the CSTD cast. Salinity as calculated by the internal circuitry was observed to be consistently lower by 2 to $3^{0}/oo$ than salinity calculated externally. Agreement between the external values and the salinities measured from bottle samples was observed to be typically within $0.5^{0}/oo$.

Subsequent work performed on the instrument by J. Stronach (personal communication) identified two factors which cumulatively are the probable cause of the inaccuracy in the internal salinity determination. The instrument employs two sets of circuitry for salinity calculation; one for salinities less than $20^{0}/oo$ and the other for higher values. Gain adjustments during the period of instrument use for this survey were such that the computed salinities do not match at $20^{0}/oo$. For salinities below this value (typically to about 6 m depth) the internally calculated values lag the true salinity by varying amounts, up to $1.5^{0}/oo$. Secondly, an overall time lag effect is thought to exist in the thermistor used to measure compensating temperature for the internal salinity calculation. At any given depth, salinity is thus being calculated using the correct conductivity, but using a temperature appropriate to a lesser depth. Since temperature in general decreases with depth (especially during the months when this instrument was used), the resultant effect is to calculate a salinity which is too low. The superposition of these two effects is seen as an explanation for the observed behaviour of internally calculated salinity. It was thus chosen to disregard all recorded salinity data, and to perform an external salinity calculation from the recorded profiles of conductivity and temperature.

This process necessitated the mechanical digitization of all temperature and conductivity profiles. By interpolating these digitized traces to a consistent series of depths, it was possible to reconstruct the salinity profiles. The agreement of salinities thus calculated with salinities determined from bottle samples proved to be consistently better than $0.5^{o}/oo$ for more than 100 profiles. This set of salinity data was employed in generating the short time-scale time-depth sections discussed in Chapter 3.

2.5 Resultant Data Base

A summary is now presented to indicate briefly the total scope of the data set compiled during this study. All data collected at bottle stations have been published in Data Reports #37, 1974 and #41, 1975, of the Institute of Oceanography of the University of British Columbia. All secondary data are maintained on file at that Institute.

During the 18-month field program, some 560 oceanographic stations were occupied. At 430 of these, temperature and salinity were determined at a series of discrete depths while at approximately 200, the concentration of dissolved oxygen was determined as well. Virtually all of those 430 stations were supplemented with either bathythermograph or CSTD casts. In addition, 130 CSTD casts were made at other times and locations. A 93-day record of near-bottom currents over the Indian Arm sill was collected, along with temperature and salinity records at the current meter location. The following chapters are a presentation and discussion of this data base.

CHAPTER 3 SHORT PERIOD TIDAL FLUCTUATIONS IN PROPERTY DISTRIBUTIONS

3.1 General Description of Tides

The general nature of tides in the Burrard Inlet system has been examined by both Waldichuk (1964) and Tabata (1971). In summary, tides in this region are described as mixed, implying the presence of both semi-diurnal and diurnal constituents. A large diurnal inequality in the heights of successive lows and successive highs is observed as a consequence of the declinational effect of the moon. This inequality is most pronounced when the moon attains its maximum declination and is minimized as the moon passes the equatorial position. Mean tidal ranges in Burrard Inlet are about 3 m, while extreme ranges are 4.8 m. These ranges are effectively the same throughout the inlet.

In contrast to the case of deep fjords where tidal extrema occur almost simultaneously at both mouth and head, there is an approximately 25 minute lag between extrema at Point Atkinson and at Port Moody. This effect is most probably a consequence of the relative shallowness of Burrard Inlet, and may reflect some effect due to the narrow channels at First Narrows, Second Narrows, and Burn's Point. Also resultant from these physical constrictions are tidal currents which at times reach maximum speeds near 6 knots on both flood and ebb through the narrows. Turbulent mixing associated with these strong tidal currents is a principal mechanism affecting the distribution of scalar properties at least at those stations nearest the narrows (Tabata, 1971).

3.2 Reference Tidal Curves

Prior to commencing a treatment of actual results, it is necessary to describe the way in which tidal data have been documented for the present program. Two empirical, 25-hour tidal curves, representative of the typical tidal curves for Burrard Inlet, are presented in Figure 3.1. Any actual tidal situation observed in Burrard Inlet during the survey can be approximated by one of these curves. Each curve has been subdivided, as shown, into 12 equal bins of length 2.08 hours. With each bottle cast or CSTD cast has been associated the bin number representative of the actual tidal condition at the time of the cast. Where pertinent in the following chapters, these bin numbers have been quoted with the graphically presented data. Figure 3.1 can thus be used in conjunction with further figures to determine the phase of the tide to within about 1 hour for any given cast.

3.3 Fluctuations at Periods Less Than 12 Hours

Data taken during the CSTD survey on Cruise 75/28, in the week of August 25, 1975, have allowed the preparation of time-depth sections of temperature and salinity for stations Van 11-1, 11, 11-5, 11-8, 17, 24, 27, 34 and Ind 0 (station locations are identified in Figure 1.1(b)). An analysis of these sections (presented as Figures 3.2 through 3.5 and 3.7 through 3.11) is now undertaken to determine the typical magnitudes of short period tidal fluctuations in the distributions of temperature and salinity.

To interpret correctly the features observed on these sections, some statement of instrument precision must be made. Inspection of pairs of CSTD profiles taken at fixed sites less than 3 minutes apart, has provided an estimate of the instrument's capability to reproduce vertical structure. On average, the depth at which a given temperature or conductivity is recorded may be expected to fluctuate over approximately a 1 m interval on repetitive casts. In terms of the time-depth sections this implies that vertical excursions up to the order of 1 m for a particular contour line may be an artifact of instrument performance. Thus, in considering these sections, only vertical fluctuations exceeding 1 - 2 m are considered to be real manifestations of short-term tidal flow or wind mixing phenomena.

The various time-depth sections have been grouped geographically by station. The basic features of each group of sections are now discussed.

3.3.1 Stations Van 11-1, Van 11, Van 11-5, Van 11-8 (Figures 3.2 through 3.5)

Tidal bin information for these sections is presented along the top axis of each figure. Each identified point represents a specific CSTD cast. Time information is given along the bottom axis.

The tidal cycle represented by bins 18 through 22 is seen from Figure 3.1 to include the final stages of flood from low low water to low high water followed by the full period of ebb from low high water to high low water. Over this portion of a full tidal cycle, the series of sections from stations at the harbour mouth show rather minimal changes in the vertical distribution of salinity and temperature. During the latter stages of the flood (bins 18 and 19), to the time of high water at 1005 h PST, the only evident measureable change takes place at station Van 11-1. Here, to a depth of 8 m, a minor deepening of the contours of both salinity and temperature is indicative of the introduction of slightly warmer, less saline water near the surface.

As the ebb develops, an apparent flow of warmer, less saline water in the top 2 to 3 m is suggested at all stations. Although no explicit directional information is available from a single transverse section, the tidal phase implies this to be a westward flowing surface layer, and the distributions (Figures 3.2 through 3.5) indicate that the flow spans effectively the entire width of the harbour mouth. Typical changes at the surface over a period of 3 to 4 hours are seen to be about $1^{o}/oo$ in salinity and about $0.5^{o}C$ in temperature. An extreme change of greater than $3^{o}/oo$ in salinity is observed at station Van 11-5. At the time of high low water (bin 22) there is a relaxation of the presumed westward flow, as evidenced by increases in surface salinity and corresponding decreases in surface temperature.

Below this shallow surface layer there are obvious differences in the property structure at the different stations. While short-term changes in structure are small at all four stations, these changes too are seen to vary along the transverse section. To the north, near Point Atkinson, station Van 11-1 (Figure 3.2) shows a sharp halocline and moderate thermocline at 3 to 4 m. Extending downward to 15 m from the base of this pycnocline region is a layer in which there is no evidence of significant change in the property distributions over the 6 hour observation period, likely implying only minimal motion at this level. Even at depths greater than 15 m, the only observed change is an intrusion of slightly more dense waters near the time of low tide. Approximately 0.8 km to the south, station Van 11 (Figure 3.3) shows a definite halocline and moderate thermocline in the region from 2 to 5 m. Although absolute differences of approximately $7^{0}/oo$ in salinity and $1.5^{0}C$ in temperature are similar to those across the pycnocline at Van 11-1, the vertical gradients at Van 11 are obviously weaker. Again at this station at depths greater than about 3 m, temporal changes in the property distributions are considered insignificant, with again the likely implication of minimal motion. The possibility is to be noted, however, that these periods of marginal change could also result in the presence of significant motion, if the properties of the advected waters were similar to those of previously resident waters. The increase in density near 18 m observed at slack water at Van 11-1 is not in evidence here.

Further to the south, stations Van 11-5 and Van 11-8 (Figures 3.4 and 3.5) show a considerably weaker pycnocline, with vertical gradients at any particular time being evenly distributed through the upper 10 m. A significant difference in temporal behaviour is noted from the two more northerly stations. Generally, throughout the entire ebb, a gradual deepening of the contours of both salinity and temperature is observed at stations Van 11-5 and 11-8. These changes are most marked at depths exceeding 10 m, where the $29^{0}/oo$ isohaline and the $10^{0}C$ isotherm are representative, but are evidenced nearer to the surface as well. This behaviour is most probably indicative of a flow of marginally warmer, less saline water at all depths. As with the earlier observed changes at the surface, a probable explanation is the advection of waters previously resident to the east of the harbour entrance.

This same situation is illustrated by the series of profiles taken in the outer harbour on July 25, 1975, and presented in Figure 3.6. These profiles are presented in pairs, one from a station on the north-south transverse section at longitude 123°13.3'W through the central portion of the outer harbour, and its counterpart from the harbour mouth transverse section at longitude 123°15.8'W. As seen from the inset tidal curve, a period of ebb is again represented. Consideration of the top few metres shows comparatively warmer, fresher water at the more easterly station of each pair except in the shallowest 3 m along the north shore (stations Van 11-1 and 14-2) where the differences are small. On an ebbing tide such a distribution would be expected to yield the behaviour earlier noted in Figures 3.4 and 3.5.

A final feature of interest at station 11-5 (shown in Figure 3.4) is the upward turning of the contours at depths shallower than about 7 m at approximately 1330 h PST, and the subsequent downward turning one hour later. As no such feature is observed elsewhere, this is considered to be a small localized intrusion of cool saline water.

In summary then, on an ebbing tide, an approximately 3 m thick surface layer is identified and is considered to have a westward component of flow across the full extent of the transverse section. Along the northern side there appears to be only minimal if any tidal flow immediately below this layer. Near 18 m a possible flow of cooler, more saline water is noted near the shore. Near mid-channel and further to the south, a potential ebb flow extending to at least 20 m depth is observed. Such behaviour is consistent with the phenomenon of a relatively narrow surface tidal jet which is known to develop along the north shore on the ebb. The present data suggest that this flow must be very shallow as well as narrow. This is to be contrasted with the broader, deeper, ebb flow which is inferred through the central and southern portions of the harbour mouth.

3.3.2 <u>Stations Van 17, Van 24 (Figures 3.7 and 3.8)</u>

Consideration is now given to the pair of stations spanning First Narrows (see Figure 1.1(b)). The tidal phase (see Figure 3.1) represented by bins 19 through 13 on Figures 3.7 and 3.8 is an ebb from low high water to high low water, followed by a flood from high low water to high high water. The time of high low water was 1355 h PST.

Two general features of the property distributions at these stations are briefly described prior to considering temporal changes in these distributions. Firstly, it is noted that at any given time, a pycnocline exists within 6 m of the surface at station Van 17, while such structure is never well defined at station Van 24. Secondly, the ranges of temperature and salinity observed outside the narrows constantly exceed the ranges observed inside. Both phenomena are resultant mainly from the considerable mixing which takes place as water passes through the narrows. A simple calculation can be undertaken to show that water observed at least at depths less than sill depth at Van 24 must recently have been mixed, on passing either through First or Second Narrows. Assuming the development of tidal currents to be sinusoidal following slack water, and using an estimated maximum speed (Canadian Tide and Current Tables, Volume 5, 1975) of 1.25 m/sec it is found that displacements of a water particle exceed 8.5 km within 3 hours. As the distance from Van 24 to First Narrows is 3.0 km and that to

Second Narrows is 5.0 km, it can be assumed that the suggested mixing of waters by passage through the narrows does in fact take place. Thus, at Van 24, only relatively weak stratification is ever in evidence. Extremes of salinity and temperature are modified as homogeneity is approached through mixing, thus reducing the range of property values observed inside the narrows.

The temporal changes in property distributions illustrated in Figures 3.7 and 3.8 are best explained by considering changes in a number of individual layers at each station. Throughout the full ebb-flood cycle at station Van 17, the top 2 to 3 m of the water column show evidence of basically non-mixed tidal flow. Within two hours of the turn to ebb at 0820 h PST, surface water at Van 17 exhibits the same properties as those of surface water earlier observed at Van 24. The trend toward cooler temperatures and higher salinities at Van 17 continues through the ebb, but reverses within a few minutes of the turn to flood at 1355 h PST. The influence of warmer, fresher water having properties such as are normally found west of Van 17 in the outer harbour, is soon observed. Lying between approximately 3 m and 6 m is a layer in which changes are not as readily described in terms of the tide. The gradual deepening of contours for about 3 hours following the commencement of the flood at 1400 h PST can be ascribed to the expected flow of warmer, fresher water as noted at the surface. However, the warming and freshening observed at Van 17 following 0930 h PST is not directly consistent with the expected effects of an ebb flow. Such behaviour could possibly be explained by extensive downward mixing of surface waters. Of particular interest in the layer below 6 m is the large vertical fluctuation observed in the $28^{o}/oo$ isohaline and in the $10.5^{o}C$ isotherm, centred at 1400 h PST. Water having such properties is seen from Figure 3.8 to reside at 15 to 18 m depth inside the narrows. The structure of the contours at Van 17 indicates that water from at least this depth has moved on the ebb through the narrows, with a sill depth of 14 m, and is now found at depths as shallow as 5 m. This water could in fact have originated below 18 m inside the narrows, and have been modified through mixing to acquire its properties as observed at Van 17. It is likely that the contribution of these deeper waters from Van 24, to flow through the narrows, is minimal in the early stages of the ebb. As the ebb progresses (say after 1100 h PST) water from greater and greater depths is entrained into the flow until a well developed flow of deeper water has been established near full ebb, at approximately 1145 h PST. At depths greater than about 12 m at Van 17, minimal changes are observed in the 29^{o}/oo isohaline and in the 10^{o}C isotherm. It is not expected that this water is significantly influenced by tidal outflow from the narrows, as water having these properties is found only below about 25 m in the vicinity of Van 24 and is not expected to be exchanged over a single tidal cycle. It thus appears from the present data that significant tidal effects at Van 17 are confined to the upper 10 to 12 m of the water column.

Again at station Van 24 (Figure 3.8) the behaviour of the upper 2 to 3 m is observed to be different from that of underlying waters. On the ebb, westward flowing surface waters from the vicinity of Second Narrows appear at Van 24 as higher salinities and slightly lower temperatures. As the flood develops, near-surface waters passing through First Narrows cause a reversal to lower salinities and higher temperatures. In the range of 3 to 10 m at this station, very little change is observed in the property distributions over a 10-hour period. At depths greater than 10 m a gradual, uniform deepening of the contours is observed through the period of ebb, followed by a comparable upturning of the contours on the flood. Such behaviour is evidence of slightly warmer fresher waters flowing westward from near Second Narrows on the ebb, and of inflow of colder more saline waters which are resident outside First Narrows at these depths during the flood. These must both be mixed with shallow waters during their flow through the Narrows, to produce the observed distributions. Thus, the properties of the mid-depth layer are actually determined by mixing, even though they are little changed during the tidal cycle. In general, it is noted that fluctuations due to tidal flow are observable to at least 20 m depth at Van 24 in contrast to the earlier identified limit of about 10 m at Van 17.

3.3.3 Stations Van 27, Van 34, Ind 0 (Figures 3.9, 3.10, 3.11)

Sections from two stations spanning Second Narrows and a third at the mouth of Indian Arm are now discussed. Again, the time interval considered is that of an ebbing tide, with the high at 0905 h PST, and the subsequent low at 1430 h PST. The earlier identified trend toward weaker stratification persists in passing eastward through Second Narrows and on to Indian Arm.

At Van 27, a distribution similar to that at Van 24 is shown (Figure 3.9). However, at Van 27, surface waters observed one day later than those at Van 24 are seen to be slightly more dense while waters at depths exceeding 12 m are marginally less dense. On an ebbing tide, the changes in the property distribution at this site are the reverse of those observed at Van 24. While earlier, a gradual downturning of the contours was noted, in this instance there exists a definite upwards trend, implying a source of cooler, more saline water. Inspection of profiles not here presented determines that salinities in excess of $26.8^{o}/oo$ and temperatures less than $12.0^{o}C$ are not to be found at any depth at Van 34. Thus, waters passing westward through Second Narrows cannot account for the observed behaviour at depths greater than about 6 m. A potential explanation can be derived from consideration of the Canadian Hydrographic Service publication "Atlas of Tidal Current Charts, Vancouver Harbour, 1973". Studies of surface currents have identified persistent eddies in the central harbour. On the latter stages of an ebbing tide, a pronounced cyclonic (anticlockwise) eddy is know to develop near Second Narrows, to the south of mid-channel. Such a feature, were it to extend vertically to 20 m depth, could provide more saline waters from further to the west, and thus explain the upward turning of contours identified at Van 27. Changes in the upper 3 to 5 m are so small that no definite statement can realistically be made as to the source of these waters, whether they be resultant from ebb flow through Second Narrows or whether they be associated with an eddy structure in the central harbour.

Through Second Narrows, at station Van 34, irregular variations are identified in the temperature section, and to a lesser extent in the salinity section (Figure 3.10). Such variability is no doubt associated with the turbulent flow so frequently experienced in occupying this station. By the presence of warmer fresher water at depths exceeding 10 m, and by the lack of vertical structure, it can be assumed that the effects of mixing in water entering from outside the Narrows must be large. Also of significance is the observed deepening of the 12^{o} isotherm after 0930 h PST, as warm waters flow westward on the ebbing tide.

Finally, at Ind 0 (Figure 3.11) tidal effects are seen to be almost insignificant. Near low water, a slight decrease in salinity and corresponding increase in temperature is noted at the surface, however, at depths greater than 2 m the distribution of properties remains unchanged through the ebb.

3.3.4 Station Van 11 (Figures 3.12 and 3.13)

On August 19, 1975 and again on September 3, 1975 a series of CSTD casts spaced at 15 minute intervals were taken at station Van 11. On both occasions, the sampling extended over approximately 4 hours through the same phase of the tidal cycle from about 2 hours following low tide i.e. most of the flood through high high water and the commencement of the subsequent ebb. Time-depth sections prepared from these casts are presented as Figures 3.12 and 3.13.

Of significance in each instance, is the indication of the brief passage of a dense water mass in the top few metres. At 3 m depth, salinity increases in excess of 3^{o}/oo and temperature decreases near 2^{o}C were observed to take place in less than half an hour. Within approximately 1 hour the disturbance had passed and salinities and temperatures had returned to near their earlier values. Given the flooding condition of the tide, it is expected that such observations may be evidence of Howe Sound surface water being advected around Point

Atkinson. No actual observations were made west of Van 11 during the course of this study which could be used as verification of this hypothesis.

3.4 Summary

Tidal influences over a period of moderate ebb have now been investigated throughout Burrard Inlet. In general, probable evidence of tidal flow has been identified in the property distributions to 3 m depth at all stations. Below this shallow surface layer, various situations have been described. At the harbour mouth, differences were noted along a north south transect, with evidence of flow at greater depths nearer the south shore. Immediately outside First Narrows, at Van 17, tidal influences appeared to extend only to 10 m while off Burnaby Shoal at Van 24, small changes were identified to at least 20 m. Station Van 27 showed potential evidence of an eddy associated with the ebb, while inside Second Narrows irregular fluctuations were observed at Van 34. Finally at the mouth of Indian Arm, salinity and temperature fluctuations were insignificant.

There remains much scope for further study of tidal influences in these regions, however, it is suggested that the present analysis has been sufficient to illustrate the basic nature of these influences, i.e. that they are small. It will hereafter be shown (Chapter 5) that seasonal fluctuations in the distributions of properties are of considerably greater magnitude than are the changes described in this chapter. On this basis it will be assumed in subsequent chapters that at depths greater than 3 m, seasonal distributions of salinity and temperature can be discussed and compared without particular concern for the phase of the tide at the time the distributions were sampled.

CHAPTER 4 ANCILLIARY INFORMATION

4.1 Meteorological Parameters

4.1.1 Precipitation

The annual cycle of precipitation on the watersheds surrounding Burrard Inlet is an important factor in determining the cycle of fresh water input to the inlet through river discharge, which in turn partially determines the distribution of salinity. To identify the basic precipitation patterns, four stations in the vicinity of Burrard Inlet have been examined. These include:

a) Buntzen Lake - located approximately 3.7 km southeast of the Buntzen power houses which are located on the eastern shores of Indian Arm, between stations Ind 1.5 and Ind 2.

b) Port Moody Gulf Refinery - located within a few hundred metres of Burrard Inlet, on the south shore approximately 1 km east of station Van 39.

c) Point Grey (UBC) - located on Point Grey within 2 km of the inlet.

d) Vancouver International Airport - located 7.5 km south southeast of the southern harbour-mouth station, station Van 11-8.

Total monthly precipitation values for these four stations are presented in Figure 4.1(a), for the period May 1974 to October 1975.

At all stations, similar annual cycles were observed. Annual precipitation maxima for 1974 occurred in December at three stations, with the November total at the airport station marginally surpassing the December value. Extreme maxima for the entire period occurred in October 1975 at all stations. Annual minima occurred in August 1974 and in July 1975. A particularly wet summer month was experienced each year, with totals in July 1974 being substantially higher than in either June or August, and August 1975 similarly recording much higher totals than June, July or September.

While the patterns observed at all four stations were similar, absolute precipitation totals varied considerably. Without exception, maximum monthly precipitation was recorded at Buntzen Lake, followed by the Port Moody Gulf Refinery. The Point Grey and Vancouver International Airport totals were very nearly the same, and were consistently less than those at Port Moody. Differences between stations were greatest during months of high precipitation, and were observed in October 1975 to be greater than 400 mm. In summer periods of low precipitation, such as in August 1974, values at all four stations were equivalent to within a few millimetres.

4.1.2 Air Temperature

Because of its close relationship to sea surface temperature, the seasonal distribution of air temperature at stations surrounding Burrard Inlet is considered. In Figure 4.1(b) are presented monthly mean air temperatures for meteorological stations at Buntzen Lake, the Port Moody Gulf Refinery, Point Grey (UBC), and the Vancouver International Airport. Similar patterns were observed at all stations with winter minima of about $2^{o}C$ occurring in January and February and summer maxima of about

$18^{o}C$ occurring in July or August. The depressions noted in the temperature curves in July 1974 and in August 1975 agree well with the corresponding periods of higher precipitation earlier noted for these months. Absolute differences between stations in any given month were less than $2^{o}C$ and at least in the case of winter temperatures at Buntzen Lake can possibly be ascribed to altitude. The reason for observance of high values in summer at the Port Moody Gulf Refinery may be its position further inland than the Point Grey and Airport stations, and its lower altitude than the Buntzen Lake site.

4.1.3 Winds

It is necessary to consider winds in the region of Burrard Inlet with respect to their effects on surface layer transport and on vertical mixing. Tabata (1971) has noted that due to local topography, winds in the Burrard Inlet area are predominantly oriented in the east-west direction. Diurnal winds are identified, typically blowing from the east at night and shifting to the west in early morning. Winds are generally light with monthly maxima seldom exceeding 25 km/hr in summer, and only occasionally reaching 35 km/hr in fall and winter.

In general, the direction records for those few time-series of winds available for the present study period are not considered to be of particularly good quality (personal communication - Pacific Weather Service, AES) likely due to localized topographic effects at the measurement sites, (only the Vancouver International Airport direction data are considered to have been accurately recorded). Assuming a basic east-west orientation as earlier commented, wind speed information for the Burrard Inlet area is presented in Figure 4.2. In Figure 4.2(a), 18-month records of monthly mean speeds are plotted for the Point Atkinson, and Vancouver International Airport stations. Two partial records are presented as well. The first record, of four months duration from May 1974, is from the First Narrows marine traffic control station located at the apex of the Lion's Gate Bridge. This station was abandoned in August 1974. The final record is from a station located on the jetty of the Jericho Yacht Club, which reported through the period March to September 1975. The more exposed stations reported mean monthly speeds mainly ranging between 10 and 18 km/hr, and reaching maximum values during December. Jericho, somewhat sheltered along the south shore of the approaches, typically registered the lowest speeds, while Point Atkinson in its exposed position at the northwestern harbour entrance generally recorded the greatest speeds. No time-series data are available from a station representative of Indian Arm. It can be noted, however, that during the 25 cruises which entered the arm, winds were most frequently calm or light, and in fact were recorded in excess of 35 km/hr on only two occasions. The maximum winds recorded on board ship during the study were 63 km/hr from the east at station Van 11, October 16, 1975.

Figure 4.2(b) is presented to illustrate the variability of wind speeds at the airport station over the duration of the study. The trend to higher wind speeds in the period December through March is noted. Most importantly, however, it is noted that winds in excess of 25 km/hr were infrequent and when observed, lasted only for the period of a few hours.

From these historical data, and from observations made in collecting considerable data aboard ship in Burrard Inlet, it is suggested that much of the time, winds play only a minor role in determining the distribution of properties and the circulation of Burrard Inlet and Indian Arm. The transport of surface waters is expected to be dominated by tidal currents rather than by winds. Vertical mixing as well is expected to be controlled more by tidal and estuarine than by wind driven mechanism. In the presence of occasional strong winds, wind mixing and wind driven transport will be of significance near the surface but only for brief periods. These processes are not likely to have a significant effect on the seasonal variations of properties.

4.2 Runoff

The primary characteristics of fresh water runoff into the Burrard Inlet - Indian Arm system have been described by Gilmartin (1962), Campbell (1954) and Tabata (1971). Qualitative features of these descriptions have been mentioned in Section 1.2. The following brief discussion presents further (quantitative) detail from these papers along with measured runoff data for the period May 1974 to October 1975.

The principal sources of fresh water for the study area have been identified as the Fraser River (most significantly through the North Arm), the Capilano River, the Seymour River, Lynn Creek, the Indian River, the Buntzen Power House outflows and the numerous small streams which enter the system predominantly from the north and west.

Of these, only the Fraser, Capilano and Seymour Rivers and the Buntzen outflows are metered. Annual discharge curves for the three rivers and for the power houses are presented in Figure 4.3. Inspection of historical data not here presented confirms the general shape of these curves to be representative of typical annual cycles for these rivers. It is immediately noted that the Fraser discharge exhibits a single annual peak in June, while the other rivers exhibit a bimodal cycle. The Fraser discharge maximum occurring during the May to August freshet period is a manifestation of melting of the previous winter's snow pack. The same mechanism explains the May-June maxima in Capilano, Seymour and Buntzen discharges. Superimposed on this cycle for the smaller rivers are direct runoff effects which generate a second peak sometime between October and December dependent on the time of maximum precipitation. For example, the exceptionally high values recorded in October 1975 can be traced directly to the particularly heavy precipitation which fell during that month (Figure 4.1(a)). In general, except in those months where the snow pack effect produces maxima, the Capilano and Seymour discharge curves are well correlated with the local precipitation curve, Figure 4.1(a). As the Buntzen curve reflects the regulation of lake level through controlled discharge, it is not expected to follow closely the precipitation curve.

In considering the total mean yearly discharge into Burrard Inlet, Campbell (1954) has shown good agreement between metered and estimated discharge rates for the Capilano and Seymour rivers and thus has accepted the validity of his estimated rates for Lynn Creek and for the Indian River. As the 1974-1975 Capilano and Seymour data fall within 15% of Campbell's values, his estimate of mean yearly discharge rates of 4 m^3/s for Lynn Creek and 18 m^3/s for the Indian River will be assumed valid for the present study as well. Employing these values, the combined mean yearly discharge rate for the Capilano, Indian, and Seymour Rivers and Lynn Creek over the present study period has been calculated as 64 m^3/s. Tabata has presented arguments which indicate that the mean discharge rate for any secondary streams entering Burrard Inlet is somewhat less than 3 m^3/s, and also that even at its maximum, the net contribution of direct precipitation on the inlet surface, to the total fresh water input is less than 7%. Coupling all these effects with the mean Buntzen outflow of 23 m^3/s, a representative mean fresh water input rate of 100 m^3/s (excluding Fraser River contribution) is calculated for the entire system.

A firm estimate of the actual volume of Fraser River water which enters Burrard Inlet is considered impossible; however, some consideration can be given to its importance relative to the other fresh water sources described above. Data quoted by Tabata indicate that 11 to 14% of Fraser River outflow is channelled through the North Arm, and that this is the primary source of Fraser River water which affects Burrard Inlet. The presence of such water in the surface layer outside First Narrows was visually evident on many occasions during the sampling program, and is amply verified by resultant salinity data. From Figure 4.3(a) it is noted that during the survey, mean Fraser River discharge rates (at Mission) varied from a high of 9880 m^3/s in June 1974 to a low of 974 m^3/s in March of 1975. The mean discharge rate for the 18-month period was 4050 m^3/s. Assuming this to be representative, it can be estimated that on average a volume of 445 m^3/s is diverted through the North Arm to discharge off Point Grey. The volume of this water which actually sweeps around the Point to enter Burrard Inlet is determined by wind and tide conditions at any given time, however, it is noted that even if 20% of this river water was to move into the inlet, this would represent a volume effectively equal to the mean input from all other sources into the entire inlet. It is thus evident that in the area outside First Narrows, the effect of Fraser River input much exceeds that of any other fresh water sources. It will be seen from property distributions presented in subsequent sections that this freshening effect is felt at least through First Narrows into the western harbour, and possibly even into the central regions. Thus, in Burrard Inlet, the Fraser River generally overshadows the effects of freshwater input from such sources as the Capilano and Seymour rivers. In Indian Arm, however, discharge from the Indian River and from the Buntzen outflows will be seen to have a marked effect on the property distributions and circulation patterns.

CHAPTER 5 SEASONAL CHANGES IN WATER PROPERTY DISTRIBUTIONS

To support a thorough synoptic discussion of the scalar property data collected over the 18-month duration of the study, three series of figures are presented. Firstly, a set of nine pairs of horizontal distributions of surface temperature and salinity outside First Narrows over the period August 1974 to October 1975 are discussed to illustrate the seasonal effects of Fraser River discharge in the harbour approaches. Secondly, time-depth sections of temperature, salinity and oxygen are presented for five representative stations to give an overview to the seasonal cycle of changes throughout the entire study area. Finally, vertical sections of temperature, salinity, density and oxygen in Vancouver Harbour and in Indian Arm are discussed cruise by cruise to provide a detailed analysis of annual changes.

5.1 Surface Behaviour in Approaches

Detailed sampling of the supplementary stations outside First Narrows (for locations see Figures 1.1(b) and 5.1(a)) was undertaken on nine regular cruises and as part of the August 1975 CSTD survey (for cruise dates see Table 2.1, column 5). Horizontal distributions of surface temperature and salinity as derived from these data are presented as Figures 5.2(a) and (b) through 5.10(a) and (b). As the interpretation of these figures is dependent on the tidal phase at the time the stations were sampled, tidal bin information (see section 3.2) is included with each figure. Also included is an arrow to indicate the sequence in which the stations were sampled. A left pointing arrow indicates that sampling commenced at station 17-8 (Figure 5.1(a)), proceeded north, then south along the "14" line and finally north again along the "11" line to conclude at station 11-1. A right pointing arrow indicates an approximate reverse of this sequence, with sampling commencing off Point Grey at 11-8, proceeding north, then south, then north to conclude at Van 17. The tidal phase at the commencement of sampling is indicated by the bin number at the tail of the arrow (see Figure 3.1 for bin definitions) while the bin number at the arrow head identifies tidal phase at the conclusion of sampling.

It is to be noted in considering these figures that the degree of contour detail varies geographically due to the irregularity of the station grid. As can be seen from Figure 5.1(a), station separation in the north-south direction is generally one half of east-west separation. For this reason, there are cases where much finer structure is noted in the contouring along north-south lines of stations, than is noted in the east-west direction. Similarly, in areas to the south and to the east of the station grid, extrapolation of contours has been necessary. In such instances, smooth curves have been plotted using dashed lines, thus distinguishing these from the interpolated contours plotted as solid lines.

Comparison of Figures 5.1(b) and 5.2(a) which show density (as σ_t) and salinity respectively, for August 1, 1974, illustrates the high degree to which density is controlled by salinity in these coastal surface waters. As the structure of the density and the salinity contours is so similar, little additional information is provided by the density section. Thus, for consideration of these surface distributions, attention is restricted to sections of salinity and temperature.

By now discussing the pairs of figures in chronological sequence, annual cycles of surface salinity and temperature in the harbour approaches are described. Also discussed are various aspects of surface circulation which are apparent from these distributions.

August 1, 1974 (Figures 5.2(a) and (b))

The secondary station grid in the harbour approaches was first sampled on August 1, 1974, at a time when the Fraser river discharge rate was high, the time being less than two months since maximum discharge. Salinities of 6.86^{0}/oo observed at station Van 11-8 and 7.49^{0}/oo observed at station Van 11-5 approximately three hours before high water on this date were among the lowest observed in the approaches throughout the entire study. This is considered to be evidence of North Arm water swinging northeastwards around Point Grey on the rising tide. Also apparent on this salinity figure is a rather high salinity core in the north central region, which is interpreted as a manifestation of ebb flow through First Narrows flanked by Fraser River water to the south and by North Shore stream water to the north. A further indication of this flow is the similar shaped tongue of relatively lower temperature water observed on Figure 5.2(b). These distributions are representative of late summer conditions with high water temperatures and with very low salinities in the river influenced water. Large horizontal salinity gradients were also observed between the well mixed waters of the earlier ebb from inside the narrows and the flooding river waters off Point Grey. On only one other occasion (September 3, 1975) was such a range of salinities observed in this area during a single cruise.

<u>August 29, 1974 (Figures 5.3(a) and (b))</u>

On this second August cruise, marked increases in surface salinity and corresponding decreases in temperature (from earlier August levels) were recorded, consistent with dropping river discharge rates and decreasing air temperatures. The tongue of river water observed off Point Grey just after the ebb had salinities almost $10^{o}/oo$ higher than those recorded a month earlier. Maximum salinity increased by greater than $4^{o}/oo$ while the observed range of salinities dropped from greater than $10^{o}/oo$ to near $5^{o}/oo$. Temperatures dropped by generally 1^{o} to 2^{o} during August. For similar tidal conditions and an identical sequence of sampling, the late August sections do not clearly show the ebbing plume of mixed water which was so evident in Figure 5.2.

<u>February 22, 1975 (Figures 5.4(a) and (b))</u>

An almost six-month gap between the late August cruise and this February cruise on which the secondary stations in the approaches were next sampled allows no detailed discussion regarding the transition from summer to winter conditions. The February cruise does, however, provide illustration of the uniformity of late winter conditions. Salinities between $27^{o}/oo$ and $28^{o}/oo$ were observed over most of the region, with a marginally lower salinity tongue (influenced by North Arm water) appearing at low water to the southwest. The $26^{o}/oo$ contour to the north illustrates minor freshening at the surface due to runoff from small streams along the North Shore. Uniform temperatures of 5.5^{o} to $6.0^{o}C$ were recorded at most stations. Slightly higher temperatures were associated with the river water to the southwest while marginally lower temperatures characterized the runoff influenced water to the north. Surface waters observed on this cruise were the most dense of any sampled here during the entire survey.

May 30, 1975 (Figures 5.5(a) and (b))

By late May, the Fraser discharge rate had climbed to approximately its level of August 1974 (Figure 4.3(a)) and air temperatures had increased considerably from late February levels. The range of salinities had again increased to about 9^{o}/oo, with maximum salinities being just less than on August 1, 1974 (Figure 5.2) and minimum salinities being about 2^{o}/oo greater. Water temperatures, while still quite uniform had increased to generally 15^{o} to 16^{o}C.

Sampling on this cruise commenced at station Van 11-8 and spanned a full ebb cycle. During the early hours of ebb, there was evidence of continued influence from Fraser River water through the southeastern and south central harbour mouth, as indicated by the low salinity tongue of Figure 5.5(a), and the low temperature tongue of Figure 5.5(b). In the later stages of ebb, outflow from First Narrows was evident. The 15^{o}/oo isohaline and the 15.5^{o} isotherm (near the centre of the section) appear to mark an approximate boundary between the river waters to the southwest and the ebbing waters to the northeast. Again, it is well to note that detail is lacking to the southeast in English Bay simply because no sampling was undertaken east of station 17-8.

June 13, 1975 (Figures 5.6(a) and (b))

These distributions, drawn from data collected only two weeks following the May cruise (Figure 5.5) illustrate a high variability of surface conditions in the approaches. Although Fraser discharge rates increased in the intervening two weeks, surface salinities observed on this June cruise over an equivalent tidal cycle were generally higher than those recorded in May. While maximum salinities in the outflowing water through First Narrows were comparable, and water temperatures in June were higher (consistent with the increase in air temperature over the two-week period), there was no evidence of the low salinity water to the west which was apparent in May. Instead, a tongue of water having salinities 2 to $3^{o}/oo$ higher than those of resident water was observed off Point Grey. Similar indication was seen in the temperature data, of a cool tongue entering the harbour mouth from the southwest. As stations Van 11-8 and Van 11-5 were sampled at approximately the time of high water, this tongue must have been associated with the previous flood. The water must have come from west and/or north of Point Grey as any contribution from the south would have been of substantially lower salinity. A plausible explanation would be a gyral circulation, set up on the previous ebb. The outflow along the North Shore on the ebb could force a cyclonic return flow from north to south outside the harbour entrance, which on the turn to flood could provide high salinity water off Point Grey as observed. Wind conditions in the preceding days had been conducive to such circulation with daily mean winds persisting from the northwest to west northwest at moderate speeds of 10 to 22 km/hr. These could possibly push the North Arm water southward, removing its usual influence.

<u>July 25, 1975 (Figures 5.7(a) and (b))</u>

Although the Fraser River discharge level had peaked in the weeks between the June (Figure 5.6) and July cruises, salinity decreases of generally 5^{o}/oo and 8^{o}/oo were recorded in July over an identical sampling sequence and comparable tidal cycle. While in June, ebbing waters through First Narrows had salinities of approximately 16^{o}/oo to 18^{o}/oo decreasing to the west, the July cruise recorded salinities of 10^{o}/oo to 12^{o}/oo in the apparent ebb flow. On this occasion, salinities increased to the west. Similar features were observed in the temperature distribution. Water temperatures in excess of $20^{o}C$ reflect maximum air temperatures recorded in July 1975. The direction of surface temperature gradient varied as would be expected from the observed salinity gradients. Temperatures near First Narrows increased to the west in June (approximately 15.5^{o} to $17.0^{o}C$) and decreased to the west in July (approximately 20.0^{o} to $18.5^{o}C$).

The decreased salinities observed in July are interpreted as manifestation of the large volume of fresh water entering the approaches through the North Arm in the weeks since the June cruise, causing a general freshening in the entire system. The variations in direction of gradient are not so readily explained. Observations on July 24, 1975 (one day prior to collection of samples from which Figure 5.7 was drawn) showed salinities at Van 17 and Van 24 to be approximately 7.9^{o}/oo and 18.6^{o}/oo respectively in the last hour of ebb before low water. This marked increase through First Narrows is consistent with most observations at this pair of stations. The indication from Figure 5.7(a) however, is of low salinity water ebbing through First Narrows on July 25. All evidence from other cruises would suggest this to be an unlikely occurrence. A more reasonable explanation of the observations of July 25 would be minor irregularity in the ebb flow. If the ebb were confined to a marginally more northerly and narrower band than usual, the waters actually sampled at Van 17 may not in fact have passed out of First Narrows. As the $10^{0}/oo$ contour of Figure 5.7(a) and the $20^{0}C$ contour of Figure 5.7(b) (both dashed) were drawn on the basis of only a single sample (Van 17), this explanation seems reasonable. If such were the case, it would be expected that more dense waters associated with the ebb would have passed to the north of Van 17 at the time these samples were taken, and that the sampled water was actually representative of ambient conditions outside the Narrows.

August 19, 1975 (Figures 5.8(a) and (b))

Data for these distributions were collected at a time when the Fraser River discharge rate had dropped to near half its magnitude at the time of the July cruise. This fact, in conjunction with the tidal sequence of late ebb through low water to the commencement of flood, during the August sampling, generally explains the uniformity observed in late summer 1975. The salinity Figure 5.8(a) shows salinities generally between $17^{0}/oo$ and $18^{0}/oo$ through most of the area on the tail of an ebb, consistent with salinities observed on an ebbing tide in late August of the previous year (Figure 5.3(a), eastern portion). Only to the southwest in the vicinity of stations Van 11-5 and 11-8 was the influence of low salinity river water observed: sampling there was completed at the commencement of the flood. Temperatures in the area (Figure 5.8(b)) showed similar uniformity in the range 16.5^{o} to 17.5^{o}C, slightly warmer than in the final week of the previous August as would be expected with the higher mean air temperatures recorded in 1975 than in 1974.

September 3, 1975 (Figures 5.9(a) and (b))

The distributions of temperature and salinity in waters observed to the south and to the east of the 15^{o}/oo isohaline and the 14.5^{o} isotherm (Figure 5.9) are representative of ambient conditions on a flooding tide for early September. The relatively low salinities would indicate substantial influence of Fraser water into the vicinity of First Narrows, suggesting tidal flooding through the southwestern harbour mouth. The approximate temperature decrease since August 19 was 2.5^{o}C.

These distributions provide further evidence of the anomalous intrusion of dense water masses around Point Atkinson which was earlier described in Section 3.3.4. In this instance a water mass having salinities up to 10^{o}/oo above and temperatures up to 2.5^{o}C below those which would be expected for water anywhere in Burrard Inlet at this time (see Figure 5.3), was recorded to have been centred near station Van 14 at approximately the mid point of the flood cycle. Influence of this water was seen to extend through the entire northwest and north central sections of the approaches. Again, such observations must be explained as waters being advected around Point Atkinson from the mouth of Howe Sound. Whether these be surface waters outflowing from Howe Sound or whether they be of Strait of Georgia origin is not discernible from the present data base. It is noted that this is not a unique observation. Figures 3.13(a) and (b) identify the passage of a similar dense water mass past station Van 11, on the same flood cycle, only a few hours after the above described conditions were recorded.

October 10, 1975 (Figures 5.10(a) and (b))

Observations taken in the final weeks of the survey illustrate an approach to winter conditions. On a tidal cycle through high water to the commencement of ebb, salinities in the range $24^{o}/oo$ to $26^{o}/oo$ were observed through most of the area. As usual, a low salinity tongue of Fraser River influenced water was seen intruding around Point Grey. Temperatures in the range 11^{o} to $12^{o}C$ reflected the continuing seasonal drop in air temperature. Excepting the river water to the west, evidence of the winter uniformity observed in the previous February (Figure 5.4), was clear.

5.2 Overview to Annual Cycles (Time-Depth Sections)

General features of the annual cycle of changes in the property distributions throughout the entire system can be interpreted from time-depth sections at key stations. Spanning the full 18-month sample period, such figures are presented to illustrate seasonal behaviour, while subsequently, vertical sections are discussed in a more detailed treatment of annual changes. Main line stations Van 11, 24 and 34 and Ind 1 and 2 are representative of conditions in the various regions of the study area.

Sections at each particular station (Figures 5.11 - 5.13) have been prepared from all available bottle sample data (see Table 2.1 for list of cruise dates and sample locations) for that station. The horizontal time scale is the same for all sections, however, the vertical depth scale varies, as water depth varies from station to station.

Care must be exercised to account for this difference when comparing slopes and depths of contours between figures. Again it is noted that the very fine structure observed on the lines of these figures is an artifact of the computer contouring program used to generate the plots. Sections of temperature (Figures 5.11(a) to 5.11(e)), salinity (Figures 5.12(a) to 5.12(e)) and oxygen (Figures 5.13(a) to 5.13(e)) from the five stations are now respectively considered.

5.2.1 Temperature

Eighteen-month time-depth sections of temperature are presented as Figures 5.11(a) to 5.11(e). At all stations except Ind 2 the near surface behaviour, and to a large degree, the subsurface behaviour of the temperature regime is closely coupled to the annual cycle of air temperature (Figure 4.1(b)). At Ind 2 the effects of direct heating and cooling are complicated at times by advective exchange of subsurface waters.

At station Van 11, Figure 5.11(a), this coupling of cycles is illustrated. The study commenced in May, at a time when air temperatures were increasing. The same trend, indicated by downward sloping contours near the surface, is observed in recorded water temperatures. As summer progressed, fluctuations in water temperatures (particularly 10 - 12^{o} contours in the depth range 5 - 15 m) continued to parallel fluctuations in air temperature. For instance, ten-day mean air temperatures through late June to mid-July remained constant, while an approximate 2^{o} increase was observed through late July. This behaviour is paralleled in the sea temperature contours as a decrease in slope is observed through early July, followed by a sharp deepening of the contours in the latter part of the month. Similar behaviour is associated with a period of relatively low air temperatures in mid-August, followed by a period of increased temperatures in late August and early September. At depths exceeding 20 m a smaller, more gradual response is noted, as longer periods are required for vertical mixing and diffusion to distribute the heat. The temperature change at 100 m depth, from May to August was less than 1.5^{o}C compared to a change of 7.8^{o}C at the surface. Cooling was observed through September and October as the temperature of the surface layer decreased and a more uniform profile of temperature developed. Generally, decreasing air and water temperatures continued through the winter, leading to the development of a very nearly isothermal water column in March with temperature differences from surface to bottom on March 26 being less than 0.3^{o}. Minimum temperatures through the winter at Van 11 dropped slightly below 7.0^{o}C. A similar cycle was observed through the spring and summer of the second year of the survey. Warming trends commenced in March, paralleling the trend of air temperature. Greater extremes of temperature were recorded than in the previous year, with maxima at the surface in the summer of 1975 exceeding 20^{o}C, and with the 10^{o}C isotherm descending to 40 m, about 10 m greater depth than in the preceding August. This is again consistent with the marginally higher summer mean air temperatures recorded in 1975 than in 1974. At mid-depth, the pocket of water cooler than 9^{o}C observed in September of 1974 did not reappear in 1975.

Over the 18-month period, the behaviour of the temperature regimes at stations Van 24, 34 and Ind 1 (Figures 5.11(b), 5.11(c) and 5.11(d)) fairly well paralleled that discussed above for Van 11. While the changes were similar, the absolute temperatures differed considerably, particularly east of Second Narrows. In the summer of 1974, the 11^{o} isotherm was observed at less than 20 m depth at Van 11 and Van 24, while further to the east, 11^{o} water was found at 50 m, partial evidence of downward mixing of warm surface waters at Second Narrows. It is evident from the diminished range of temperatures in the vertical, that in passing from Van 11 to Van 34, direct heating and cooling plays a decreasingly important role than does mixing, in controlling subsurface temperatures. Outside First Narrows, direct heating effects predominate, while at Van 34, mixing appears to be the controlling agency. Both factors are clearly important in the western harbour, represented by Van 24.

Station Ind 1 (Figure 5.11(d)) illustrates a more gradual warming through spring and summer than do the harbour stations, reflecting the different nature of the circulation pattern here. Mixing of waters at this location is less vigorous than at stations Van 24 and 34. Consequently, the summer input of heat causes a gradual deepening of the temperature contours. Again, the increased air temperatures of the summer of 1975 are evidenced in the depth of penetration of the 12^{o} isotherm in August, compared to the previous year. There are no particularly dramatic winter temperature changes clearly evident at Ind 1 to suggest major exchanges of water masses: this, however, may be a consequence of the restriction of sampling at this station to depths less than 60 m.

Among the temperature sections, station Ind 2, Figure 5.11(e) is unique. Until January of 1975, a pattern somewhat similar to that at Ind 1 was observed. Shallower than about 10 m depth, direct heating appears to have controlled the distribution of temperature. The restriction of this behaviour to a surface layer is indication of an estuarine circulation pattern, with an outflowing surface layer usually less than 10 m in thickness. Below this layer, the gradual sloping of the isotherms is indicative of downwards diffusion of heat. Were simple cooling to proceed through the winter, a progressive rising of the contours as observed through October to December would be expected. However, commencing in January of 1975, marked changes in temperature were recorded at all depths, with substantially cooler waters appearing at Ind 2. Such temperature decreases through the late winter months provide direct evidence of intrusions of new water. These intrusions will be thoroughly detailed in later discussions of vertical sections. As earlier noted for the other stations, warming commenced again in March, as indicated by the downward sloping isotherms. Again the warmer summer of 1975 is evident in the behaviour of the 11^{o} isotherm.

5.2.2 Salinity

In interpreting the seasonal fluctuations of salinity, the effects of both runoff and of precipitation are of considerable importance. Inspection of sections 5.12(a) through 5.12(e) for the same five stations discussed above in relation to temperature, reveals three rather distinct regions in terms of salinity changes.

Firstly, the region outside First Narrows, which is characterized by station Van 11, Figure 5.12(a), is again (see discussion of surface distributions, section 5.1) assumed to be basically controlled by Fraser River discharge and by proximity to the Strait of Georgia. The principal feature here, best illustrated by the $29^{o}/oo$ and $30^{o}/oo$ isohalines, was the decrease in salinity of waters at greater than 10 m depth coincident with the peaking of Fraser discharge in both years of the study (Figure 4.3). While runoff was high (May - July) a freshening of waters at all depths greater than 10 m was observed, a result of downward mixing of fresh surface waters. As runoff diminished through the summer and into the winter of 1974, higher salinity waters from the Strait of Georgia caused a decrease in the depth of the $30^{o}/oo$ isohaline from greater than 100 m in July to approximately 25 m in December. Salinity at depth generally decreased from December, dropping marginally below $30^{o}/oo$ in early March, then rising slightly, later in the month. A pronounced change was again noted at the time of freshet in May and June. The lesser spring freshening of deep waters at this station in 1975 than in 1974 is consistent with the substantially lower peak in Fraser discharge levels recorded in this latter year.

At all depths shallower than 10 m, the seasonal changes in salinity reflect effects of both runoff and of precipitation. Minimum surface salinities were observed in July of 1974 at a time of high runoff and of relatively high summer precipitation (see Figures 4.3 and 4.1(a)). Precipitation extremes in November and December of that same year, possibly coupled with direct runoff peaks in Capilano and Seymour River discharges must account for the considerable freshening noted near the surface at that time. Later, with decreasing precipitation and runoff, the presence of Strait of Georgia water with salinities exceeding 28^{o}/oo was felt. In April 1975, the spring freshening associated with increased Fraser River discharge commenced, decaying again as the freshet passed. Finally in the last weeks of the study, the effects of abnormally high October precipitation were felt, as evidenced by the downturning of the isohalines at less than 15 m depth.

Stations Van 24 and 34 (Figures 5.12(b) and 5.12(c)) identify a second region in terms of salinity cycles. At these stations, the effects of mixing of waters passing through the narrows complicates the seasonal cycles even though they are principally controlled by precipitation and runoff. A simple illustration of this effect is to be seen by considering maximum winter salinities at approximately 20 m depth, just greater than sill depth (First and Second Narrows sill depths are 14 m and 18 m respectively). Outside the First Narrows sill, salinities only fractionally less than 30^{o}/oo were recorded near 20 m depth. At Van 24, between First and Second Narrows, salinities at this depth barely reached 29^{o}/oo while at Van 34, inside Second Narrows, values were restricted to near 27.5^{o}/oo. Such behaviour is interpreted as evidence of the occurrence of considerable mixing across both First and Second Narrows.

The magnitude of surface salinities at Van 24 is generally greater than at Van 11, again at least partially due to mixing. Generally lower values at Van 34 must reflect the effects of surface layer outflow from Indian Arm. At both stations, changes are basically controlled by precipitation and runoff. Significant freshening was noted in July and in November of 1974 at both of which times runoff and precipitation were high. Again at Van 24 and at Van 34 in late January and in mid-March of 1975 a degree of freshening was noted in the top few metres. The March event is attributable to a secondary peak in Capilano and Seymour discharge, possibly coupled with simultaneous low salinity outflow from Indian Arm. The January event occurred at a time of low runoff from the Capilano and Seymour watersheds, however, high runoff into Indian Arm at this time could be responsible for low salinity estuarine outflow, which could expalin the low salinities recorded near the surface in the harbour.

At depths greater than about 15 m at these stations, salinity changes roughly parallelled those described for Van 11. An abrupt freshening was noted in each year at the time of Fraser River freshet, due to the decreased salinity of source waters entering the system from outside First Narrows. Again, a lesser effect was noted in 1975 (see 28^{o}/oo isohaline at Van 24, Figure 5.12(b), and 26^{o}/oo isohaline at Van 34, Figure 5.12(c)) due to lower Fraser River discharge. Winter behaviour again followed that described for Van 11, with mixing accounting for decreases in absolute salinity values through November and December 1974. Salinity decreases resulting from this period of high precipitation and high runoff from the Capilano and Seymour watersheds were evidenced more dramatically at these stations than at Van 11, due to the closer proximity of Van 24 and Van 34 to the river mouths. At both stations, the entire water column was affected as salinities fell below 29^{o}/oo at 50 m at Van 24 and below 27^{o}/oo at 50 m at Van 34. A time lag is suggested in the downward propogation of this freshening effect as the downturn of contours appeared later at increasing depths down to approximately sill depth. The contours reversed their downward trends at progressively later times to all depths through December as runoff diminished (see Figure 4.3(b)). This delay is suggestive of differences in the intensity of estuarine circulation across First Narrows through the period of freshening. It is likely that when stratification was greatest, at the time of peak runoff, a strong estuarine circulation was established, with an inflowing layer at depth accounting for still high salinities below sill depth at Van 24. Later, as runoff diminished, it can be expected that the weakened estuarine circulation allowed greater downwards mixing of fresh water inside the narrows, which caused the observed salinity decreases. Finally, as runoff volumes diminished even further, the source of fresh water effectively disappeared, and salinities at all depths began to increase as mixing of waters from outside the Narrows again became the dominant influence. For reference in later discussions of Indian Arm exchange, it is noted that maximum salinities (and therefore densities) at greater than 10 m depth at these stations were recorded in the interval January through March. Finally, the spring freshet of 1975 and the high precipitation and runoff values for October 1975 explain further fluctuations in surface salinity at Van 24 and at Van 34.

Indian Arm constitutes a third distinct region in terms of seasonal salinity patterns. The pertinent stations are Ind 1 (Figure 5.12(d)) and Ind 2 (Figure 5.12(e)). The earlier discussed temperature data showed evidence of an estuarine circulation in Indian Arm with a typical outflowing surface layer. This conclusion is further enhanced by the salinity sections which identify an approximately 10 m thick surface layer through which salinity gradients are high. Within this layer salinities are determined predominantly by runoff and precipitation. Though no discharge data for the Indian River have been quoted, the annual runoff pattern as inferred from surface salinity measurements near the head of Indian Arm is similar to those presented in Figure 4.3(b). Surface salinity minima occurred in early summer at times of maximum runoff. A secondary minimum in surface salinity was noted in November as an expression of both high runoff and high precipitation. Again in January and in March at Ind 1 and in January at Ind 2, low surface salinities were observed. Precipitation and runoff values though relatively high, were not extreme at these times, offering a possibly tenuous explanation of the observed low salinities. That the extent to which such interpretation may be pursued is restricted becomes evident upon consideration of some closely spaced (in time) surface salinity measurements at Ind 2. At 1126 h PST, December 5, 1974, a surface salinity of approximately 1.7^{o}/oo (below the limits of the 1966 UNESCO tables used in the present analysis) was recorded at Ind 2. Less than 24 hours later, at 0935 h PST, December 6, 1974, a surface salinity of 18.30^{o}/oo was recorded at the same station, a change of some 16.6^{o}/oo. Such variability could well be explained by the varying position of the outflow plume from the Buntzen powerhouses, this being dependent on tide and wind conditions. Given the probable reality of such short period salinity fluctuations it becomes clear that some specific details illustrated in the 18-month time-depth sections may be unrepresentative of mean conditions, and thus may not be readily explained in terms of mean runoff and precipitation cycles. At greater than about 10 m depth, the distribution of salinity in Indian Arm appears to be controlled by diffusive and by weak mixing processes, and by advective exchange. At Ind 1, increased volumes of fresh water near the surface in the interval May through July caused a gradual deepening of the salinity contours. The upswing of the contours in the late summer months is most probably evidence of higher salinity waters from Burrard Inlet mixing below the surface across the Indian Arm sill and finding their depth (as dictated by density) in the water column at Ind 1. The presence of lower salinity water in December than in November or in late January is further illustration of this process as salinities beneath the surface layer observed at Ind 1 are consistent with those observed at Van 34 and at Ind 0 on the same cruises. The pattern of change observed in the late spring of 1975 is comparable to that observed in the previous year. Again, as was described for the harbour, absolute salinities were higher in 1975 than in 1974, as river discharge rates were lower.

Between 10 m and 60 m depth at Ind 2, (Figure 5.12(e)), the annual salinity cycle closely parallels that described for Ind 1, however, information provided by changes at depths greater than 60 m serves to clarify the processes which control this cycle of change. It is to be noted in considering this figure that at 27.0^{o}/oo the contour interval shifts from 1.0^{o}/oo to 0.1^{o}/oo. Thus, the structure observed at depth illustrates absolute changes of less than 0.5^{o}/oo.

The earlier suggestion of intrusion of Burrard Inlet waters in October is here confirmed as a sharp upswing was observed at depths less than 130 m in the 27.0^{o}/oo through 27.2^{o}/oo isohalines. Subsequently, through November and December, vertical mixing and diffusion resulted in decaying salinities again above 90 m. As will be seen more clearly from later vertical sections, the salinity minimum observed between 90 and 140 m during November resulted from displacements associated with the intruding waters at lesser depths.

The January exchange of Indian Arm deep waters which was illustrated in the earlier presented temperature section is again evident in the salinity data. Salinity increases in excess of $0.25^{o}/oo$ were recorded between January 3 and February 19, 1975 at all depths greater than 50 m at Ind 2. Salinities at depths exceeding 130 m continued to climb through May, with a maximum value of $27.75^{o}/oo$ being recorded at 200 m depth on May 30. Shallower than about 100 m depth, the increased salinities associated with the intrusion began to drop again in early May as the presence of fresher waters near the surface was felt to ever increasing depths. In the deeper waters, decay of salinity maxima lagged the surface by at least 30 days. From June, the decrease continued at all depths greater than about 90 m until the end of the survey in October. Nearer the surface, however, a late summer salinity increase was recorded as a second season of mid-depth exchange with Burrard Inlet waters commenced.

5.2.3 Oxygen

Oxygen sections corresponding in time and location to those described above for temperature and salinity are presented as Figures 5.13(a) through 5.13(e). While production and utilization of oxygen in the water column are biologically controlled, physical processes such as diffusion and mixing also act to redistribute oxygen. An interpretation of seasonal changes in oxygen distribution based upon these agencies is complementary to the interpretations of temperature and salinity cycles already presented.

At less than about 15 m depth at Van 11, Figure 5.13(a), oxygen concentrations are kept high throughout the year by biological productivity (see peaks in July, September and November 1974 and the interval May to July, 1975), and by transfer and solution of atmospheric oxygen into the surface layer. The high values observed at Van 11 even through the winter months suggest substantial turbulent mixing of surface waters. As wind and wave conditions in the Strait of Georgia are known to be more severe than those in the inlet, such an observation provides further evidence that waters found at Van 11 are predominantly of Strait of Georgia origin.

In considering the oxygen distribution at depths greater than 20 m at Van 11, two principal factors are of importance. Firstly, consumption of oxygen in the process of detrital decomposition is assumed to account for the decrease in oxygen concentration observed at depth in the interval May through November. During this time of high biological productivity near the surface, dead plankton sink in the water column, consuming oxygen as they decompose. An oxygen minimum at depth in late October coincides with the approximate end of the high productivity season in both years of the study (A.G. Lewis, personal communication). In the intervening months November through May, when biological activity is at a minimum, physical processes must account for changes in oxygen concentration. An increase in oxygen throughout the water column from November to February reflects downward mixing of oxygen rich surface waters, diffusion of oxygen to depth in the absence of significant biological consumption, and subsurface advection. Again it is to be noted that Strait of Georgia surface waters are the assumed source of oxygen for this deeper water oxygen replenishment. Downward mixing or sinking of surface water was clearly evident in March 1975, when pockets of water having oxygen concentrations in excess of 6.0 ml/l were observed at 25 to 50 m depth at a time of low stability with temperature and salinity profiles being nearly vertical. As biological production of oxygen began to increase again near the surface in April, oxygen concentrations at depth correspondingly began to drop.

Oxygen cycles at Van 24 and Van 34, Figures 5.13(b) and 5.13(c) can be explained in terms of conditions outside First Narrows, mixing through First and Second Narrows, and in situ biological productivity. As at Van 11, relatively high oxygen concentrations in the surface layer prevailed throughout the entire observation period at both Van 24 and Van 34. These high concentrations must reflect the same atmospheric oxygen source as for waters outside First Narrows, with the relative strength of winds at the two locations possibly accounting for the marginally lower magnitudes recorded at Van 24. Turbulent vertical mixing of these waters in their passage through First Narrows could also provide partial explanation of the generally lower oxygen values observed at 2 m at Van 24 than at Van 11 (this station being representative of conditions in the approaches). At Van 34, oxygen values remained high near the surface, possibly due to local oxygen production, in spite of the downward mixing and consequent decrease in oxygen concentration anticipated in waters passing from the western harbour through Second Narrows. Maxima observed in August 1974 and in July 1975 are ascribed to such production. It is probable as well that outflowing surface waters from Indian Arm contributed to keeping values high at Van 34.

At greater than about 15 m depth at both Van 24 and Van 34 the seasonal cycle again paralleled that described for Van 11, with modifications to absolute oxygen concentrations. A general pattern of decreasing oxygen concentration at depth between April and November followed by a gradual increase through the winter to a maximum in March is consistent with the similar cycle observed in source waters outside First Narrows. The actual oxygen values at depth were conditioned by consumption and by mixing. From the high spring values at depth in May 1974, both stations showed decreases to below 4 ml/l in November, this value being higher than the values near 3 ml/l observed at Van 11. Such behaviour indicates a lesser oxygen demand at depth, implying a lesser concentration of detrital material, which in turn implies a lesser plankton concentration near surface. Oxygen values at depth at both stations increased from November to March when both maxima exceeded March values at Van 11, providing further evidence of downward mixing of oxygen rich surface waters through the narrows.

Less detail is observed near the surface on the oxygen sections for Indian Arm than in those from harbour stations as the top bottle sample at the Indian Arm stations was from 5 m depth in contrast to both 2 m and 5 m samples which were taken at the other locations. Nevertheless, a seasonal cycle is apparent in the surface layer. At Ind 1, Figure 5.13(d), high oxygen values near the surface in the interval May through October are ascribed to biological production of oxygen. Winter values at 5 m depth were considerably lower than those at corresponding depths outside the Arm, a fact which is consistent with the lesser degree of wind, wave and tidal mixing affecting waters at Ind 1. At depths exceeding 15 m, oxygen concentrations exhibited the typical decrease due to detrital utilization through the summer to a minimum in December followed by a gradual increase extending into May. The abrupt increase in oxygen concentration observed at 33 m depth at Ind 1 in January (see 4.5 ml/l contour) is probable evidence of waters intruding from outside the sill, where January oxygen values were greater than 5.0 ml/l at all depths exceeding 10 m.

During both years of the study at Ind 2, Figure 5.13(e), near-surface maxima were observed in the appropriate seasons, consistent with previously described stations. Lesser maximum concentrations measured inside the arm than in the harbour are further evidence of the lesser mixing induced by generally lighter winds and weaker tidal effects. The cycle of oxygen changes at greater than 20 m depth was, however, radically different from that observed elsewhere. In the interval May through September 1974, the behaviour would be considered typical with a gradual decrease in concentrations from the surface to about 75 m depth being ascribed to detrital utilization. In the layer between about 75 m and 110 m, only slight fluctuations in concentration were recorded over this period indicating a near balance between consumption and downwards mixing and diffusion. At depths greater than 110 m a gradual decrease due to consumption was again noted. In late October, between about 75 m and 125 m depth a marginal increase in oxygen concentration was recorded. As will later be seen in the presentation of vertical sections, this event coincided with a minor intrusion of Burrard Inlet water at approximately these depths near the mouth of Indian Arm. Though the intruding waters did not penetrate northwards to Ind 2, a minor advection of waters previously resident nearer the mouth could have been forced by the intrusion, thus bringing slightly higher oxygen concentrations to the water column at Ind 2. Such horizontal motion was also likely through December as oxygen values at greater than 80 m depth continued their gradual decline.

Early in January 1975, a major intrusion of Burrard Inlet water began. The oxygen section at Ind 2, Figure 5.13(e), indicates that at least at depths greater than 90 m, the waters of the Indian Arm basin were completely replaced by this intruding water mass. Oxygen values at 200 m depth at Ind 2 rose from 0.53 ml/l on January 3, 1975 to 4.53 ml/l on January 22, 1975. A gradual change in oxygen concentration at depth continued through April, with a maximum of 5.18 ml/l being recorded at 200 m on April 29, 1975. At depths less than 90 m a substantial increase of greater than 1.5 ml/l was recorded in February, well after the deepwater intrusion had commenced. Later presentations of vertical sections will show this increase to be associated with an outflow in the upper layers, precipitated by the intrusion, rather than to be a direct manifestation of intruding waters. In May 1975, following the time of oxygen maximum at depth, the expected gradual decrease associated with consumption began, and continued through the end of observations in October.

5.3 Detail of Annual Cycles (Vertical Sections)

The preceding discussion of time-depth sections at five stations has described seasonal changes in temperature, salinity, and oxygen in the Burrard Inlet system and has suggested the major processes controlling these changes. Given this basic understanding of the physical nature of seasonal cycles a chronological sequence of vertical longitudinal sections through Burrard Inlet and Indian Arm is now presented to illustrate the spatial distributions of properties at time steps averaging about six weeks. Of major importance in this exercise is the further documentation of the winter exchanges of intermediate to deep Indian Arm waters which were (from the time-depth sections) shown to occur.

Two sets of vertical sections are jointly presented. The Burrard Inlet sections incorporate data from stations Van 11, 14, 17, 24, 27, 34 and 39 (see Figure 1.1(b) for station locations) to provide an east-west longitudinal slice through the inlet. The Indian Arm sections incorporate data from (some of) stations Van 34, Ind 0, 1, 1.3, 1.5, 2, 2.5, 2.8 and 3 to provide a basically north-south view through the Arm. It is to be noted that Van 34 is common to both sets of sections. In many instances, Indian Arm data collected as part of this survey have been supplemented by data collected at stations Ind 1.3 and Ind 2.8 on preceding or subsequent cruises. With only one exception, all such supplementary stations were occupied within 30 hours of the time of sampling at regular Indian Arm stations. On each vertical section, the locations of only those stations used in preparing the section are indicated.

Three line types were employed in contouring the sections. Solid lines were used for standard isopleths common to all sections, where sufficient data were available to allow confident interpolation between stations or where only minor extrapolation was required. Standard contour intervals are as follows:

	Burrard Inlet	Indian Arm
Temperature	$0.5^{o}C$	$0.5^{o}C$ above $8.0^{o}C$ $0.1^{o}C$ below $8.0^{o}C$ (below $7.5^{o}C$ in exceptional cases)
Salinity	$1.0^{o}/oo$	$1.0^{o}/oo$ below $27.0^{o}/oo$ $0.1^{o}/oo$ above $27.0^{o}/oo$ (above $27.5^{o}/oo$ in exceptional cases)
Density (σ_t)	1.0	1.0 below 21.0 0.1 above 21.0 (above 21.5 in exceptional cases)
Oxygen	0.5 ml/l	0.4 ml/l or 0.2 ml/l (dependent on required detail)

In regions of strong gradient, alternate contours were sometimes deleted.

Dashed lines were employed for portions of standard isopleths where major extrapolation was necessary or where interpolation was questionable. In particular, all oxygen isopleths in Burrard Inlet were dashed, as oxygen data were available only from stations Van 11, 24 and 34. Finally, dotted lines were employed for supplementary contours, used occasionally to illustrate fine structure. In late winter, the complicated temperature structure near the surface in Indian Arm necessitated that surface temperatures be quoted, to supplement the contoured information presented on the vertical sections: such quoted values are bracketed.

The distribution of cruises in time was earlier presented in Table 2.1. As conditions at times changed only minimally over the interval spanned by two or even three cruises it has been unnecessary to present vertical sections for all the cruises listed in this table. Rather, selected sets of sections (i.e. temperature, salinity, σ_t, and oxygen for a given cruise) have been presented to illustrate major changes. Comments have occasionally been inserted concerning conditions in the intervening periods, without actually presenting the figures. As deep water conditions in Indian Arm are of particular interest, all available sections for this area have been presented, generally with their accompanying figures for Burrard Inlet.

<u>May 14, 1974 Burrard Inlet (Figures 5.14(a) through (d))</u>

When the survey commenced in May 1974, late winter conditions were observed in Burrard Inlet with temperatures being uniform, salinities beginning to drop from winter maxima but still being generally high, and oxygen being abundant throughout the water column. As is generally the case for this area, density was controlled principally by salinity at this time, thus explaining the similarity between density and salinity sections. (The importance of the included density sections will be more pronounced in late winter, in discussions of deep water exchanges).

Some aspects of the effects of mixing through First and Second Narrows can be seen particularly from the temperature section, 5.14(a). The downturning of the 8.0^{o} isotherm at the First Narrows sill, accompanied by the upturning of the 9.5^{o} isotherm at the surface illustrates the moderation in temperature range experienced by waters passing through the Narrows. Surface waters become cooler; deeper waters become warmer, thus decreasing the temperature range through the water column. Similarly at Second Narrows a moderating trend is evident from the section, showing the approach toward isothermal conditions in the well mixed water at Van 34. An increased thermal gradient near Van 39 reflects less turbulent motion nearer the head, and possibly heat input from the Burrard Thermal Generating Station. Similar indication of the same mixing phenomenon is seen in the salinity section 5.14(b), particularly in the downturned isohalines at First Narrows. At Second Narrows, surface outflow from Indian Arm provided low salinity water at the surface, thus masking somewhat the effects of mixing. The steep drops in the 25.0^{o}/oo isohaline and in the 20.0 isopycnal over the Second Narrows sill however, provide further evidence of mixing near the bottom. Again in the oxygen section 5.14(d) there is minor indication of mixing at First Narrows, but the Indian Arm outflow of oxygen rich surface water coupled with oxygen demand beneath about 10 m obscured any major indication of mixing at Second Narrows.

June 25, 1974 Burrard Inlet (no sections presented)

While the structure of contours in June was similar to that illustrated above for May, a definite warming and freshening of waters at all depths was noted. Temperatures at depths greater than 10 m increased by generally 1^{o} to 2^{o} while salinities dropped by approximately 0.5 to 1.0^{o}/oo. In the approaches, oxygen concentrations at depth dropped by about 20% while little change was recorded in oxygen values inside First Narrows. Near-surface gradients of both temperature and salinity were much stronger than in the preceding month.

July 17, 1974 Burrard Inlet (Figures 5.15(a) through (d))

Mid-July temperatures showed increased warming throughout the water column as summer air temperatures continued to climb. Maximum surface temperatures exceeding 15^{o}C were recorded at Van 39. In contrast to the May section, little evidence was seen here of intense mixing through First Narrows. In what will be seen from later sections to be a very unusual occurrence, the 9.5^{o} isotherm was observed at almost identical levels both inside and outside First Narrows. Typically, temperatures at Van 24 were nearly 0.5^{o} higher than those at corresponding depths exceeding 15 m outside the Narrows. The July observations suggest the recent eastward passage of a volume of mid-depth water over the sill, with very little modification due to mixing. The warmer temperatures at depth at Van 24 (note the absence of a 9^{o} isotherm) indicate that the above described exchange did not cause displacement of the bottom water off Burnaby Shoal, (see Figure 1.1(b)).

A more typical example of mixing is seen on temperature section 5.15(a) across Second Narrows. Here, the level of the 10.5^{o} isotherm dropped approximately 20 m between stations Van 27 and 34, evidence of intense downward mixing of warm water.

The corresponding salinity section 5.15(b) illustrates similar features to those just described, with the 28^{o}/oo isohaline appearing at almost identical levels inside and outside First Narrows, with the absence of 29^{o}/oo water at depth at Van 24, and with an approximate 15 m drop in the position of the 24^{o}/oo isohaline across Second Narrows. In absolute terms, salinities were lower at all depths in July than in

May, but were similar at depth outside First Narrows, to those recorded in June. July salinities were particularly low near the surface, with strong haloclines being observed in the top few metres both near the mouth and near the head of the inlet.

Oxygen values remained high near the surface, while a slight increase over June values was noted at mid-depth at Van 11. The presence of water having oxygen concentrations of less than 4.5 ml/l at 20 m depth at Van 24, with no such low values being recorded outside the Narrows need not discredit the explanation earlier presented for anomalous temperature and salinity observations at this location. It must be remembered that oxygen concentrations were determined only at stations Van 11, 24 and 34. Water with the appropriate (less than 4.5 ml/l) oxygen concentration may have been present between Van 11 and the First Narrows sill, even though it was not detected; however, oxygen demand could also explain this lower value.

August 27, 1974 Burrard Inlet (Figures 5.16(a) through (d))
Indian Arm (Figures 5.17(a) through (d))

Having passed the time of maximum temperature and minimum salinity in late July, this late August cruise illustrated the commencement of transition from summer to winter conditions. It was also the cruise on which secondary sampling in Indian Arm was initiated.

The Burrard Inlet temperature section portrays what is becoming a recognizable pattern with a degree of mixing evident across First Narrows, and substantial mixing evident across Second Narrows. Temperatures were higher at depth inside First Narrows than in July but at greater than 10 m depth.

outside the Narrows, temperatures had begun to fall.

Responding to decreases in runoff and in precipitation since July, salinity increased at all depths. On this August section there is little indication of significant fresh water outflow from Indian Arm at Van 34, a fact consistent with low runoff values (Figures 4.2(b)) recorded in this month. Oxygen values throughout the entire inlet dropped since the previous cruise, reflecting a decrease in biological production or possibly a continuation in oxygen demand away from the surface.

The first illustration of summer conditions in Indian Arm is presented in Figure 5.17. The estuarine circulation is clearly evident in the temperature section. Outflow appears to be restricted to depths less than 15 to 20 m. South of Ind 2, at depths between 20 and 50 m, water temperatures in excess of $11^{o}C$ identify water recently intruded from Burrard Inlet where such temperatures were recorded near sill depth at Van 34. Similarly, the $26^{o}/oo$ isohaline, the $\sigma_t = 20$ isopycnal, and the 4 ml/l isopleth of oxygen all illustrate the approximate vertical extent (about 50 m) of direct estuarine exchange at this time of year. At greater than 100 m depth, recorded ranges in temperature and salinity were small. The quiet conditions at depth are well illustrated by the oxygen section. At depths exceeding about 70 m, oxygen concentrations decreased uniformly at all points in the fjord. Oxidation of detrital material must have led to the low concentrations while downwards mixing of water near 50 m from outside the sill must account for decreasing concentrations with depth.

September 26, 1974 Burrard Inlet (no sections presented)

Through September, temperatures dropped slightly, and salinities continued to increase. The first $30^{o}/oo$ water was observed at 50 m depth at Van 11. Oxygen values increased near the surface at Van 11, but maintained similar values to August, elsewhere in the inlet.

October 16, 1974 Burrard Inlet (no sections presented)

Indian Arm (Figures 5.18(a) through (d))

The expected seasonal decrease in temperature and increase in salinity was observed throughout Burrard Inlet in October. Oxygen values throughout the water column at Van 34 were near 4.3 ml/l while values of σ_t at this station varied from 19.4 at the surface to 20.7 at 50 m.

While the conditions in Indian Arm in October were similar to those described for August, minor changes were noted. An inflowing subsurface layer was indicated in the temperature data, as was a cold tongue extending seaward at 20 m depth near Ind 2.8 at the head of the inlet. Salinities at depths shallower than about 100 m had increased considerably with the $26^{o}/oo$ isohaline rising from 65 m in August to about 5 m in October. Salinities in the deep water had decreased, by approximately $0.1^{o}/oo$. The October density section, in conjunction with the above quoted density data for the Van 34 suggests a slightly greater vertical excursion of waters exchanging across the sill between the inlet and Indian Arm than was indicated in August, (65 to 70 m versus 50 to 55 m). The secondary 20.5 isopycnal identifies the approximate depth to which Burrard Inlet waters would appear to have penetrated by October, as the subsurface component of the estuarine circulation. With the presence of densities up to 20.7 at 50 m at Van 34 it seems possible that waters crossing the sill could have settled to depths even greater than 70 m inside the Arm.

Such hypotheses are not obviously supported by the oxygen section 5.18(d). As oxygen values at Van 34 were continually greater than 4.5 ml/l up to this time, the 4.0 ml/l isopleth of the oxygen section, extending only to 50 m depth and only half way up the inlet would appear to mark an approximate boundary of intruding Burrard Inlet waters. However, as oxygen is non-conservative and as October was earlier identified as a month of maximum consumption, it is likely that intruding waters would experience a decrease in oxygen concentration at this time even after only a brief residence in the Arm. Allowing for decreases of the order of 0.5 to 1.0 ml/l and for the effects of mixing the earlier description of intruding waters based upon density considerations would be acceptable. It is to be noted as well that oxygen concentrations at depth continued to decrease from August levels. The depth of the 1.2 ml/l isopleth rose from 130 m in August to near 105 m in October. The August concentration at 200 m at Ind 2 was 1.06 ml/l, while in October it had dropped to 0.79 ml/l.

November 7, 1974 Burrard Inlet (Figures 5.19(a) through (d))
Indian Arm (Figures 5.20(a) through (d))

By early November, the characteristic winter uniformity had developed in Burrard Inlet. Temperatures were generally between 9.3^{o} and $10.0^{o}C$, with slightly warmer water being observed near Van 39. Salinities were generally high and particularly inside First

Narrows were uniform. The $30^{o}/oo$ water had progressed to Van 14 at 40 m depth. Values east of First Narrows were between 26.0 and $28.5^{o}/oo$. A minor freshening effect was noted at the surface near Van 17 as a result of high November runoff from the Capilano River watershed. The density profile at Van 34 was very nearly vertical, with changes of only 0.22 in σ_t from the surface to 50 m. Finally, oxygen values too were uniform, being between 4.0 and 4.5 ml/l at all points east of Second Narrows.

The November salinity and density sections provide continued evidence of intense mixing through First and Second Narrows. A range of salinities exceeding $6^{o}/oo$ at Van 17 was reduced to a range of $1.5^{o}/oo$ at Van 24. This was further reduced through Second Narrows to a range of $0.4^{o}/oo$. Water having a salinity of $29.0^{o}/oo$ was observed at sill depth (14 m) at Van 17, but passage through the Narrows reduced salinities at 50 m at Van 24 to $28.56^{o}/oo$. Such pronounced effects further emphasize the anomalous nature of the July observation of similar water masses at Van 17 and at Van 24.

In the August through October data, all property changes in Indian Arm were explicable in terms of some number of explicit processes (diffusion, freshening due to runoff, oxygen consumption etc.) or in terms of an estuarine circulation with surface outflow in the top 15 to 20 m accompanied by mid-depth inflow. In particular, changes in the depth range 20 to 70 m were readily ascribed to this estuarine inflow. Water properties at these depths in Indian Arm matched those of source waters in the vicinity of Van 34. No unusual change in any property was recorded at greater than about 75 m depth.

However, in the interval October 16 to November 7 changes occurred in water properties at depths exceeding 70 m in Indian Arm which cannot readily be explained in terms of estuarine exchange with resident waters inside Second Narrows. While changes were evident in oxygen and temperature distributions at 100 m depth at Ind 1.3, it is the increase in salinity at this location and depth which disallows interpretation in terms of ambient November conditions at Van 34.

As is illustrated by the salinity section 5.20(b) salinities in excess of 27.3^{o}/oo were recorded on November 7 at 100 m depth at both Ind 1.3 and Ind 1.5, the maximum value being 27.34^{o}/oo (σ_t = 21.03) at Ind 1.3. As no such high salinities were recorded anywhere in the Arm in October (Figure 5.18(b)) and as no in situ physical processes can account for such changes, it can be concluded that this water must have entered Indian Arm from Burrard Inlet. This conclusion is supported by the salinity distribution further toward the head which also shows evidence of intruding waters. Tongue-like structures in the 27.2 and 27.1^{o}/oo isohalines are indications of up-inlet displacement of waters in the 50 to 150 m depth range. The successively shallower inflections in these contours, towards the head, also indicate upward motion in the displaced waters. The effectively horizontal 27.2^{o}/oo contour at 150 m indicates minimal activity below this level, while the downturning contours near Ind 2.8 suggest only minor disruption at depths greater than 60 m near the head. Thus a mid-depth (shallower than 150 m) intrusion of high salinity water, extending well towards the head, is indicated by the November salinity data.

A less pronounced but still conclusive indication of intrusion is inferred from the oxygen section 5.20(d). The pocket at Ind 1.3, with oxygen concentration exceeding 3.8 ml/l is a disruption of the estuarine exchange pattern illustrated by the October oxygen section (5.19(d)). Oxygen isopleths sloping toward the head are further indication of a gradually rising, up-inlet flow as was suggested by the salinity data. The absence of oxygen observations at Ind 3 in November results in a speculative picture at the head, but based on salinity observations, the contours are here shown to level off. Consistent again with the salinity data is the indication by the horizontal 0.8 ml/l isopleth, of no motion below about 150 m. A possible conflict between the oxygen and salinity data is the apparently greater depth of the core of intruded water as indicated by salinity (100 m versus about 85 m). Such discrepancy may possibly be explained as evidence of differing rates of oxygen consumption at different depths.

Temperature data (Figure 5.20(a)) provide rather inconclusive evidence of a major intrusion, excepting the up-inlet tilt of the isotherms at depths less than 150 m. Finally the density section shows stable conditions with densities at depths greater than 100 m being almost identical to those illustrated by the october section 5.18(c). This suggests that at the time of observation in November, inflow had ceased, and conditions had had ample time to stabilize. The minor upswing of the 21.0 isopycnal north of Ind 2 is most likely a result of flow associated with the intrusion.

Waters resident inside Second Narrows at the time of the November cruise had salinities (maximum 27.14^{o}/oo at 40 m at Van 34) and densities (maximum 20.89 at 40 m at Van 34) which were lower than those of the core of intruded water at 100 m at Ind 1.3 (27.34^{o}/oo and 21.03^{o}/oo). As waters observed inside Second Narrows on the previous (October 16) cruise were even less dense, it must be concluded that the waters which intruded to 100 m depth in Indian Arm had their origin at least west of Second Narrows where densities and salinities in the appropriate ranges were observed both in October and in November, and further that following the period of inflow, dense water resident at depth at Van 34 experienced decreases in density to the levels recorded on November 7. Though the mechanism by which such exchange occurs is not evident from the present data, a process based upon tidal and wind forcing can be postulated. At some time between the October and November cruises, it is suggested that tide and wind conditions must have prevailed such as to transport water of sufficient density across the Second Narrows sill from the vicinity of Van 24, that after mixing the resulting density was equal to that of indigenous water at approximately 100 m depth in Indian Arm. In purely a density driven flow it must then have passed over the Indian Arm sill and settled to a level inside the Arm consistent with its density. In doing so, it would displace indigenous water northward, toward the head of the inlet. Again dependent on density, such displaced water could rise gradually in its passage northward.

Inspection of tide and wind data for the period October 16 to November 7 reveals that spring tidal ranges peaked on November 2 - 3 (following the neap tidal range minimum of October 24), and that an approximately 24-hour period of abnormally strong (33 km/hr daily mean speed) west northwesterly winds was recorded on October 28. It is plausible that such conditions could have initiated the observed intrusion.

It was earlier inferred from the density section 5.20(c) that by November 7, the intrusion has ceased. Although tidal exchange across Second Narrows must have continued to transport at least some small volume of dense water eastward, it is suggested that mixing effects most probably account for the observed decrease in density at depth at Van 34. With the November increases in precipitation and runoff providing substantial volumes of fresh water to the surface layer, downward mixing at Second Narrows is considered a probable mechanism by which the density of waters below sill depth at Van 34 could have decreased.

Thus emerges a picture of intermittent exchange of Indian Arm basin waters, principally controlled by tidal transport of waters from outside Second Narrows, and possibly assisted by wind forcing.

November 25, 1974 Burrard Inlet (no sections presented)

Salinity and density sections from this late November cruise, though similar in structure to the previously presented Burrard Inlet sections, show a distinct contrast in magnitudes to the November 7 observations (Figure 5.20). In that earlier instance, dense waters found in Indian Arm were traced to a source at least as far west as Van 24. On November 25 however, unusually dense waters observed at Van 24 and at Van 34 showed no evidence of intrusion into the Arm. Salinity increases of $1.25^{\circ}/oo$ to a maximum of $28.39^{\circ}/oo$ were recorded at depth at Van 34 through November. Likewise, density increased by 1.09, to σ_t = 21.98. Within Indian Arm, density increases at greater than 15 m depth over the same period were at most an insignificant 0.05, this being attributed to dropping temperatures. The confinement of this dense water to depths below that of the Indian Arm sill is explained by conditions in the outflowing surface layer. Through November, precipitation and runoff increased substantially, providing a much increased supply of fresh water to the surface layer. The increased volume caused a deepening of the outflowing layer with fresher water penetrating to greater depths than had previously been observed, and thus restricting the cross-sectional area of return inflow across the sill. The measured salinities clearly show that no significant volume of the dense water from 30 - 50 m depth at Van 34 passed unmodified into Indian Arm. It must thus be concluded that the return deep flow was sufficiently modified by mixing across the Indian Arm sill, that it acquired salinities (and densities) similar to those of indigenous Indian Arm water. Entrainment into the surface outflow, and continued turbulent mixing at Second Narrows must eventually then have modified the dense water at depth to yield the fresher December conditions described below.

December 5-6, 1974 Burrard Inlet (Figures 5.21(a) through (d))
Indian Arm (Figures 5.22(a) through (d))

Further influence of winter cooling was noted in Burrard Inlet in December as temperatures decreased by about 1°C at most depths from their November values. The nearly uniform water mass inside First Narrows had temperatures ranging between 8.5° and 8.9°C while to the west, lack of mixing near the surface and the remnants of summer heating at depth maintained temperatures between 7.6^{o} and 9.1^{o}C. Salinities showed an increased influence of Strait of Georgia water at depth outside the narrows, as 30^{o}/oo water now resided at 20 m depth near the sill. However, at depths shallower than 15 m in the approaches and throughout the rest of the inlet to the east, high precipitation and runoff in November accounted for a general decrease in salinity from previously recorded values. The dense deep water observed at Van 34 in late November had been replaced, the new waters showing a decrease in salinity of 2.20^{o}/oo to 26.19^{o}/oo and in density of 1.69 to 20.29. As illustrated by the salinity contours, mixing was intense through First Narrows. As station Van 27 was not sampled on this cruise, and as conditions at Van 24 were relatively uniform in the vertical, the intensity of mixing across Second Narrows was not clearly evident. Oxygen values had increased by about 0.5 ml/l throughout the entire system since early November.

By December 6, the initial effects of the October-November intrusion of mid-depth waters into Indian Arm were much smoothed. The pocket of water having salinities in excess of 27.3^{o}/oo which had earlier marked the core of the intrusion was no longer visible (Figure 5.22(b)). The rise in the 27.2^{o}/oo isohaline in the northern portion of the inlet from approximately 140 m depth in November to near 80 m depth in December is probable evidence of the mid-depth advection and mixing of these more saline intruding waters to yield increased salinities. The possibility remains as well that a minor additional intrusion could have contributed to the salinity (and density) increases. As no absolute conclusions can be drawn as to the extent of modification experienced by waters crossing the various sills at a given time, the continued presence of dense water at Van 24 implies the continued possibility of intrusion. At 200 m depth at Ind 2, salinities decreased by approximately 0.02^{o}/oo from November levels, indicating a continuation of relatively quiet conditions. Near the head, continued high runoff and precipitation account for the observed low salinities.

The temperature section 5.22(a) shows a downward sloping tongue of high temperature water extending from about 25 m depth at the head to near 60 m depth at Ind 1.5, which is consistent with earlier suggestions of northward advection of mid-depth waters, possibly rising toward the head. Nearer the surface, cold runoff waters, increased winter cooling and shallow exchange with Burrard Inlet waters account for observed structure (from head to mouth) in the temperature regime. At depth, temperatures had increased approximately 0.04^{o}C since November 7.

In the oxygen section 5.22(d), some degree of influence of the November intruded water or possibly of later intruded water is observed near 100 m depth at Ind 1.3 as the depression of the isopleths suggest a contribution of oxygen, through mixing and diffusion. At depth, consumption accounts for further observed decreases in oxygen concentration. By December 6 the value at 200 m depth at Ind 2 had dropped to 0.54 ml/l from its November 7 value of 0.70 ml/l. Finally, at depths shallower than 50 m and in the region north of Ind 1.5, oxygen values were higher than in early November, suggesting major influence by recently exchanged Burrard Inlet waters.

In summary, the December sections give no indication that further major exchange occurred at mid-depth after early November. Changes in salinity and density can possibly be explained by mixing of the previously intruded waters, however, the possibility remains that further small volume intrusions could have taken place. If so, property changes affected by the intruding waters were so small as to be masked by the potential effects of mixing. In any event waters which had entered and settled near 100 m depth on November 7 appear to have moved northward, and to have risen in the water column. There is continued evidence that estuarine exchange was taking place at depths shallower than 50 m near the mouth. At greater than about 125 m depth, little change associated with intruding waters had been felt.

<u>January 3, 1975 Burrard Inlet (no sections presented)</u>

Due to various ship and equipment problems on this January cruise, stations Van 27, 39 and Ind 1.5 were excluded from the sampling program. Neither was any secondary sampling conducted in Indian Arm. Consequently, insufficient data were available for the preparation of detailed vertical sections. From profiles at Van 24, 34 and at Ind 0, 1 and 2 it is possible, however, to identify basic conditions.

As was evidenced during November, significant increases in salinity (therefore, density) also took place at depth at station Van 34 through December, but there was still no indication of further major exchange of mid to deep Indian Arm waters. An approximate $1^{o}/oo$ increase in salinity was observed through the harbour east of Second Narrows, with increases from December 5 at 50 m at Van 34 being $1.29^{o}/oo$. In contrast, at 60 to 100 m depth in Indian Arm, salinity decreases of up to $0.2^{o}/oo$ were recorded, indicating an absence of recent mid-depth exchange. By January, precipitation and runoff had begun to decline, with the consequent weakening of surface outflow from Indian Arm. At depth, oxygen concentrations of about 0.5 ml/l continued to indicate quiet conditions, definitely confirming that there had been no major exchange before January 3.

January 23, 1975 Burrard Inlet (Figures 5.23(a) through (d))
Indian Arm (Figures 5.24(a) through (d))

The January 23 sections for Burrard Inlet show further evolution of the trends identified in the January 3 data. Further decreases in air temperature were accompanied by still lower water temperatures, with values throughout the system being between 7.5^{o} and $8.0^{o}C$. The high salinity waters from the approaches continued to mix across the sills of both First and Second Narrows, thereby increasing the salinity of waters in the inner basins. Salinities of $27^{o}/oo$ were recorded at 10 m depth at Van 34 for the first time in the study. Near the surface at Van 34, the freshening influence of Indian Arm outflow was still evident, though in a shallower layer than in December. Paralleling salinity, the density section shows σ_t values between 21 and 22 at greater than 15 m depth at Van 34, these being the highest densities yet observed inside Second Narrows. Finally, the oxygen section shows a further increase throughout the harbour of approximately 0.5 ml/l from December values.

Within Indian Arm, a major flushing event had commenced since January 3. While temperature, salinity and density changes associated with the intrusion were small (yet measureable), oxygen concentrations changed by up to 800% thus providing a most vivid indicator of the exchange and overturn. From the oxygen section 5.24(d) it is seen that oxygen rich waters had penetrated the entire deep basin of Indian Arm, displacing indigenous low oxygen waters upwards and toward the head. The oxygen minimum recorded at 50 to 100 m depth north of Ind 2.8 on January 23 identifies waters previously resident at greater than about 180 m depth in the centre of the fjord. Based upon the December distribution of oxygen, it appears that the 3.2 ml/l and 3.6 ml/l isopleths angling downwards toward the head (on Figure 5.24(d)) from the vicinity of Ind 1 mark an approximate boundary between the intruded waters to the south and the indigenous Indian Arm waters to the north. The non-conservative nature of oxygen concentration makes a clear definition of such a boundary difficult. Obviously there had been considerable mixing associated with the intrusion, as oxygen values in the deep water were less than 4.6 ml/l while oxygen values in the source water at Van 34 ranged between 5.0 and 5.5 ml/l. Such mixing, coupled with continued consumption must account for the observed moderation of oxygen extremes throughout the entire inlet. Even in crossing the sill near Ind 0, intruding waters at depth were being modified to lower oxygen content by mixing with low oxygen waters outflowing at the surface. In general terms, however, it is clear from section 5.24(d) that some of the old Indian Arm water had already left the Arm in the surface layer and that that which remained was restricted to depths less than about 110 m in the north and central reaches of the Arm. The remainder of the basin was now occupied by recently intruded waters.

Although such detail as to the distribution of intruded waters in the Arm is not as clear from the other sections in the set, various inferences can be drawn to support the above conclusion. Tongues in the 7.9^o to 7.8^o isotherms between Ind 1.3 and Ind 1.5 give indication of waters flowing down the southern slope of the inlet, while southward pointing tongues above 20 m on the temperature section again identify the outflowing surface layer. At greater than 100 m depth, the abundance of water having temperatures less than 7.8^{o}C is further confirmation of the intrusion. Higher temperature waters at mid-depth near the head are again interpreted as being the Indian Arm deep water of the December cruise. The prime feature of interest on the salinity section is the continuity of the 27.2^o/oo isohaline (and most probably the 27.3^o/oo isohaline) over the Indian Arm sill, which allows confident interpretation that waters from approximately sill depth at Van 34 had penetrated to the deeper parts of Indian Arm. Absolute increases in salinity at depth were in the range of 0.10^o/oo from early January values. The horizontal 27.1^o/oo isohaline marks an approximate lower boundary to surface outflow, while the slope near Ind 1 in the 27.2^o/oo isohaline is evidence of intrusion near this level as well. Similar comments apply to the density section, as the σ_t = 21.25 isopycnal (and most probably the σ_t = 21.3 isopycnal) are continuous over the sill.

In contrast to the October - November intrusion, when source waters were identified as existing only west of Second Narrows, this January event was clearly a density driven inflow of waters from the vicinity of Van 34. From conditions observed simultaneously in Burrard Inlet it is clear that the late January observations were of a dynamic process.

The overturn caused by the intrusion had clearly not stabalized. The intrusion itself may have been ongoing at the time of the January 23 cruise.

February 19-21, 1975 Burrard Inlet (Figures 5.25(a) through(d))
Indian Arm (Figures 5.26(a) through (d))

Rather minimal changes were recorded in conditions in Burrard Inlet during the first weeks of February. Temperatures decreased by an amount varying from 0.5^{o} to $1.0^{o}C$, marginally increasing density. Salinities increased only slightly, with the salinity of water at sill depth at Van 34 rising by approximately $0.2^{o}/oo$ to greater than $27.5^{o}/oo$, again causing an increase in σ_t. Density (σ_t) values at sill depth rose from 21.40 in January to 21.60 in February. Oxygen concentrations west of Second Narrows rose by a further 0.5 ml/l to nearly 6.0 ml/l, while near Van 34 values of about 4.5 ml/l, likely associated with outflow of low oxygen water, were recorded. While values changed as indicated above, the form of the distributions changed little, with the shapes of the contours on the February sections closely parallelling those for January.

The increased density of source waters near sill depth at Van 34 further continued the exchange of Indian Arm waters which had begun in January. Again referring first to the oxygen section, it is noted that oxygen values at all depths (except in a shallow surface layer near the mouth) increased during February, with changes ranging from less than 0.5 ml/l at depth to greater than 4.0 ml/l near the head. The small changes observed at depth indicate a lesser moderation of intruding waters due to mixing, as waters crossing the sill were now mixed with much more oxygen rich surface outflowing waters than was the case in January. Large oxygen increases recorded in waters near the head reflect the further displacement of waters from depth, upwards and toward the head. Waters shallower than about 25 m depth, north of Ind 2, again appear to have been pushed up the north slope, as was the case in January. These in turn must have displaced that portion of the pre-January deep water which resided here in January, and which by now had almost entirely been flushed out of the Arm in the surface layer. Low oxygen concentrations near the surface at the head in February marked the final manifestation of the presence of old, low oxygen water.

From the temperature, salinity and density sections, further evidence of continued and almost complete exchange is available. The substantial drop in temperature of waters deeper than about 20 m (certainly beneath the 7.5^{o} isotherm) cannot be ascribed to cooling but must rather be indication of a volume exchange of at least 80% of the capacity of Indian Arm during February. Likewise from the salinity section it is clear that at least those waters below the $27.4^{o}/oo$ isohaline had intruded since January, as no $27.4^{o}/oo$ water was found in the Arm previously. Again, the continuity of the $27.5^{o}/oo$ isohaline and the σ_t = 21.5 isopycnal over the sill suggests an ongoing exchange at the time these observations were recorded.

March 26, 1975 Burrard Inlet (no sections presented)

Indian Arm (Figures 5.27(a) through (d))

The almost uniform 7^{o}C water temperatures observed in Burrard Inlet in March mark the end of the winter cooling trend. Along with the commencement of an increase in air temperatures, small increases over previous water temperatures were recorded on this late March cruise. The distribution of salinity also closely matched that of February 19. While at sill depth at Van 34 salinity had increased by approximately 0.07^{o}/oo since the February cruise, there had been a 0.95^{o}/oo decrease at 50 m depth at this same station. Similarly, σ_t values were comparable (to within 0.04) to those of February 21 at sill depth, but had decreased by 0.78 at depth. Similar shapes of the contours in February and March reflect the basic similarity of conditions, with the exception of the noted density decreases at depth inside Second Narrows. Only in the oxygen distribution was there any major change, with increases throughout the inlet of 0.5 ml/l. Increases exceeding 1 ml/l at Van 34 most probably reflect increased oxygen content in the outflowing waters from Indian Arm.

The structure of the Indian Arm sections for late March suggests earlier exchanges at two levels across the sill. The following exchanges are postulated. As evidenced by water beneath the 7.1^{o} isotherm, the 27.6^{o}/oo isohaline, and possibly the deeper part of the 4.8 ml/l isopleth of oxygen, there had been further deep water intrusion down the south slope to the bottom, after the February cruise. The intruding volume was rather smaller than during February as the displacement of deep waters towards the head was apparently less. The development of an oxygen minimum layer extending southwards from the head between 30 m and 100 m depth was noted. The water in this tongue had entered the Arm earlier in February, possibly as deep water which was displaced upwards to about these depths before February 21. This water now formed an identifiable layer of older water which probably moved southward but was modified by mixing at some time following February 21. It is probable that changes in the deep water occurred shortly after the late February cruise, at a time when the density of deep water at Van 34 was still greater than that of deep water in Indian Arm. Later, however, as densities at Van 34 dropped, the water at sill depth at Van 34 must have reached a lower density such that it could no longer displace the deep water in Indian Arm. Most probably, small volumes of water continued to intrude at levels not much greater than sill depth; however, major deep water exchange had stopped. As intruding waters at these shallower depths penetrated further and further northward, the top of the oxygen minimum layer became more well defined. Prior to, and at the time of the late March cruise, this shallow intrusion represents a simple estuarine exchange with surface outflow and mid-depth inflow. Waters deeper than about 50 m had densities greater than did the inflowing waters, thereby preventing at least for a time, any further deep water exchange.

April 29, 1975 Burrard Inlet (Figures 5.28(a) through (d))

Indian Arm (Figures 5.29(a) through (d))

The late April sections illustrate a transition from winter to spring conditions. Warming at all locations in Burrard Inlet through April raised temperatures by 0.5 to 2.0^{o}C, with values now ranging between 7.3^{o} and 9.7^{o}C. Stronger temperature gradients had begun to develop near the surface. Salinities at less than 15 m depth in the approaches had decreased by up to $4^{o}/oo$, however, the $30^{o}/oo$ water below 20 m depth had not changed appreciably from March levels. In the harbour, lesser salinity decreases were recorded than in the approaches, with maximum changes being near $2^{o}/oo$. Waters deeper than the Indian Arm sill depth at Van 34 had experienced salinity decreases of up to $0.39^{o}/oo$, with corresponding density decreases of 0.40. Oxygen values were similar to those recorded in March, with small increases near the surface being ascribed to increased biological production.

The April sections for Indian Arm (Figures 5.29) indicate that further deep water exchange had taken place during April. As was the case with the October - November intrusion, the April changes cannot be explained in terms of ambient late April conditions at Van 34, but must again be the result of a period of dense inflow from the vicinity and west of Van 24. Following this period of inflow, tidal exchange across Second Narrows must account for the replacement of dense waters at Van 34 with the less saline waters observed there on April 29.

As in earlier months, the most pronounced changes were observed in the oxygen distribution. At all depths greater than about 90 m, oxygen rich water (oxygen concentration exceeding 5.2 ml/l) had intruded into Indian Arm. Consequently, the oxygen minimum layer which had developed in March must have been pushed upward. Its core rose from approximately 75 m in March to near 50 m in April, however, by this time oxygen consumption was contributing to changes in the distribution. Nevertheless to satisfy continuity, it must be inferred that the surface outflow volume had increased to compensate for the volume of inflow at depth. In addition to being forced upward, the oxygen minimum layer had become more elongated than in March, now extending south of Ind 1, almost to the south slope. Oxygen concentrations in the core had dropped by approximately 1 ml/l to levels below 3.6 ml/l, evidence of consumption associated with increased productivity near the surface. Similar evidence of consumption was noted at the deepest point in the Arm, as values dropped marginally below 5.2 ml/l. Estuarine exchange probably continued above sill depth, contributing to high oxygen values in the upper 40 m.

The salinity and density sections yield further evidence of dense intrusion at depth. The 27.6^{o}/oo isohaline rose from near 175 m in March to 65 m in April, with the actual salinity increase at 200 m at Ind 2 being 0.14^{o}/oo, from 27.60^{o}/oo to 27.74^{o}/oo. On this same cruise, such salinities were recorded within 5 m of the surface at Van 24, but were not observed at any depth at Van 34 nor at Ind 0, illustrating that deep water exchange had halted prior to April 29, and that the dense waters which must have resided at Van 34 during the exchange had subsequently been replaced. Increases in σ_t at depth in Indian Arm, corresponding to increases in salinity, were near 0.1.

As the deep exchange which took place in April involved warmer waters than those resident in the Arm during March, the structure of the April temperature section is complicated. Whereas in March, a temperature maximum layer had begun to develop, extending southwards from the head near 50 m depth, the April section identified a minor temperature minimum layer at about 75 m depth. Water temperatures between 7.2 and 7.3^{o}C at depth are further indication that the exchange took place early in the month, as late April temperatures even at Van 24 were up to 1.5^{o}C higher than this value. Nearer the surface, the dip near Ind 1.5 in the 7.6^{o}C isotherm is probable evidence of continued estuarine inflow penetrating to approximately 50 m depth.

This April cruise marks an end to the observation of major winter exchanges of deep water in this survey. No secondary sampling was again conducted in Indian Arm until late August. Observations at main-line stations Ind 1, 1.5 and 2 in the intervening months however, indicate that no further deep water exchange took place, and that the August section (later presented) well represents the return to summer conditions in the Arm.

June 13, 1975 Burrard Inlet (Figures 5.30(a) through (d))

The commencement of this second year of observations in Burrard Inlet yields distributions of properties similar to those recorded in 1974, but conditioned by the increased heating and lesser runoff volumes already noted for 1975. Mid-June temperatures near the surface in the approaches were higher in 1975 than those recorded two weeks later in the previous year. Similarly, due to the lower runoff peak in 1975, salinities were higher. The general forms of the June distributions, however, were similar to those observed previously.

Temperatures in June 1975 ranged from approximately 9^{o} to 16^{o}C, with the strongest gradients being observed in the upper 5 m of the water column. Continued mixing effects were noted in the temperature section across both First and Second Narrows, with Indian Arm surface outflow at Van 34 masking the impact in the near surface waters. Salinities in the range 16^{o}/oo to near 30^{o}/oo were recorded, with again the indication of considerable mixing through the Narrows. The dip in the 27 through $29^{o}/oo$ isohalines and corresponding isopycnals at Van 14 stands as an anomaly, as almost simultaneous observations at Van 14-2 and at 14-5 (data not shown) recorded salinities exceeding $27^{o}/oo$ at depths shallower than 10 m. Inspection of salinity profiles at stations Van 11, 14 and 17 gives no ready indication that a mis-sequencing of salinity sample bottles could account for the observed distribution. The oxygen section is typical of early summer conditions with high biological productivity keeping values above 6.5 ml/l in the surface layer, and with detrital consumption accounting for the lesser values at greater than 30 m depth. Density data from Van 34, Ind 0, 1 and 2 (not shown) indicate that estuarine exchange was restricted during June to depths shallower than about 40 m in Indian Arm.

August 18, 1975 Burrard Inlet (Figures 5.31(a) through (d))
Indian Arm (Figures 5.32(a) through (d))

With air temperatures having peaked in July, and with runoff volumes having dropped substantially from high June and July values, the August 1975 sections again illustrate late summer conditions in Burrard Inlet and Indian Arm. Surface temperatures of $17^{o}C$ recorded in August were down by $2.5^{o}C$ from those recorded in July, however, high temperatures and strong gradients observed in the upper 10 m (upper 15 m in the approaches) were consistent with earlier observations. As in July 1974, in August 1975 data show evidence of only minor mixing across First Narrows, although intense mixing across Second Narrows is still indicated by the diverging contours near 10 m depth. Salinities throughout the inlet generally exceeded $20^{o}/oo$, and in fact exceeded 30^{o}/oo below 40 m depth in the approaches. It is noteworthy that in the previous year, 30^{o}/oo water first appeared in late September. As in the temperature section, strong mixing is indicated across Second Narrows while anomalously weak mixing is indicated at First Narrows. Low precipitation and runoff values in August account for the high salinities recorded near the surface at Van 34 as outflow from Indian Arm was weak. Oxygen concentrations at depths less than 10 m remained high while further consumption decreases from July were noted at depth.

By August, with deep water intrusion into Indian Arm having ceased, a uniform horizontal distribution of all properties was noted at greater than about 50 m depth, consistent with observations in August 1974. Due to the extent of winter exchange and to annual differences in temperature and precipitation regimes, however, significant differences in property magnitudes were recorded from the previous summer.

Temperatures in the deep basin, though similar to April values, were 0.5^{o}C lower than 1974 values. Between about 60 and 100 m depth, mixing and the penetration of summer heating effects, however, had raised temperatures nearly to 1974 levels. At the surface, 1975 temperatures were up to 2^{o}C higher than those recorded in the previous summer. The observed structure in the 11.5^{o} through 13.0^{o} isotherms is continued evidence of estuarine inflow across the sill.

By August, salinity values at depth had decreased marginally from April maxima, but were about 0.3 to 0.4^{o}/oo above 1974 values. The 26^{o}/oo isohaline marks an approximate lower depth limit to estuarine exchange, as 26^{o}/oo water was present only deeper than 40 m in August at Van 34. Near the surface, higher salinity values than observed the previous summer are again consistent with weakened 1975 runoff: they do not, however, reflect the anomalously high precipitation recorded in this month. The higher densities recorded in August 1975 than in 1974 are a consequence of the winter exchanges and lower than average runoff.

Because of the major winter intrusions through 1975, the August oxygen section differs significantly from the August 1974 section; however, the former can be interpreted with reference to the April section (Figure 5.29(d)). By August, the confined oxygen minimum layer centred at 55 m depth in April had disappeared. There was, however, a minimum at about 90 m depth near the middle of the inlet. If consumption rates were equal at all depths, this shift would indicate a movement of the water mass in the minimum to greater depths in the months since April. However, due to varying concentrations of detrital material, oxygen consumption rates vary with depth. The shift is instead considered to be evidence of an imbalance between eddy transfer and rates of consumption. Below the depth of continued oxygen replenishment through estuarine exchange, oxygen values had dropped by up to 1.4 ml/l. Nearer the surface, due mainly to high productivity and surface exchanges, oxygen values remained generally in excess of 5.0 ml/l.

October 9, 1975 Burrard Inlet (Figures 5.33(a) through (d))

To conclude the survey, Burrard Inlet sections from October 1975 are presented. The general features here identified are compatible with patterns and mechanisms previously discussed. October water temperatures in the range 9^o to 12^oC were comparable to those recorded in 1974. The diminishing range of temperatures is evidence of the trend toward winter uniformity. Salinities between $23^o/oo$ and $30.4^o/oo$ were recorded, with the $30^o/oo$ isohaline now reaching 20 m depth at First Narrows. Low salinities near the surface are attributed to the extremely high precipitation recorded during this month (see Figure 4.1(a)). As usual, all sections illustrate the effects of strong tidal mixing through both First and Second Narrows. Finally, the oxygen section, with values ranging from less than 3 ml/l at depth to greater than 6 ml/l near surface illustrates a time of maximum consumption following the high productivity season.

CHAPTER 6 CURRENT METER MEASUREMENTS

6.1 Time-Series Current Meter Record

6.1.1 Location, Timing and Data Recovery

In an attempt to measure near-bottom currents at the mouth of Indian Arm, an Aanderaa recording current meter with attached temperature, conductivity and depth sensors was deployed in the vicinity of station Ind 0 on the cruise of December 5, 1974. The actual location of the mooring is illustrated in Figure 1.1(b). Moored in approximately 40 m of water, the instrument was suspended about 3 m from the bottom, between a buoyant subsurface pontoon above, and an acoustic release and concrete clump below. The meter recorded current speed and direction, temperature, conductivity and pressure at 15 minute intervals through the period December 5, 1974 to March 7, 1975. It was serviced once, on January 22, 1975. Deployment, servicing and recovery of the instrument, as well as the initial data tape translation were conducted under the direction of Mr. W.S. Huggett and Mr. F. Hermiston of the Tides and Currents Division, Canadian Hydrographic Service, Sidney, B.C. Detailed inspection of the resulting record revealed that the instrument recorded throughout effectively the entire interval, with the only significant data gap interpreted to be during about 12 hours on February 19, 1975. There are no obvious features in the data records of current or pressure to suggest sensor failure. Constant temperatures during intervals of up to about 30 hours in the temperature record, however, introduce a suspicion that small changes may at times have passed unrecorded. The overall trend in the temperature record does appear consistent with seasonal cycles described from bottle samples.

Similarly in the salinity record (calculated from the recorded conductivities and temperatures), constant salinities over occasional intervals of 6 to 20 hours were recorded after about one month's operation, giving this latter part of the time-series the same "clipped" appearance as that of the temperature record. It appears that these intervals of constant salinity were generally coincident with intervals of constant temperature, however, the temperature intervals were generally longer and were consistently more frequent. Figure 6.1 is presented to illustrate marked incidents of this kind during 7 days in February. Again, the appearance of the overall trend in salinity suggests that any instrument malfunction associated with these periods of constant salinity is in the resolution of small changes rather than in the absolute determination of conductivity.

6.1.2 Time-Series of Currents

The time-series of near-bottom currents recorded over the period December 5, 1974 to March 7, 1975 is presented in Figures 6.2(a), (b) and (c). Figure 6.2(a) which spans the period December 5, 1974 to January 4, 1975, is followed by Figures 6.2(b) and 6.2(c) which span the periods January 5, 1975 to February 4, 1975, and February 5, 1975 to March 7, 1975 respectively. The two upper traces in these figures present North-South and East-West component speeds respectively, while the lower trace is a "stick plot" of current vectors. The component traces are plotted from the individual samples, at a frequency of four samples per hour. The "stick plot" however, presents hourly vector averages from each hourly set of four samples calculated by components. In this "stick" representation, the direction of the vector is the true direction toward which the current flowed, while the length of the vector is a representation of current speed (see ordinate for scale). The common time scale for all three traces is presented at the bottom of the page; cruise numbers indicate the dates when water property sampling was accomplished.

An immediate interpretation from both the component traces and from the stick plot is that throughout the entire observation period, the flow was restricted to two rather narrow directional bands, centred at approximately 340° True and at approximately 160° True. While occasionally, currents flowed in significantly different directions from these, the majority of hourly average currents were within $\pm 10^{\circ}$ of these principal directions. From the Canadian Hydrographic Service navigational chart 3435 (Indian Arm) it is observed that the channel at the mouth of Indian Arm is oriented at 340° - 160° True. Thus, the current meter record first confirms that near-bottom flow is basically restricted to the long-channel directions, with significant cross channel flow being a transient feature, persisting at most for two to three hours. From these plots, maximum current magnitudes of approximately 35 cm/s are noted (infrequently), with mean speeds (over 2 to 3 days) appearing to be in the range of 10 - 20 cm/s.

The feature of principal interest in the context of winter exchange of Indian Arm deep waters is the variation in net inflow (outflow), deduced from the current meter record. Two basic flow regimes dominate the record, separated by transition periods. In some instances, (characterized, for example, by the interval December 5 - 7, Figure 6.2(a)) the semidiurnal tidal oscillation appears as alternating flow up and down the channel (i.e. toward 340^{o} and 160^{o} respectively). Little net inflow (outflow) over a tidal cycle is suggested by such a case. Through the majority of the record, however, (as characterized, for example, by the interval January 2 - 22, (Figures 6.2(a) and 6.2(b)), a second regime is evident, consisting of tidal oscillation about a mean inflowing current (towards approximately 340^{o}). Substantial net inflow at depth is suggested by this case, as no southward component of outflow is evident for periods of many days. The transition periods between these two regimes illustrate varying degrees of net inflow, dependent upon the extent of down channel outflow. A more comprehensive discussion of the inflow (outflow) characteristics is later presented with an averaged form of the current meter record.

6.1.3 Time-Series of Temperature and Salinity

Figure 6.3 has been included to illustrate the basic features of the time-series records of temperature and salinity. These records have again been plotted from the full set of data, at four points per hour. The interval here presented, December 5, 1974 through January 4, 1975 (in conjunction with the earlier presented Figure 6.1) exhibits all the principal short time-scale features of the entire record. Fluctuations of up to 1.1^{o} were recorded over periods of less than 6 hours on a number of occasions, however, more typical changes in the range of 0.2^{o} - $0.4^{o}C$ appear frequently. While it must be assumed that much of the temperature fluctuation over periods of a few hours is coupled to tidal motion, the strong semidiurnal tidal frequency which was clearly evident in the component traces of Figure 6.2 is not readily apparent except in scattered instances, in the temperature record. Examples of the earlier mentioned intervals of constant temperature are exhibited on December 15 - 16 and again on December 22 - 23. While these observations do not necessarily imply a faulty sensor, (since changes of less than 0.1°C would have been unresolvable with the Aanderaa's thermistor) it appears likely that many of the expected small fluctuations in temperature were not recorded. As the averaged temperature record is later employed only to identify trends and not to make absolute comparisons of temperatures, the bias introduced into long-term averages by these occasional intervals of poor resolution is not expected to be significant.

In contrast to the temperature record, the early part of the salinity trace (Figure 6.3) shows little if any indication of data loss. Typical fluctuations of up to about 0.1°/oo were observed over most intervals of one to two hours. Maximum fluctuations of up to 1.1°/oo in intervals of about six hours were recorded (see December 9, Figure 6.3). Such changes represent the extremes (over intervals of a few hours) for the entire record. After January 2, 1975, short-term salinity changes in excess of 0.5°/oo were seldom recorded. It is after this time as well that the salinity record shows possible evidence of data loss due to poor resolution of small fluctuations. A semidiurnal tidal oscillation is more evident in the salinity than in the temperature record.

6.2 Averaged Time-Series Current Meter Record

6.2.1 Averaging

In order to illustrate the character of net inflow (outflow) at depth, a simple averaging was undertaken to eliminate the major tidal component from the time-series of current, temperature, and salinity.

As earlier noted, the most significant tidal constituent in the area of Burrard Inlet is the Principal Lunar M_2 component, having a period of 12.42 hours. To remove fluctuations at this frequency from the time-series records, running means over six M_2-cycles, (74.5 hrs, approximately three lunar days) were calculated. Each successive 74.5 hour interval commenced 24 hours (approx. two M_2 periods) into the preceding interval. Averaged component and stick plots of the records (corresponding to those of Figure 6.2) are presented as Figure 6.4. Similarly, averaged temperature and salinity traces (resulting from those partially illustrated in Figure 6.3) are presented as Figure 6.5.

6.2.2 Time-Series of Averaged Currents

The principal feature of both the component and stick plots of Figure 6.4 is the persistent net inflow (directed to the north northwest) recorded through the entire observation period. This is consistent with earlier conclusions drawn from the analysis of property distributions. An estuarine circulation of surface outflow and subsurface inflow during December through February was earlier inferred from the vertical sections for Indian Arm (Section 5.3). It is noted from Figure 6.4 that on only four brief occasions between December 5, 1974 and March 1, 1975 did the net inflow reverse. On these instances, mean outflowing currents of less than 3 cm/s persisting for intervals of only two to four days represent a very small volume transport out of the Arm (at depth) in comparison to the inflow volume transported by currents of 4 - 12 cm/s which persisted at times for 15 - 30 days. Near the end of the recording interval (during the first week of March 1975) a more significant outflow at depth had commenced as mean current speeds reached nearly 7 cm/s. Separated by the brief periods of outflow, three major periods of inflow are identified on Figure 6.4. These are:

December 14	- December 27	14 days
December 29	- January 24	27 days
January 27	- March 1	33 days.

6.2.3 Time-Series of Averaged Temperature and Salinity

Visual inspection of the averaged temperature and salinity traces, Figure 6.5, reveals strong correlation between changes over a few days in these properties and changes in current pattern illustrated in Figure 6.4. The early stages of the latter two of the three major periods of inflow are seen to correspond to times when rather sharply decreasing temperatures and increasing salinities (therefore, increasing densities) were being recorded. In a like manner, the late stages of net outflows were accompanied by increasing temperatures and decreasing salinities, i.e., decreasing densities. The correlation between temperature and salinity changes and currents associated with the onset of the first inflow period is not as strong. The commencement of this period from December 14 was accompanied by the usual drop in temperature as were the other periods, however, no significant increase in salinity was recorded. As a brief interval of net outflow developed on December 27, water temperatures continued to fall, rather than showing the usual increase. A sharp decrease in salinity was, however, recorded at this time.

6.3 Relation of Current Meter Record to Property Distributions

The above described observations appear to be fully consistent with changes in the Indian Arm property distributions earlier discussed in section 5.3. It will be recalled that major deep water exchange was noted to have commenced at some time following the cruise of January 3, 1975, and to have continued into April of that year.

The December 14 - 27 inflow identified on Figure 6.4 is seen from the temperature and salinity data of Figure 6.5 to have been of considerably less dense water than were the later inflow events. No major changes were observed in the denser water at depth in Indian Arm during December and inflowing waters at this time were shown to have penetrated no deeper than to about 60 m inside the sill. It must, therefore, be concluded that this December event was essentially an estuarine inflow across the Indian Arm sill.

The second major inflow event commenced about five days prior to the January 3, 1975 cruise. As no unusual changes in property distributions at depth were recorded on this cruise, and as significant salinity increases in the inflowing water did not commence until about January 2 (see Figure 6.5) it is probable that the inflowing waters in the first few days of this period penetrated to only mid-depth (less than 100 m) in Indian Arm. Commencing on January 3, however, the mean salinity of the inflowing water rapidly increased by about 0.7^{o}/oo, providing sufficiently dense water to penetrate to the greatest depths in Indian Arm. With minor fluctuations in mean current speed (Figure 6.4) and in salinity (density) this strong inflow continued until approximately January 16 at which time a decrease in mean current speed commenced. By January 24, when the net inflow ceased, the mean salinity at the current meter site had decreased by about 0.4^{o}/oo. As confirmed on the cruise of January 23, however, this 27 day period of net inflow had transported sufficient water to displace a significant volume (see estimates in following section) of indigenous Indian Arm water. Between January 24 and January 27 inflow and outflow intensities were similar, such that almost negligible net transport was experienced. During this time, temperature passed through a maximum and salinity and density passed through minima at the current meter site on the sill.

About January 27, the third major interval of net inflow, with its associated density change, commenced. Similar in most respects to the previous interval, this event continued for 33 days until significant outflow commenced again about March 1. Increasing dominance of outflow at the depth of the current meter in the ensuing week then led to the substantial net outflow noted in the final few days of the record of Figure 6.4. That a major inflow had occurred during the period January 23 to March 7 was illustrated earlier from property sections through Indian Arm (section 5.3). Thus, consistency is again observed with the implications of the current meter record.

It is clear from the mean temperature and salinity data of Figure 6.5 that the different flow regimes past the current meter are associated with waters of different density. In all instances of net outflow after mid-December (December 27 - 29, January 24 - 27, and post March 1), the outflowing water was of relatively lesser density than was water of the preceding (and for the first two instances, of the following) inflow periods. Comparison of bottle sample salinities from 30 m and 40 m depth at Van 34 at times of net outflow (for example December 27 - 29, and January 24 - 27) with salinities determined at the current meter (37 m depth) at the corresponding times gives no indication that it is the density of source waters at Van 34 which ultimately controls the nature of deep flow into Indian Arm. Even during these periods, the salinity (and, therefore, the density) of waters in the depth range 30 m to 40 m at Van 34 was at least a few tenths of a part per thousand (a few tenths in σ_t) higher than the salinity of waters surrounding the current meter. Maximum salinity excesses of greater than $1^{o}/oo$ were recorded at times, of the 40 m bottle sample over the simultaneous measurement at the current meter. Thus, it must be concluded that the less dense water flowing past the current meter during times of net outflow is a deep manifestation of lighter Indian Arm surface outflow. The mechanism which determines the depth of penetration of this outflowing layer is not evident from the present data base.

6.4 Deduced Versus Measured Inflow Volumes

6.4.1 Method

Property distribution data from the cruises of January 23 (Figure 5.24) and February 19 and 21, (Figure 5.26), coupled with the averaged current meter record (Figure 6.4), provide an opportunity for the comparison of deduced and measured inflow volumes. Simply, the areas under the component curves of averaged speed, between selected dates (the run past the meter in the north and west component directions) are calculated. In conjunction with an assumed cross-sectional area of inflow, these are used to generate estimates of inflow volume. These are compared with estimates of inflow volume deduced from the property distributions. Computations are now undertaken to allow comparisons of measured versus deduced inflow volumes for the latter two inflow intervals of Figure 6.4.

6.4.2 Preparatory Assumptions and Calculations

An element required in making speed and volume comparisons is the assumed cross-sectional area of inflow past the current meter. For the purposes of an initial comparison, idealized estuarine circulation is assumed, with an outflowing surface layer and an inflowing deep layer, through both of which a uniform (but different) current profile exists. Thus, currents measured by the near-bottom meter in the inflowing layer are at this point assumed to be representative of the entire layer. Maximum depth at the location of the current meter is 40 m. Two calculations of cross-sectional area of inflow have been undertaken, assuming outflowing surface layer depths of 10 m and 15 m respectively. The resultant cross-sectional areas of inflow for the 1450 m channel width are:

(a) for 10 m surface layer: 1.59×10^4 m^2

(b) for 15 m surface layer: 1.06×10^4 m^2.

In preparation for making estimates of intrusion volumes from vertical sections, an irregular three dimensional grid was visualized enclosing Indian Arm, and volume estimates for each grid element were made. The Arm was divided along its length into eight segments, each having a relatively uniform width. A representative cross-section was plotted across each segment, and its area calculated. Multiplication by the length of the segment then gave an estimate of volume of the segment. The Arm was further hypothetically sectioned into 10 m layers, and the volume of each such layer within each segment was calculated. With this information it is quickly possible to make reasonable volume estimates from longitudinal sections.

6.4.3 Inflow Interval December 29, 1974 to January 24, 1975

From Figure 6.4, a net inflow at depth is noted over the period December 29, 1974 to January 24, 1975. Water property sampling in Indian Arm was conducted twice during this period, on January 3 and again on January 23. As no change in water properties at depth in the Arm was evident on the January 3 cruise (from early December conditions) it was earlier concluded in Section 5.3 that inflow between December 5 and January 3 was restricted to at most mid-depth. Thus, it is suggested that the probable duration of the inflow event which led to the overturn identified by January 23 was about 21 days, commencing on January 3. Further justification for this assumption is that any water which intruded to mid-depth between December 29 and January 3 was likely itself replaced when the more dense intrusion commenced. On this basis, a period of 21 days of net inflow (leading to the changes recorded on January 23) is assumed in the following calculations.

In the discussion (Section 5.3) of the January 23 Indian Arm oxygen section, Figure 5.24(d) it was shown that the 3.2 ml/l or the 3.6 ml/l isopleth of oxygen marks an approximate boundary between intruded and indigenous waters. Maintaining this as an assumption, the volume of intruded water north of Ind 0 to the 3.2 ml/l isopleth, and at depths greater than 10 m, was calculated to be 1.24×10^9 m^3.

In summary then, the following quantities have been deduced or measured:

- inflow volume (from property distributions) $V = 1.24 \times 10^9\ m^3$
- cross-sectional inflow area assuming a 10 m deep surface layer $X_1 = 1.59 \times 10^4\ m^2$
- cross-sectional inflow area assuming a 15 m deep surface layer $X_2 = 1.06 \times 10^4\ m^2$
- period of inflow $t = 21$ days

Employing the earlier described method, the areas under the component traces of Figure 6.4, between the dates of January 3 and January 23 were computed yielding: (for the components of water run past the meter)

Northwards 1.78×10^5 m

Westwards 7.24×10^4 m.

From these a resultant run of 1.92×10^5 m was calculated. Again employing the two cross-sectional areas discussed in section 6.4.2, inflow volumes (estimated from the current meter record) were calculated as:

$V_1 = 3.05 \times 10^9\ m^3$ for 10 m surface outflow

$V_2 = 2.04 \times 10^9\ m^3$ for 15 m surface outflow.

The comparative figure, deduced from water property measurements will be recalled to be $1.24 \times 10^9\ m^3$.

6.4.4 Inflow Interval January 27, 1975 to March 1, 1975

The final inflow event identified on the current meter record extends from January 27 to about March 1, 1975. For the purpose of volume calculations, however, consideration must be restricted to a period spanned by cruises, over which changes in property distributions were measured. During this final inflow event, the cruise of February 21 provides an appropriate opportunity for such calculations. From the current meter record, an interval of effectively zero net outflow is evident between January 24 and January 27. Thus, for the purposes of present calculations, it can be assumed that the changes in property distributions recorded on February 21 (from January 23 conditions) actually evolved over the period January 27 to February 21; a span of 26 days.

Earlier discussion in Section 5.3 illustrated that major exchange had taken place between January 23 and February 21. It was concluded that waters at all depths beneath the 7.5^o isotherm (Figure 5.26(a)) had intruded since the late January cruise. Accepting this isotherm as a boundary, and assuming a 10 m thickness for the outflowing surface layer, a minimum intruded volume of $1.85 \times 10^9\ m^3$ was calculated. (It is noted that alteration of surface layer thickness to 15 m would cause a reduction of only 3% in the estimated volume of intrusion.

This effect is considered insignificant, in contrast to the case of estimation of cross-sectional area at the current meter location for which the change in surface layer thickness leads to a one-third reduction in area).

In summary, the pertinent parameters associated with the February intrusion have been calculated or estimated as follows:

- inflow volume (from property distributions) $V = 1.85 \times 10^9 \text{ m}^3$
- cross-sectional inflow area assuming a 10 m deep surface layer $X_1 = 1.59 \times 10^4 \text{ m}^2$
- cross-sectional inflow area assuming a 15 m deep surface layer $X_2 = 1.06 \times 10^4 \text{ m}^2$
- period of inflow $t = 26$ days

The areas under the component traces (the run past the meter) of Figure 6.4, between the dates of January 27 and February 21 were computed to be:

Northwards 1.50×10^5 m

Westwards 5.82×10^4 m.

The corresponding resultant run is 1.61×10^5 m, which when multiplied by the two estimates of cross-sectional inflow area yields estimated inflow volumes of:

$V_1 = 2.55 \times 10^9 \text{ m}^3$ for 10 m surface outflow

$V_2 = 1.70 \times 10^9 \text{ m}^3$ for 15 m surface outflow.

The comparative figure, deduced from water property measurements is $1.85 \times 10^9 \text{ m}^3$.

6.4.5 Summary and Discussion

Table 6.1 (below) has been compiled as a summary of the calculations in the preceding two sections. Also recorded here (in %) are comparisons of inflow volume to total Indian Arm volume for the two inflow events. Total Indian Arm volume is approximately 2.3 x 10^9 m^3.

TABLE 6.1

SUMMARY OF VOLUME COMPARISONS

Inflow Interval	Cross-Sectional Area (m^2)	Volume from Property Distributions (m^3)	% of Total	Volume from Currents (m^3)	% of Total
Jan 3 -	1.59 x 10^4	1.24 x 10^9	54	3.05 x 10^9	133
Jan 23/75	1.06 x 10^4	1.24 x 10^9	54	2.04 x 10^9	89
Jan 27 -	1.59 x 10^4	1.85 x 10^9	80	2.55 x 10^9	111
Feb 21/75	1.06 x 10^4	1.85 x 10^9	80	1.70 x 10^9	74

It is first to be noted that all comparative figures agree to within (at worst) a factor of 2.5, suggesting that scales estimated for the inflow events are certainly of the proper order of magnitude. Given this acceptance, consideration can be given to the noted differences, and various reasons for these can be suggested.

In the worst case, assuming a surface outflow layer depth of 10 m during the January inflow period, the inflow volume estimated from the current meter record is 2.46 times that estimated from property distributions. Increasing the surface layer depth to 15 m reduces this factor to 1.65. Two obvious possibilities exist to explain these differences. Firstly, it is unlikely that the total volume of water entering the Arm during the interval in question can be identified simply from a pair of cruises. Some of the water entering the Arm is probably subsequently entrained in the outflowing surface layer. This water would leave the Arm by the time of the second cruise, from which the volume estimates were made. Such a situation would lead to low estimates of volumes from the property distributions.

Secondly, it is to be recalled that all volume calculations were based on the assumption of a homogeneity of the current through the entire inflow cross-section. Certainly near the top of the inflow layer, a lesser velocity must have prevailed, as at some depth, representing the interface between the layers, the direction of flow reversed. Additionally, it is known that the source of the dense inflowing waters lies outside First Narrows to the west. It is not likely that this water enters the Arm as a uniform current across the entire inflow cross-section at the site of the current meter. It is possible that the dense water penetrates eastward into the upper Burrard Basin and then flows northwards into Indian Arm, driven by a pressure gradient. Alternatively, the dense flow would have to turn to the left as it approached Indian Arm from the vicinity of Second Narrows. In any event, flow velocities through the inflow cross-section along the shores adjacent to Ind 0 could be expected to be less than those at mid-channel. Such variation in current velocity would act to decrease the volumes estimated from the current meter record, yielding better agreement with volumes calculated from the property distributions.

Agreement between volume estimates for the February period is better than for a month earlier, with ratios between volumes calculated from currents and from properties being 1.37 and 0.92 respectively for 10 m and 15 m surface layer depths. Some combination of variation in inflow velocity through the inflow cross-section, exchange of recently intruded waters, and/or variation between 10 and 15 m in the depth of surface outflow could rationally explain these observed differences.

CHAPTER 7 SUMMARY

7.1 Summary of Major Observations

In Section 1.1 the three major objectives stated for this research project were:

a) to describe features of the large scale circulation pattern in Burrard Inlet and Indian Arm through analysis of annual changes in temperature, salinity and oxygen distributions.

b) to infer qualitative information concerning mixing processes in First and Second Narrows from the analysis of property distributions.

c) to estimate spatial and temporal scales associated with mid-winter deep water exchange between Burrard Inlet and Indian Arm, if such exchange were observed.

Analysis of serial CSTD casts taken over intervals of a few hours, temperature, salinity, and oxygen distribution data taken over a period of 18 months, and near-bottom currents at the mouth of Indian Arm recorded over a 93-day interval through mid to late winter, have to a large degree satisfied the demands of these stated goals. The following summary provides a synopsis of the major observations and conclusions.

From 11 short time-series of CSTD casts spanning intervals of from 3 to 10 hours, consideration is given in Chapter 3 to the effects of tidal flow at various Burrard Inlet stations (see Figure 1.1 for station locations). At all stations, changes of properties associated with tidal flow are identifiable to at least 3 m depth. During ebb tide through First Narrows, a shallow narrow westwards flowing surface jet appears to extend along the North Shore to at least the vicinity of Point Atkinson. Towards the southern side of the harbour mouth off Point Grey, the ebb flow is evidently broader and deeper. At First Narrows, the effects of tidal mixing are evident with property ranges being consistently less inside than outside the Narrows. Ebb tides influence waters to much greater depth inside (at least to 20 m) than outside the Narrows (approximately 10 m). Between First and Second Narrows, ebb flows seem possibly to be associated with an anticlockwise deep eddy. Significant mixing during flood tides is evident in both narrows: just inside each the incoming waters mixed to depths of 50 m, well in excess of the 14-18 m sill depths. In contrast, at the mouth of Indian Arm no significant changes of temperature and salinity due to single tides extend beneath the surface layer. A significant conclusion is that short-term effects on property distributions associated with tides are small compared with seasonal fluctuations.

The annual cycle of changes in the distribution of surface temperature and salinity in the outer harbour west of First Narrows is dominantly controlled by Fraser River water, presumed to enter from the North Arm. A surface tongue of this fresh water enters on the south side along Point Grey on flooding tides. There is clearly concentration of ebb flows along the North Shore. In addition, evidence was presented to suggest the occasional intrusion of dense water masses from the west in the vicinity of Point Atkinson.

The analysis of 18 months of temperature, salinity, and oxygen distribution data in Burrard Inlet and Indian Arm yielded a picture of seasonal property cycles and an overview of circulations through the system. The seasonal cycles of air and water temperatures are both in accord with the annual cycle of solar radiation. Surface temperatures occasionally exceed 20°C in the approaches in mid to late summer and drop to near 5°C in winter. Extremes through the harbour are somewhat moderated due to mixing. Coldest surface temperatures of between 4° and 5°C were recorded in low salinity water in Indian Arm during March. Seasonal ranges of temperature decrease substantially with depth: typical ranges at 50 m depth in the approaches, the central harbour and in Indian Arm are 6.5° to 9.5°C, 6.5° to 12.5°C and 7.5 to 11.5°C respectively. At 200 m depth in Indian Arm, temperatures during the survey varied only marginally from about 7.0° to 7.5°C.

Salinity is controlled jointly by runoff and by precipitation, with runoff being the dominant feature. Fraser River discharge, particularly during its peak in May to early July is of prime importance as far east as the region just inside First Narrows. Outside the narrows, salinities drop as low as 6 to 7°/oo during freshet. Even with the winter influx of Strait of Georgia water, when river discharge is much reduced, maximum surface salinities reach only about 27°/oo. The effects of Fraser River water are felt to all depths as absolute maximum salinities are restricted to about 30°/oo. Within the harbour, brackish surface outflow from Indian Arm is evident near Second Narrows and has increasing importance to the east of these narrows. Subsurface salinities in the harbour show influences of Strait of Georgia water from the approaches, increasingly modified by mixing in passage through First and then Second Narrows. Annual ranges at 50 m between the narrows are 28 to 30°/oo while at the same depth inside Second Narrows, ranges are 26 to 28.5°/oo. Within

Indian Arm, surface salinities drop to as low as $2^{o}/oo$ during the fall high runoff season and rise to about $25^{o}/oo$ at times of low runoff. Salinities at 200 m depth changed during the survey from about 27.1 to $27.7^{o}/oo$.

Oxygen concentrations in Burrard Inlet are generally between 4 and 7 ml/l, and reflect a seasonal cycle assumed to be controlled by biological production coupled with atmospheric exchange near the surface, and by detrital consumption at depth. Changes in the Indian Arm oxygen distribution, though partially controlled by these same processes, seem to be dominated by advective winter exchange.

Circulation in the Burrard Inlet/Indian Arm system is basically estuarine: relatively fresh surface waters normally flow down the inlet overlying more saline waters which enter from the Strait of Georgia. However, except in Indian Arm, the more dominant estuarine characteristics are obscured by mixing over the series of shallow sills.

As water leaves Indian Arm in a fresh outflowing surface layer it mixes with more saline water across the Indian Arm sill. It appears as brackish surface water outside the Arm and may be clearly traced almost to Second Narrows. Further mixing ensues at these narrows and again at First Narrows.

As dense water entering First Narrows at depth moves up the inlet, it is progressively freshened as downward mixing of near surface water occurs. A similar freshening at depth is more intense across Second Narrows.

Generally in the region between the narrows, the conflicting influences of fresh water outflow from Indian Arm, relatively fresh water tidal inflow at the surface across First Narrows (oscillating), and strong mixing with more saline waters across both First and Second Narrows, yield surface waters which are always more saline and cooler in summer than would be expected in a less complicated estuarine environment. A further deviation from a simple estuarine flow is that surface waters which pass to the west through First Narrows enter an area (the approaches) where densities at the surface are often lower than those of the outflowing waters owing to the influence of Fraser River water. This is to be contrasted with the more traditional situation where brackish surface outflow from a fjord enters a coastal region where the density of surface water is much closer to that of the open ocean. At those times when runoff is highest from the Capilano and Seymour watersheds, the estuarine nature of the flow through Burrard Inlet intensifies.

That a strong estuarine-type circulation persisted through the winter of 1974-1975 must be inferred from the observed intrusion of deep water into Indian Arm (Section 5.3 and Chapter 6). During September and early October 1974, waters from just outside Indian Arm were regularly penetrating into the Arm, across the sill to about 70 m depth. Between the cruises of October 16 and November 7, a more substantial intrusion took place at depth, with these denser waters penetrating at least to 100 m depth. A corresponding persistent fresher surface outflow was also evident. During January, the first of a series of major deep water intrusions to 200 m took place, replacing approximately 55% of the volume of Indian Arm. For purposes of comparison, it is noted that the volume of water contained in Burrard Inlet from the Harbour mouth at Point Grey/

Point Atkinson to Port Moody is effectively the same as that contained in Indian Arm north of its sill. The volume of that portion of Burrard Inlet lying east of First Narrows (excluding Indian Arm) is about 27% of this total. Thus for a 55% volume exchange to occur in Indian Arm, a substantial volume of dense water must have entered from outside First Narrows. Likewise to preserve continuity, an equal volume of less dense water which was displaced must have passed over all the sills, including First Narrows, in an outflowing surface layer. The evidence demands substantial volume exchange between Indian Arm and Burrard Inlet, with the origin of intruding waters being at least as far west as the approaches, and with large volumes of water leaving the system in a westward flowing surface layer.

Further estimates of inflow suggest that at least 80% of the volume of Indian Arm was replaced during the interval January 27 to February 21, 1975. Such a major exchange further supports the conclusions drawn above concerning significant net transport at depth across First Narrows accompanied by a corresponding net volume outflow near the surface.

Comparison of estimates of intrusion volumes made from changes in property distributions with estimates of inflow volumes derived from the record of near-bottom currents over the Indian Arm sill, for the January and February periods mentioned above yielded agreement to within at worst a factor of 2.5. Allowing for variation in flow speed through the inflow cross-section or possibly for greater volume exchange than the minimum deduced from the property distributions, these volume estimates were argued to be compatible.

As the current meter record ended on March 7, quantitative comparisons of intrusion volume estimates for ensuing months were not possible. It was noted, however, that deep water exchange did continue into April of 1975. Rough estimates from Figures 5.26, 5.27 and 5.29 suggest that volume exchanges of at least 30-40% and 40-50% respectively occurred over the periods February 21 to March 26 and March 26 to April 29, 1975. As these volumes are comparable to those exchanged through the January inflow period, it can be inferred that still, source waters must have come from the approaches through the western and central harbour, and that mean inflow speeds of 5-10 cm/sec in the deep inflowing layer must have persisted for a further two months from late February. Similarly, significant volume outflow must have persisted in the surface layer.

7.2 Potential Further Investigations

After conducting a study of this nature and performing the subsequent analysis, various questions remain, the answers to which require further observation and measurement. It is suggested that principal among these are the following:

1) What is the actual nature of flow across the sills at First and and Second Narrows? How is the overall estuarine circulation pattern modified by tidal flow through these restricted channels?

2) What is the actual mechanism which controls mixing in the passage of waters through the various narrows? Under what conditions does mixing relax and allow the passage of basically unmodified water masses as was recorded in July 1974?

3) In addition to density differences, what are the mechanisms which control inflow of near-bottom waters into Indian Arm? How do these vary? Under what conditions does outflow from the Arm occur at depth, thereby yielding periods of net outflow between extended periods of net inflow along the bottom?

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APPENDIX I PHOTOGRAPHIC DYE-TRACKING STUDY

Introduction

In the fall of 1975, a photographic dye-tracking technique was developed in an attempt to remotely measure tidal surface currents through First Narrows. In February of 1976, the procedure was successfully applied, however, time and priority constraints precluded application over a sufficiently long time to generate much useful data. The following discussion then, is included only to describe the technique and to present a sample of the resulting data.

Photographic Technique

As a data base for the generation of cross-channel velocity profiles, it was desired to acquire time-series photographs of lines of fluorescent dye in the narrows. The Lion's Gate Bridge which spans the Narrows provided the rigid camera platform required for the temporal analysis and thus fixed the camera-to-subject distance at 61 m. With this constraint and with resolution desired across the full 530 m width of the channel, it followed that the chosen lens would have to have an angle of view of at least 150^{o} to adequately cover the scene. Surveying the availability of lenses it was apparent that only "fisheye" lenses for the 35 mm format would be able to satisfy this width-of-field demand.

"Fisheye" lenses for 35 mm format have focal lengths of 16 mm or shorter. They have extremely wide angles of view, typically 180^{o} or wider. Because of this width-of-field, rectilinearity cannot be preserved. Thus, lenses of this sort generally have such pronounced barrel distortions that images are rendered as circular on the film. For some "fisheye" lenses the consequent distortions follow explicit projection formulae, thus making possible the analytical rectification of the "fisheye" image back to rectilinear format.

The lens selected for the present study was a 6 mm f/5.6 Fisheye Nikkor. It has an angle of view of 220^{o} and adopts the equidistant projection formula:

$$d = (C) \cdot (\theta) \tag{1}$$

d = distance to image centre

C = constant

θ = zenith angle.

(J.D. Cooper, Nikon Nikkormat Handbook p.6-5 (Amphoto, N.Y.))

Transformation

To develop analytically the coordinate transformation $F(d',\phi') = (D,\Phi)$ from the "fisheye" image to an unscaled real frame centred at the sea surface vertically beneath the camera, consider a point (d',ϕ') as in Figure I-1(a).

The bearing-preserving property of the projection formula (1) specifies Φ immediately:

$$\Phi = \phi' \tag{2}$$

Actual range D can be expressed (Figure I-1(b)) as:

$$D = H \tan \theta \qquad \text{for } \theta < \frac{\pi}{2} \tag{3}$$

$$= H \tan \left(\frac{d'}{C}\right)$$

The constant C is evaluated from the maximum dimensions of the "fisheye" image,

$$C = \frac{r'}{\theta \max} = \frac{r'}{110^0} \quad (4)$$

thus determining the basic transformation:

$$F\ (d',\phi') = (D,\Phi) = \left[H \tan\left(\frac{d'}{r'} \cdot 110^0\right),\ \phi' \right] \quad (5)$$

Finally, converting to the (X,Y) frame and introducing a scale factor $\frac{1}{s}$ we have:

$$X = \left[\frac{H}{s} \tan\left(\frac{(x'^2 + y'^2)^{\frac{1}{2}}}{r'} \cdot 110^0\right) / \left(1 + \left(\frac{y'}{x'}\right)^2\right)^{\frac{1}{2}}\right] \quad (6)$$

$$Y = \frac{Xy'}{x'}$$

Where the remaining unknowns x', y', and r' can all be measured from the "fisheye" image.

Field Operation

The physical operation of photographing the dye lines involved the mounting of a Nikon F-250 motor-drive system, with the 6 mm lens, on a painter's trolley beneath the car deck of the Lion's Gate Bridge. The optical axis was oriented normal to the water surface. Built-in lens filters 057 or R60 were employed to enhance the water-dye contrast on the black-and-white images.

Lines of 20% (by weight) Rhodamine WT solution were introduced across the channel from a small skiff and were photographed at fixed time intervals as they passed under the bridge.

Analysis and Presentation of Results

Position Transformation

The initial steps of analysis were the sorting, documentation, and screening of the sets of images from individual dye lines in order to choose those which displayed best contrast. These selected sets were then printed in 10 x 10 inch format with principal point and fiducial marks overlaid, thus establishing uniform references for the measurement of ranges and bearings.

The position of the leading edge of the dye line on each successive print was mechanically digitized. This coordinate information was then transformed via relations (6) to yield the rectilinear (X,Y) coordinates. Figures I-2(a) through I-2(d) present the sequential transformed positions of four particular lines, along with corresponding tidal information. The time increment is uniform within each set of lines but varies from figure to figure. The figures follow a tidal sequence from approximately one half hour after high slack to approximately one half hour before full ebb on the afternoon of February 9, 1976.

Velocity Calculations

To facilitate the calculation of velocities, plots corresponding to Figures I-2(a) through I-2(d) were generated at a scale of 1:1500. For each plot, a single cross-channel profile line was selected approximating the mean horizontal dye line position. A set of "long-channel" axiis were then created with the exact orientation of each particular axis adjusted to match the apparent flow direction at the corresponding sampling point on the cross-channel profile line. Digitization of the axis intersections with each sequential dye line yielded a series of spatial intervals representing the distance travelled in one time increment. In this manner, mean velocities were calculated for discrete points along the profile line. Figure I-3 is the presentation of the resultant mean velocity profiles for the four data sets.

Summary

A wide field of view and limited camera-to-subject distance dictated the use of a "fisheye" lens to photograph the passage of dye lines through First Narrows. Transformation of distorted "fisheye" images via the equidistant projection formula yielded sequential position plots and velocity profiles in rectilinear coordinates.

FIGURES

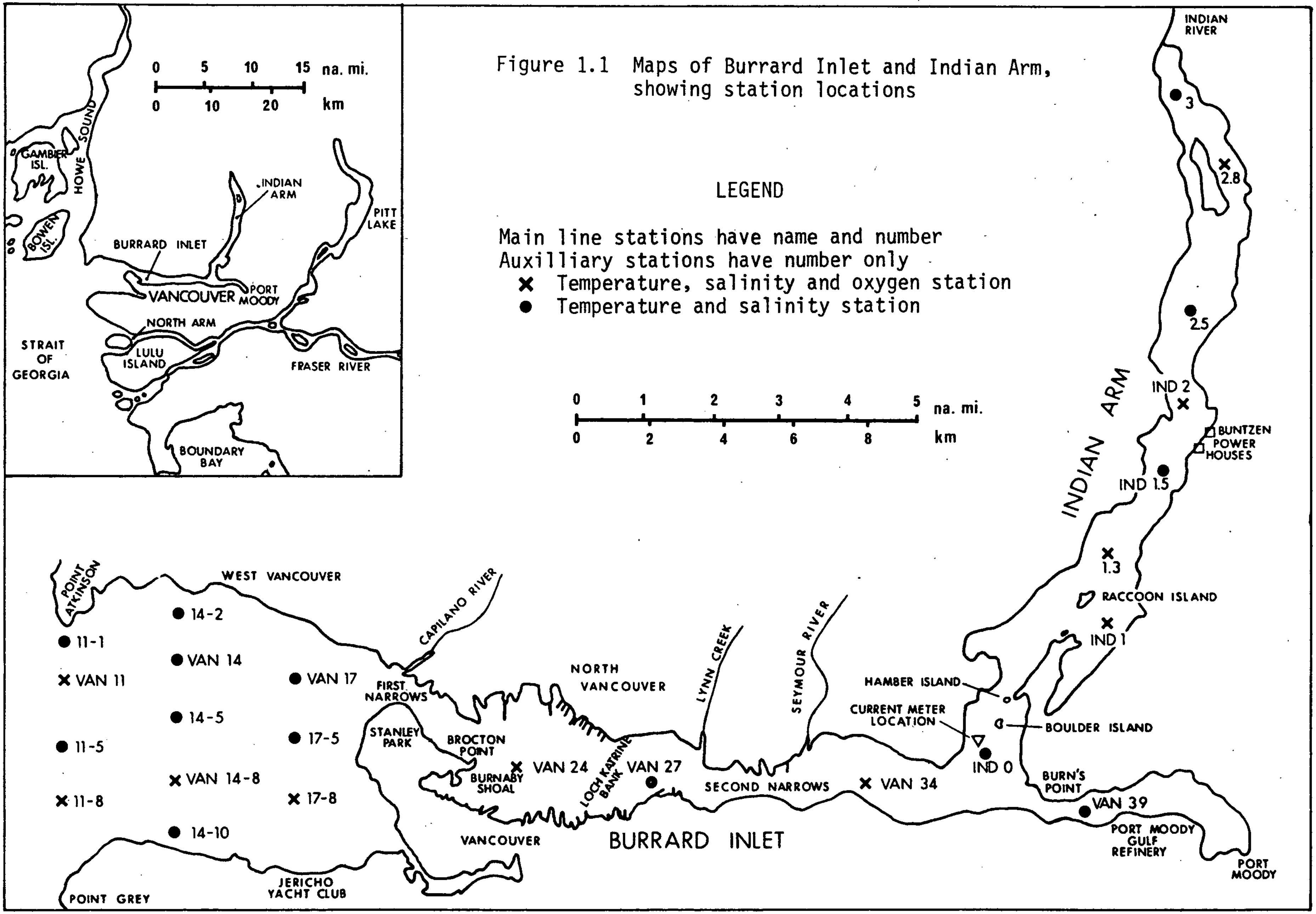


Figure 1.1 Maps of Burrard Inlet and Indian Arm, showing station locations

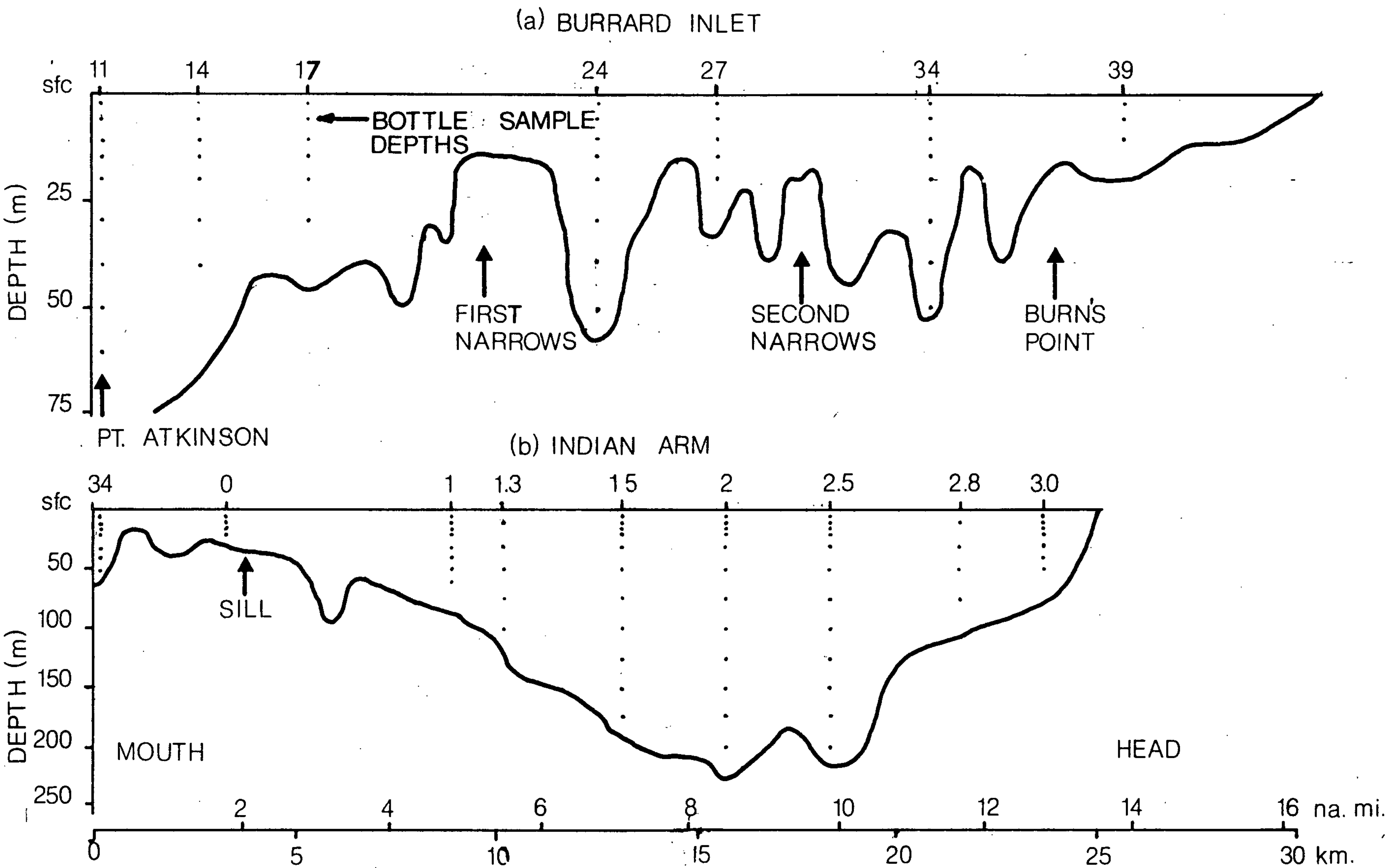


Figure 1.2 Longitudinal depth profiles of (a) Burrard Inlet and (b) Indian Arm

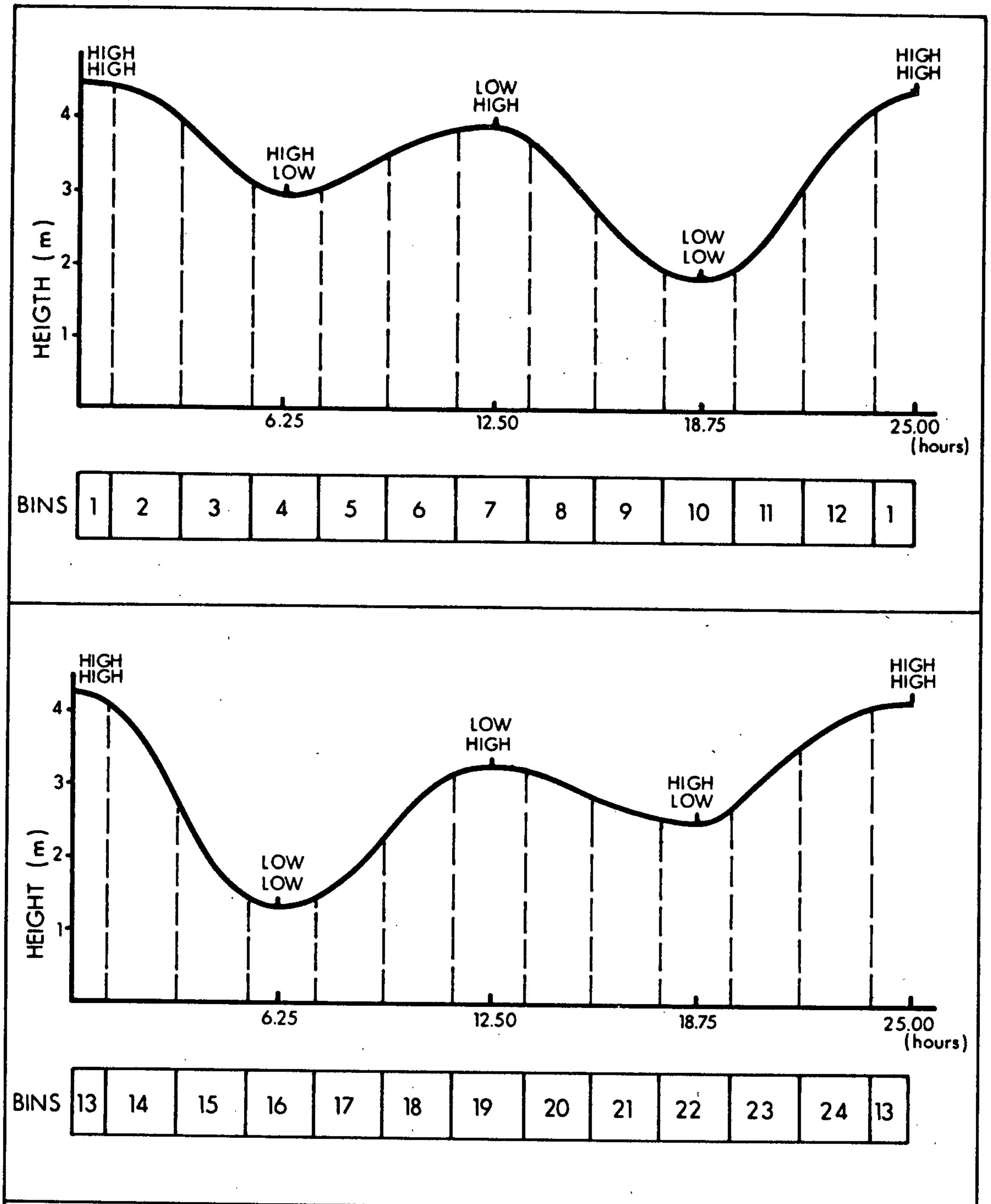
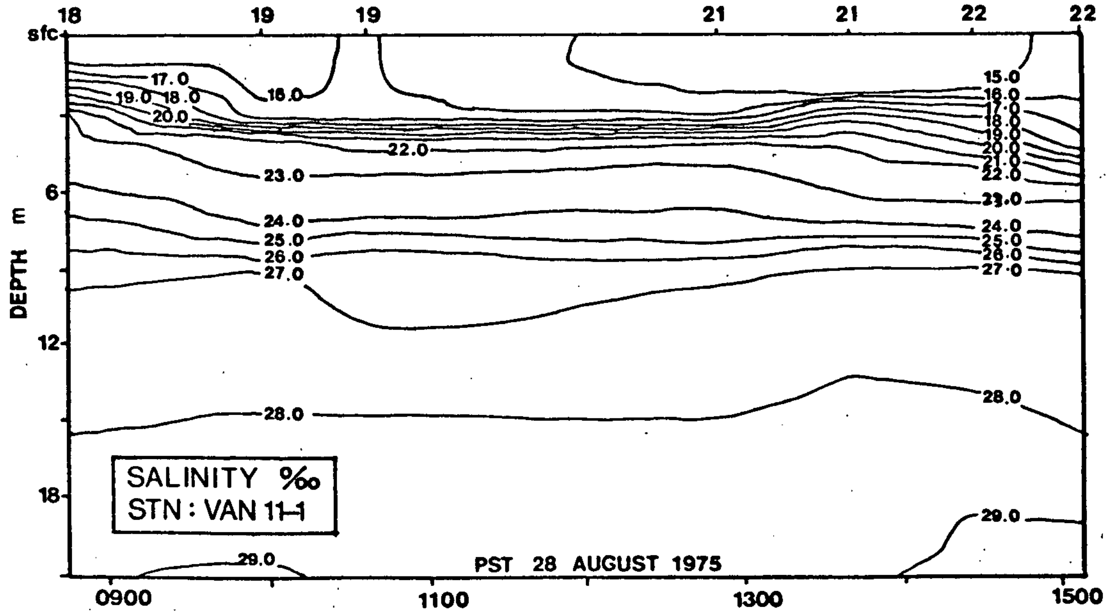


Figure 3.1 Empirical tidal curves (representative of Burrard Inlet tides) showing "tidal bin" definitions

(a)



(b)

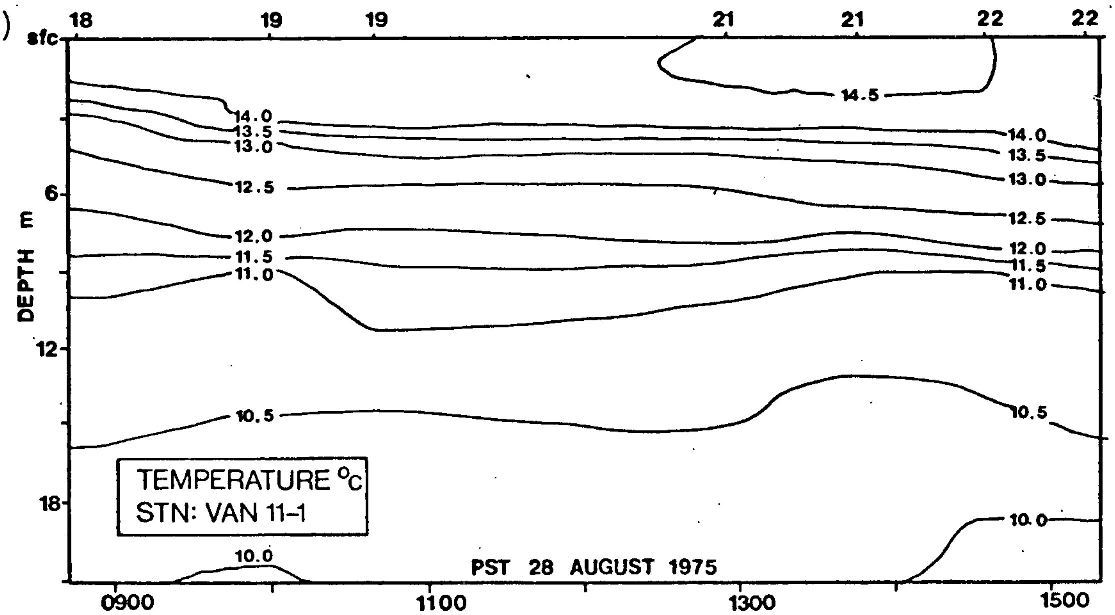
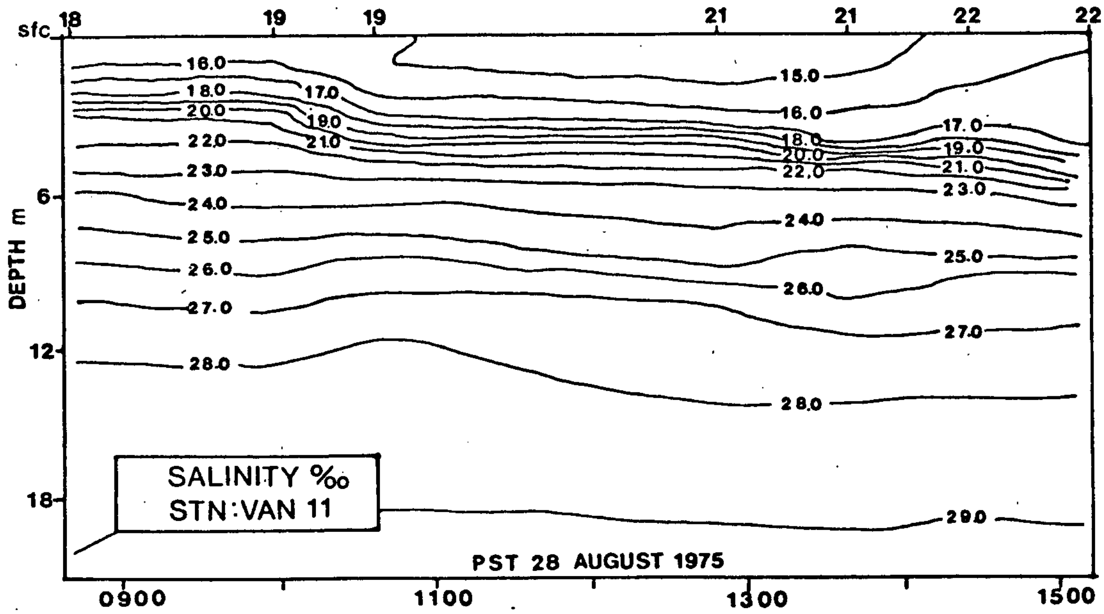


Figure 3.2 Time-depth sections of (a) salinity and (b) temperature at Van 11-1, August 28, 1975

(a)



(b)

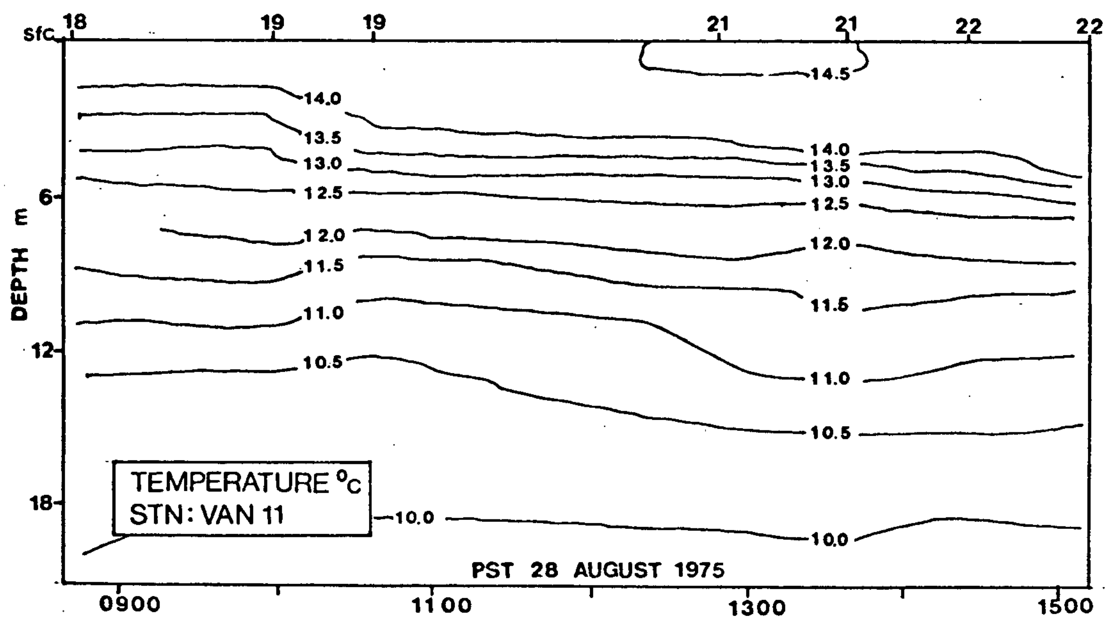


Figure 3.3 Time-depth sections of (a) salinity and (b) temperature at Van 11, August 28, 1975

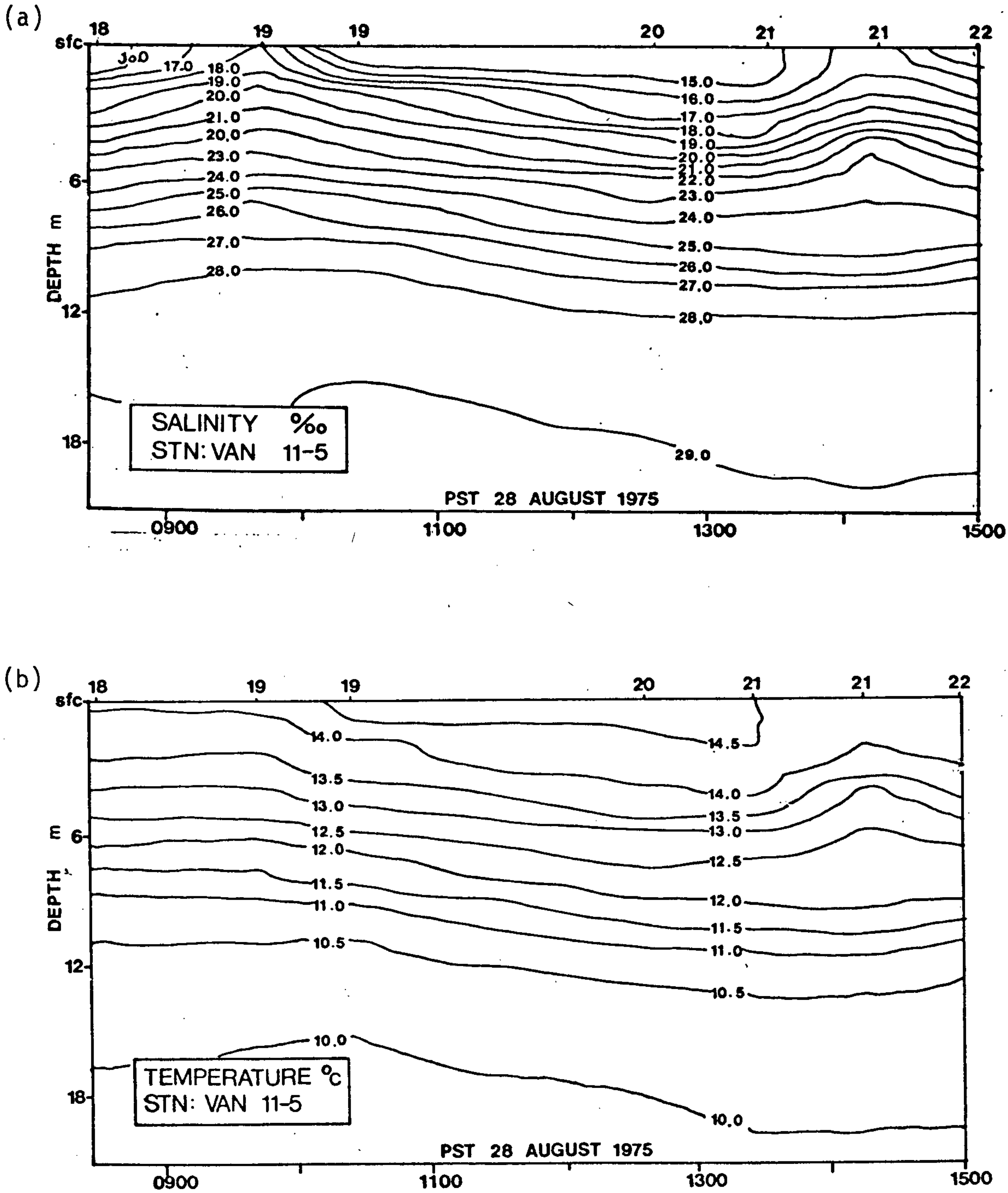
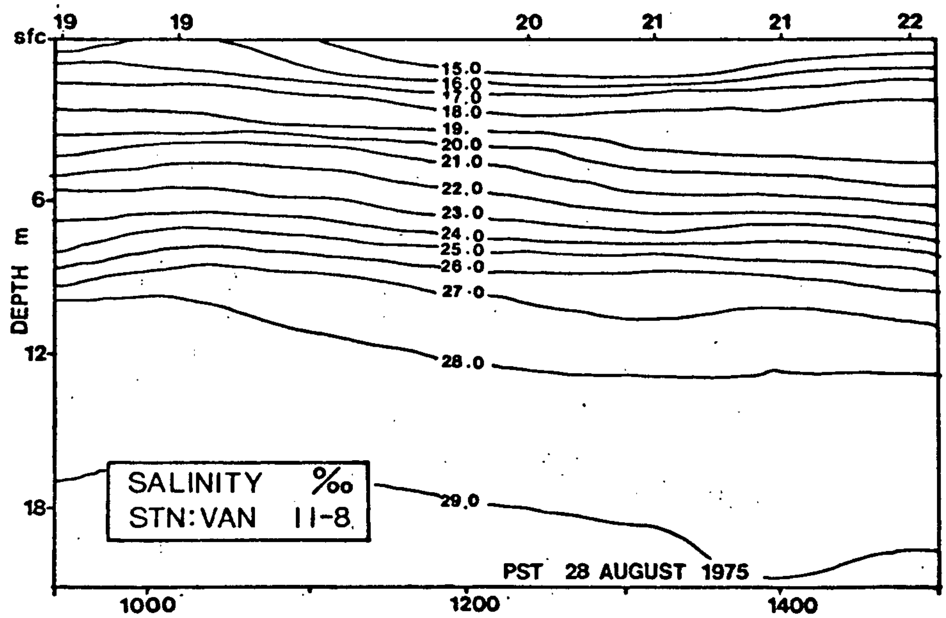


Figure 3.4 Time-depth sections of (a) salinity and
(b) temperature at Van 11-5, August 28, 1975

(a)



(b)

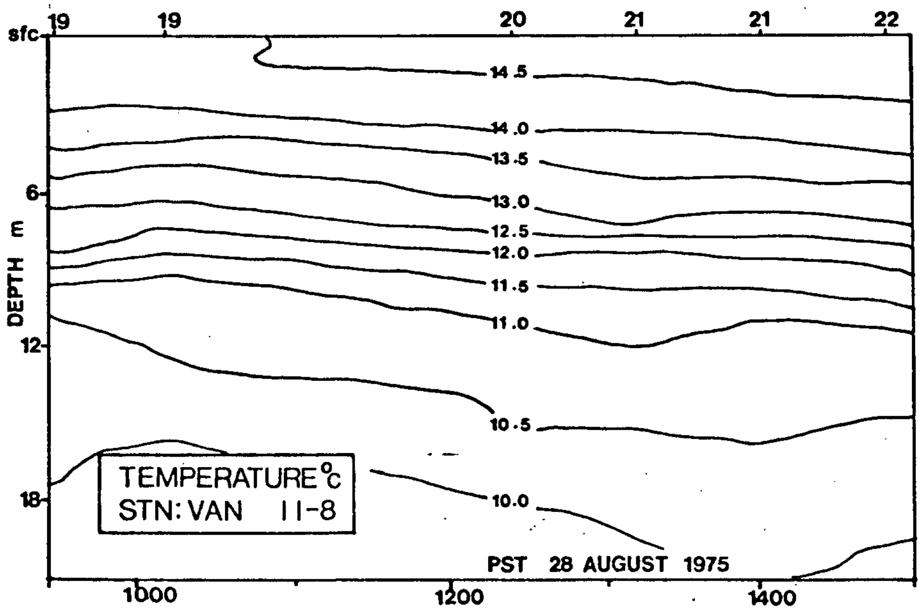


Figure 3.5 Time-depth sections of (a) salinity and (b) temperature at Van 11-8, August 28, 1975

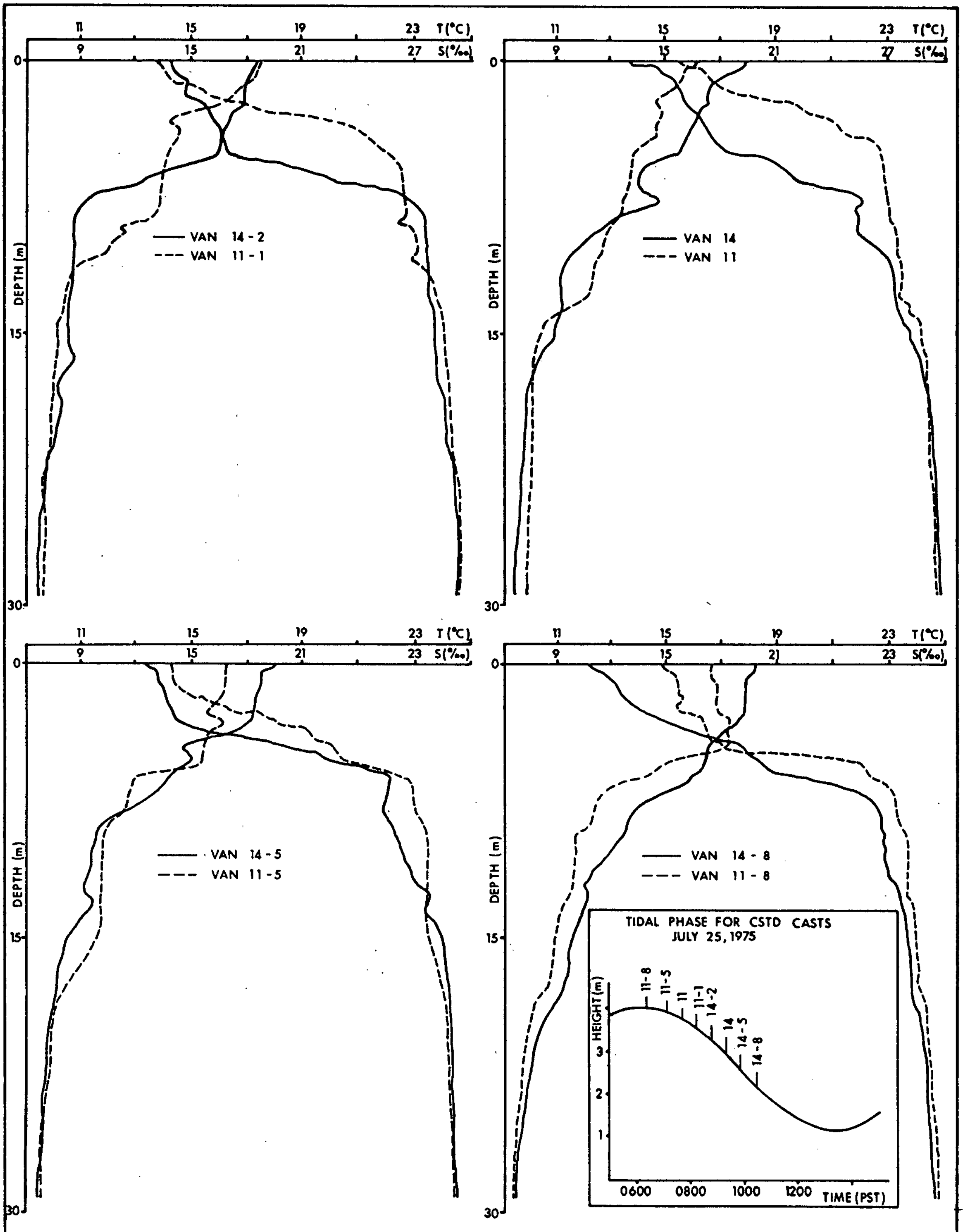


Figure 3.6 Comparative temperature and salinity profiles from Burrard Inlet Approaches, July 25, 1975

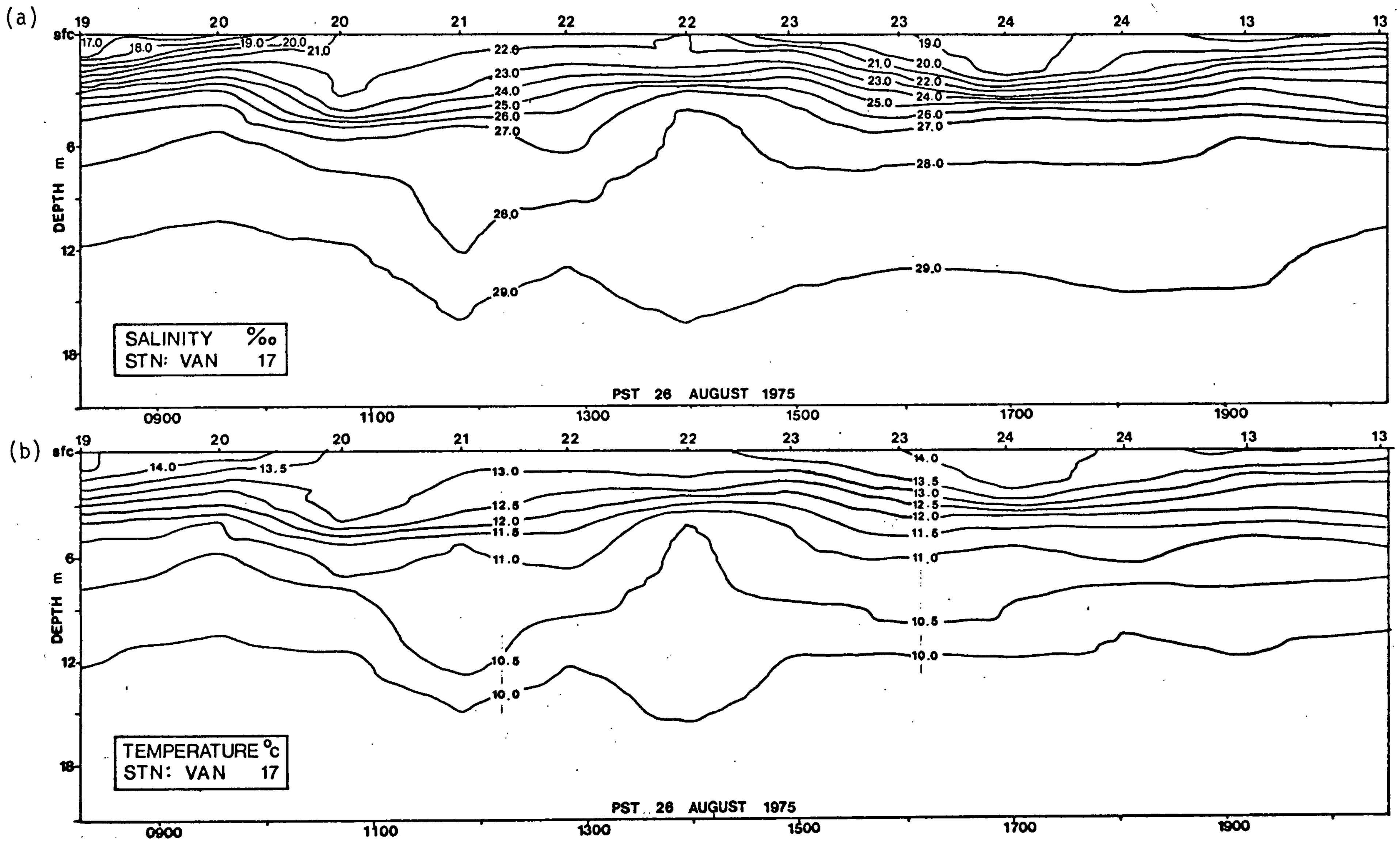


Figure 3.7 Time-depth sections of (a) salinity and (b) temperature at Van 17, August 26, 1975

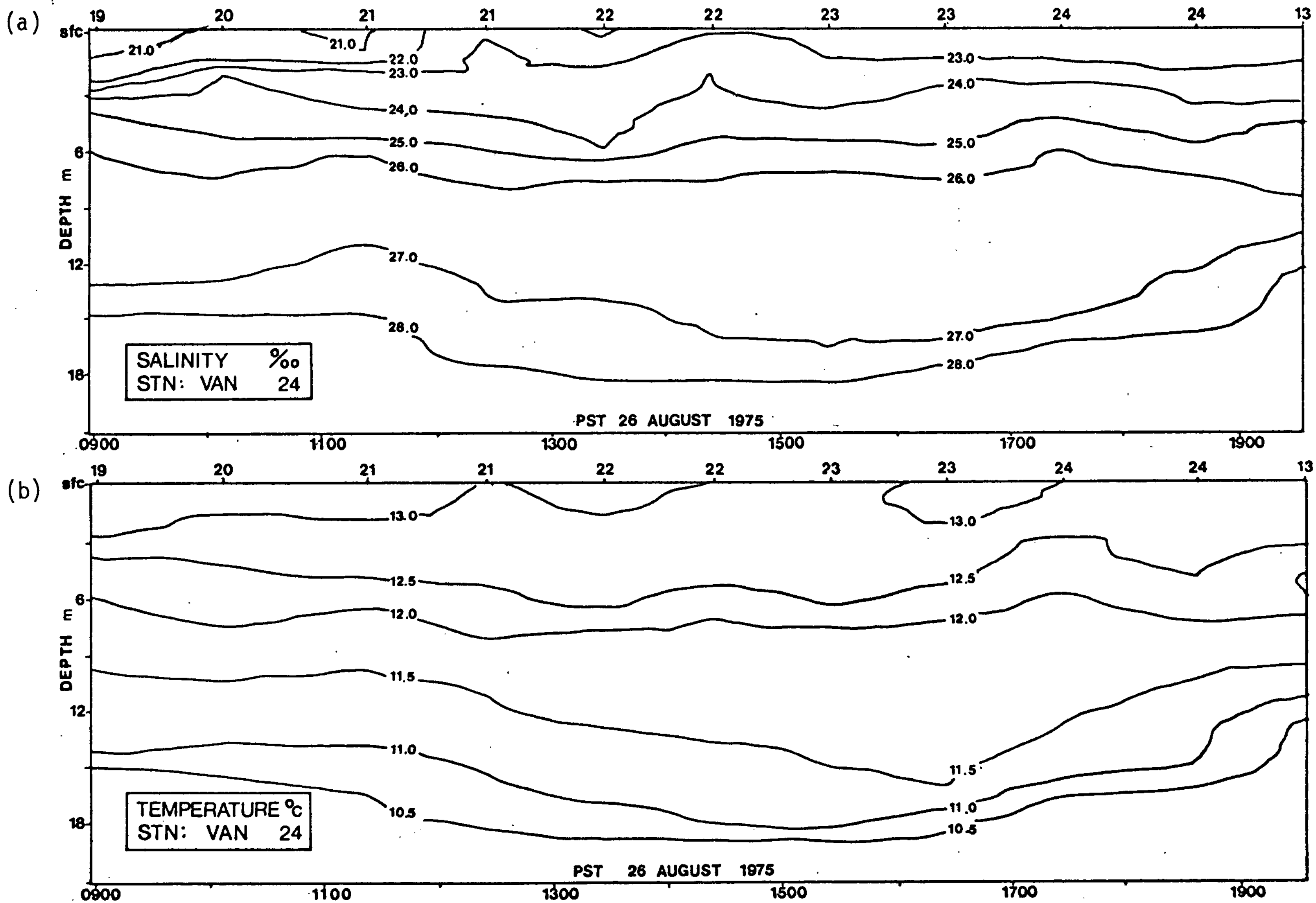


Figure 3.8 Time-depth sections of (a) salinity and (b) temperature at Van 24, August 26, 1975

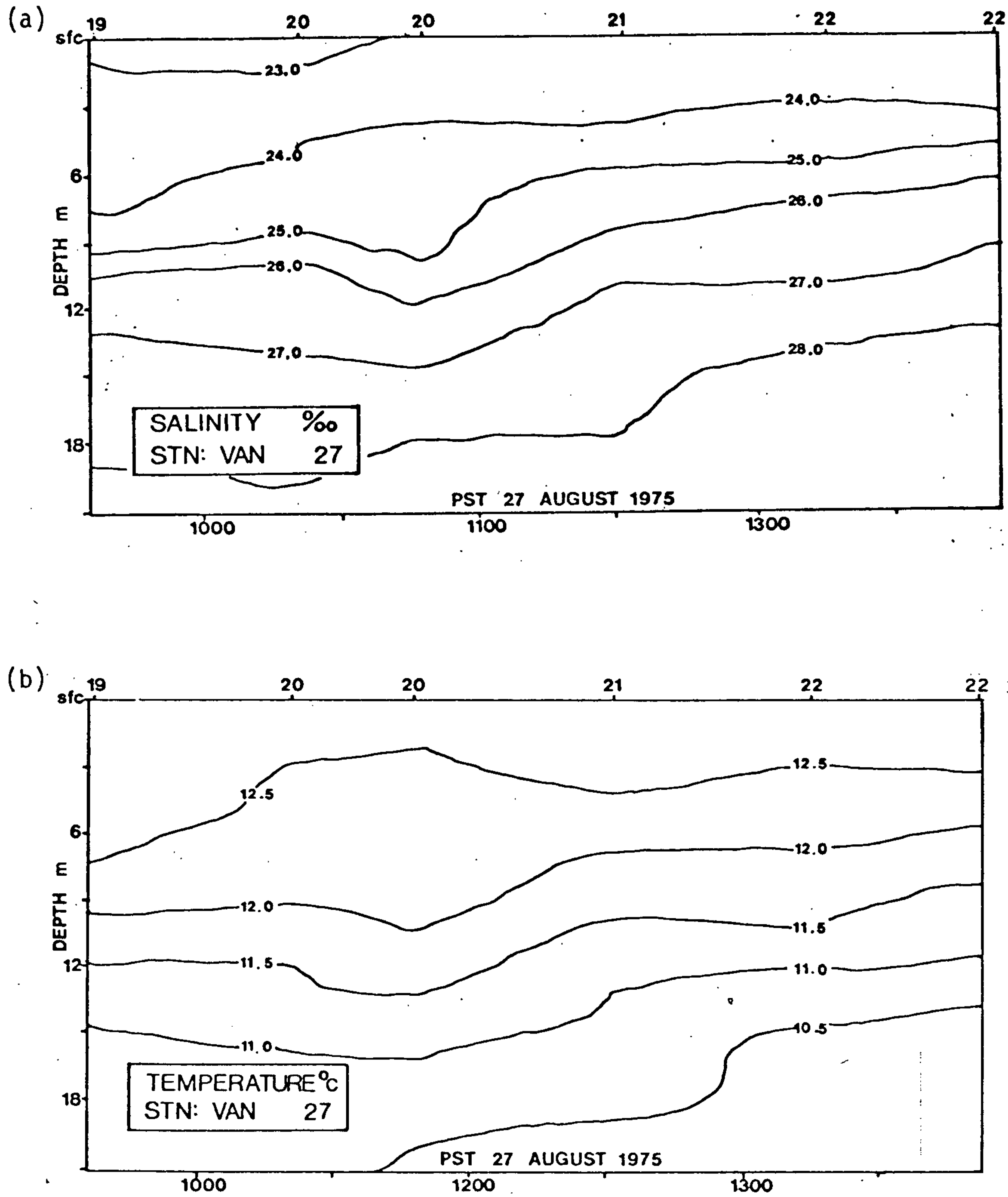


Figure 3.9 Time-depth sections of (a) salinity and (b) temperature at Van 27, August 27, 1975

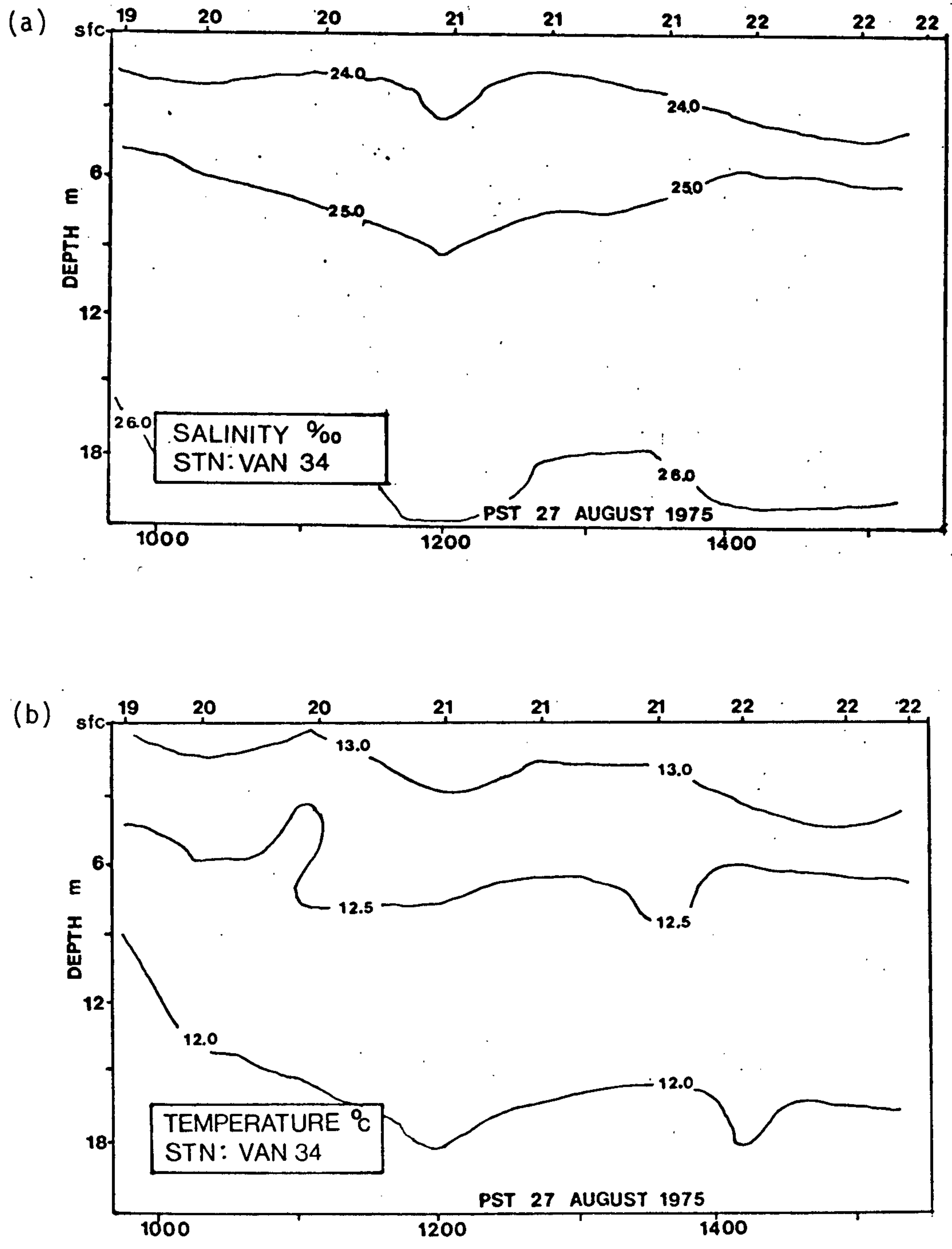
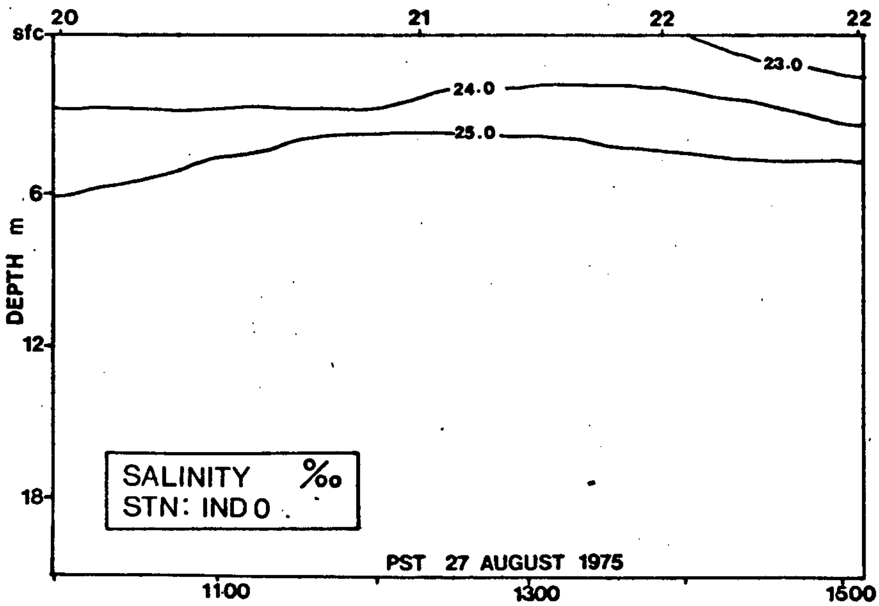


Figure 3.10 Time-depth sections of (a) salinity and (b) temperature at Van 34, August 27, 1975

(a)



(b)

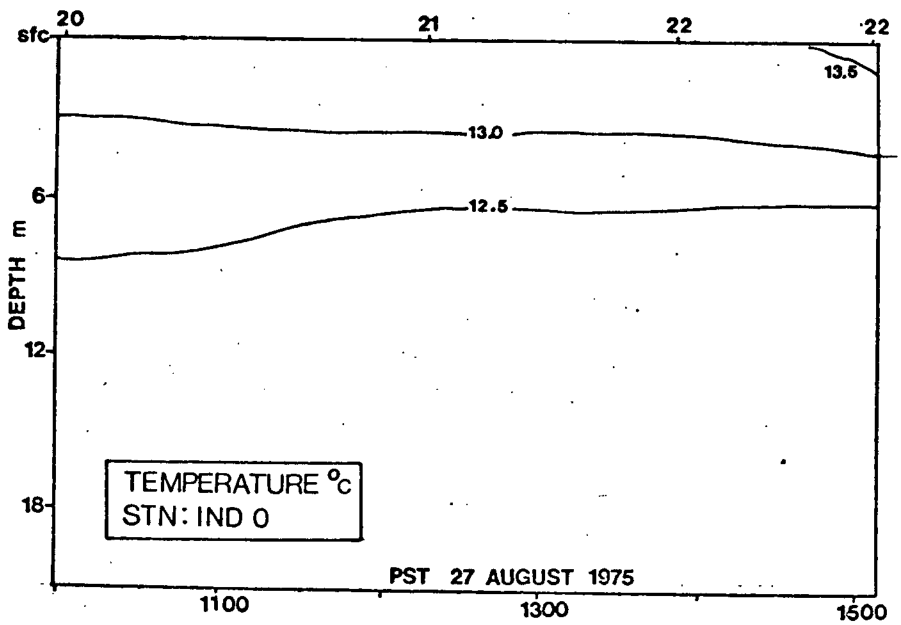
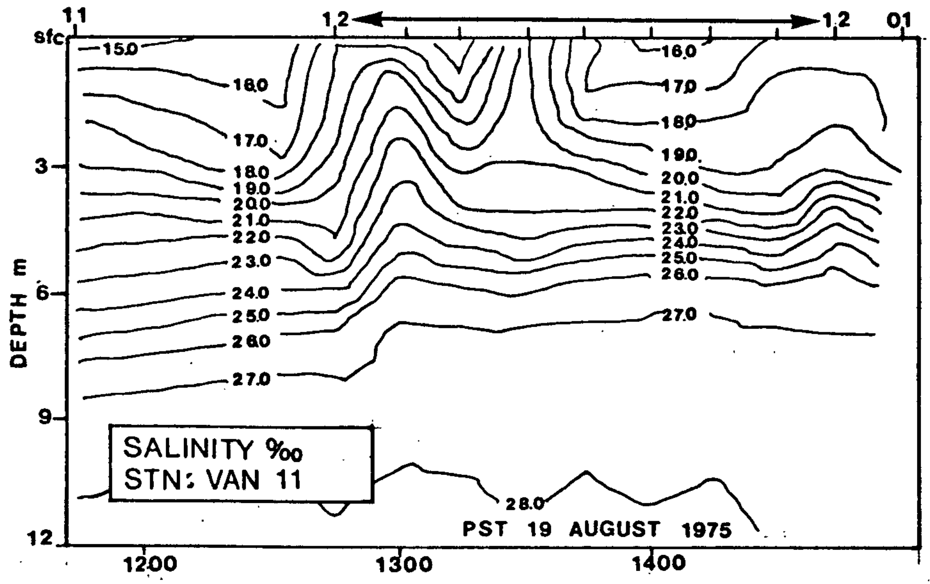


Figure 3.11 Time-depth sections of (a) salinity and (b) temperature at Ind 0, August 27, 1975

(a)



(b)

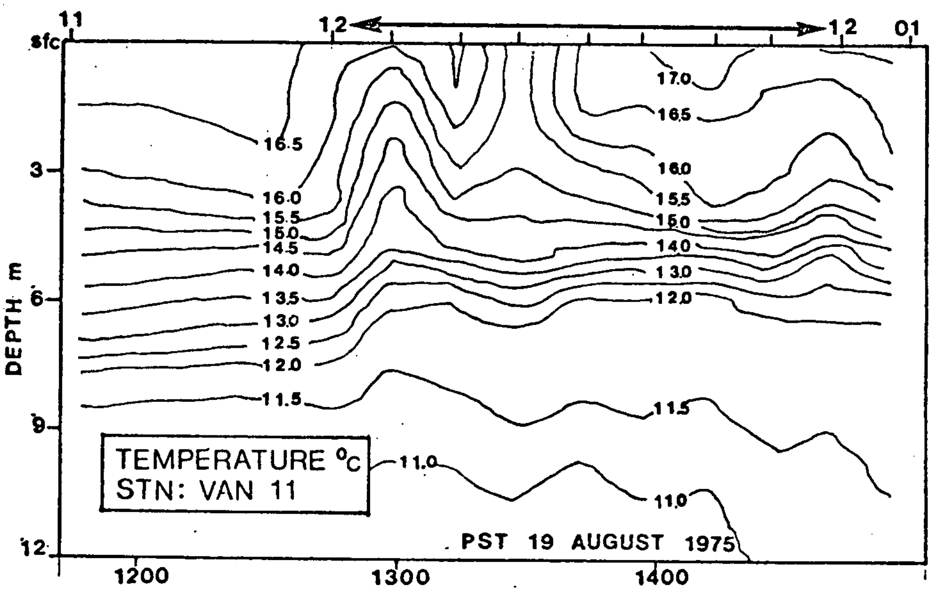


Figure 3.12 Time-depth sections of (a) salinity and (b) temperature at Van 11, August 19, 1975

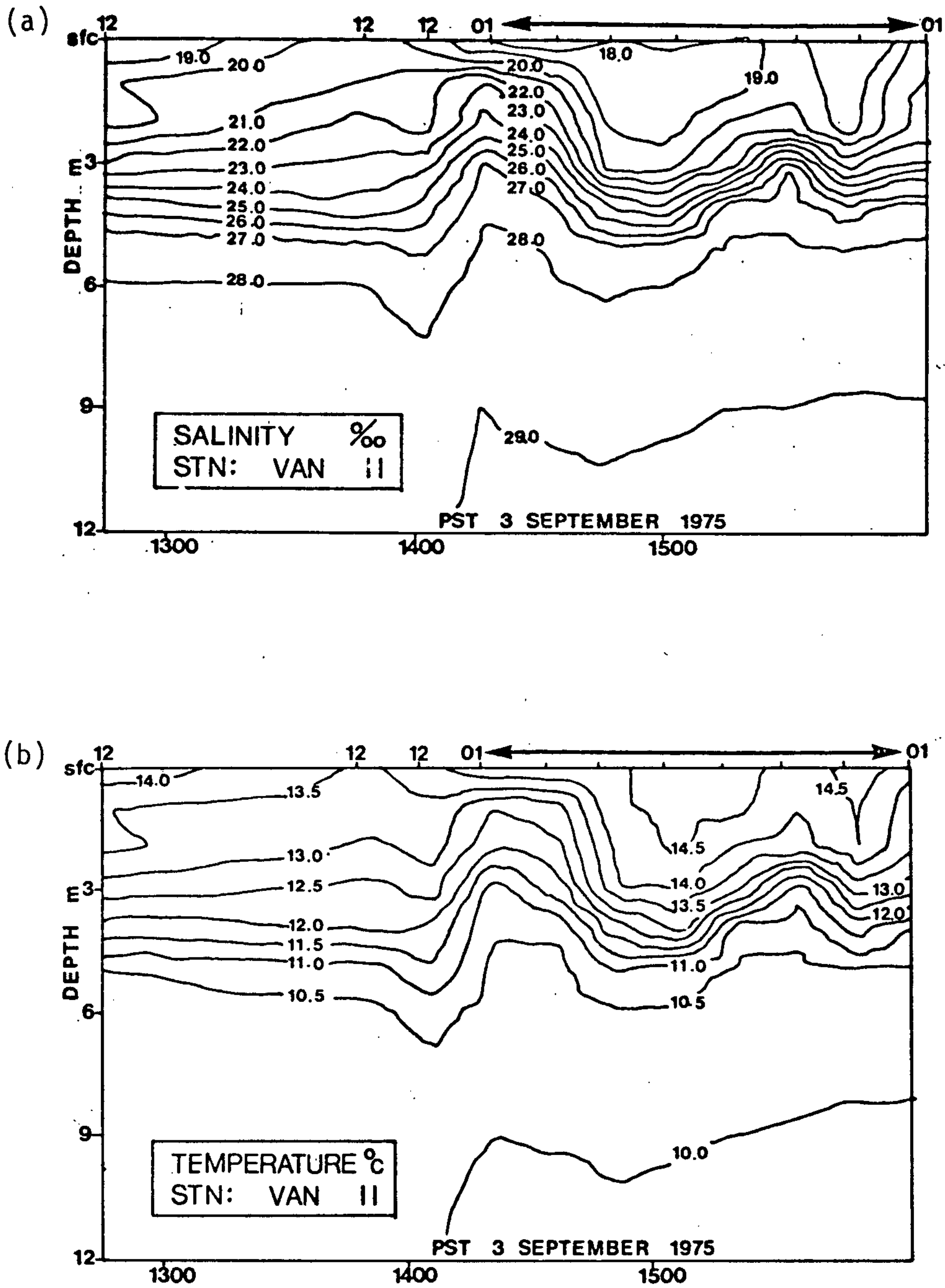


Figure 3.13 Time-depth sections of (a) salinity and (b) temperature at Van 11, September 3, 1975

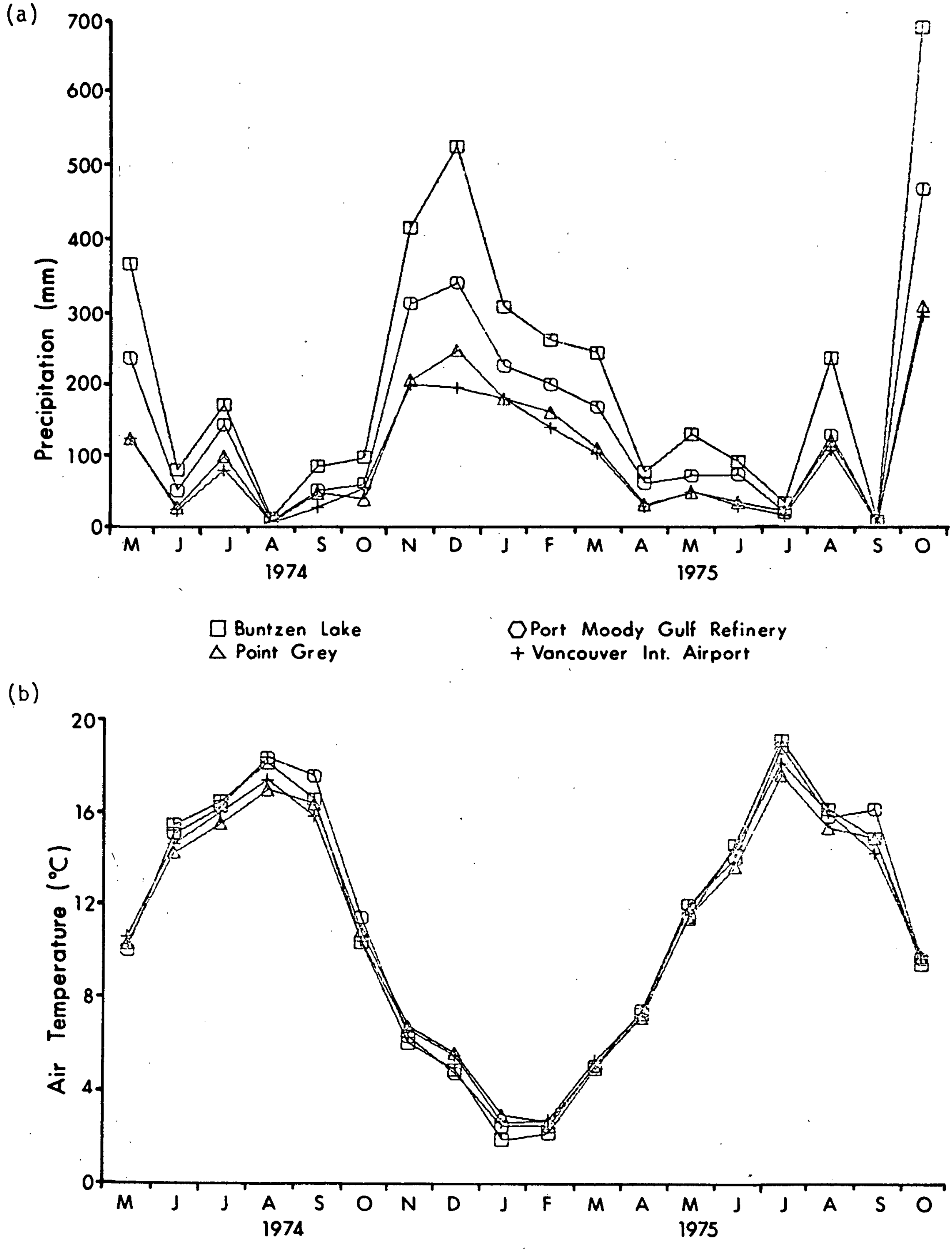


Figure 4.1 Seasonal variation of (a) precipitation and (b) air temperature at stations surrounding Burrard Inlet

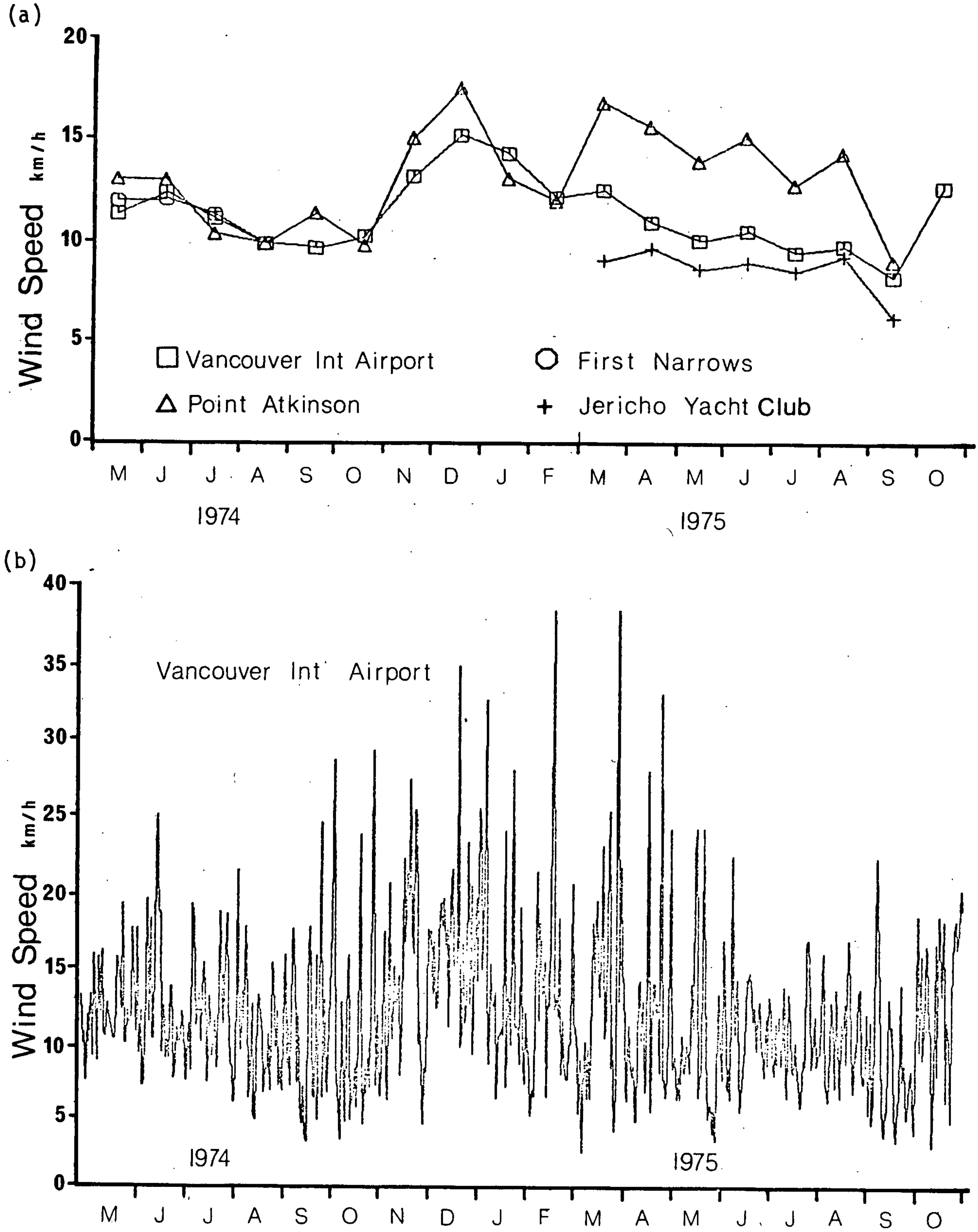


Figure 4.2 Seasonal variation of (a) monthly mean wind speed and (b) daily mean wind speed at stations surrounding Burrard Inlet

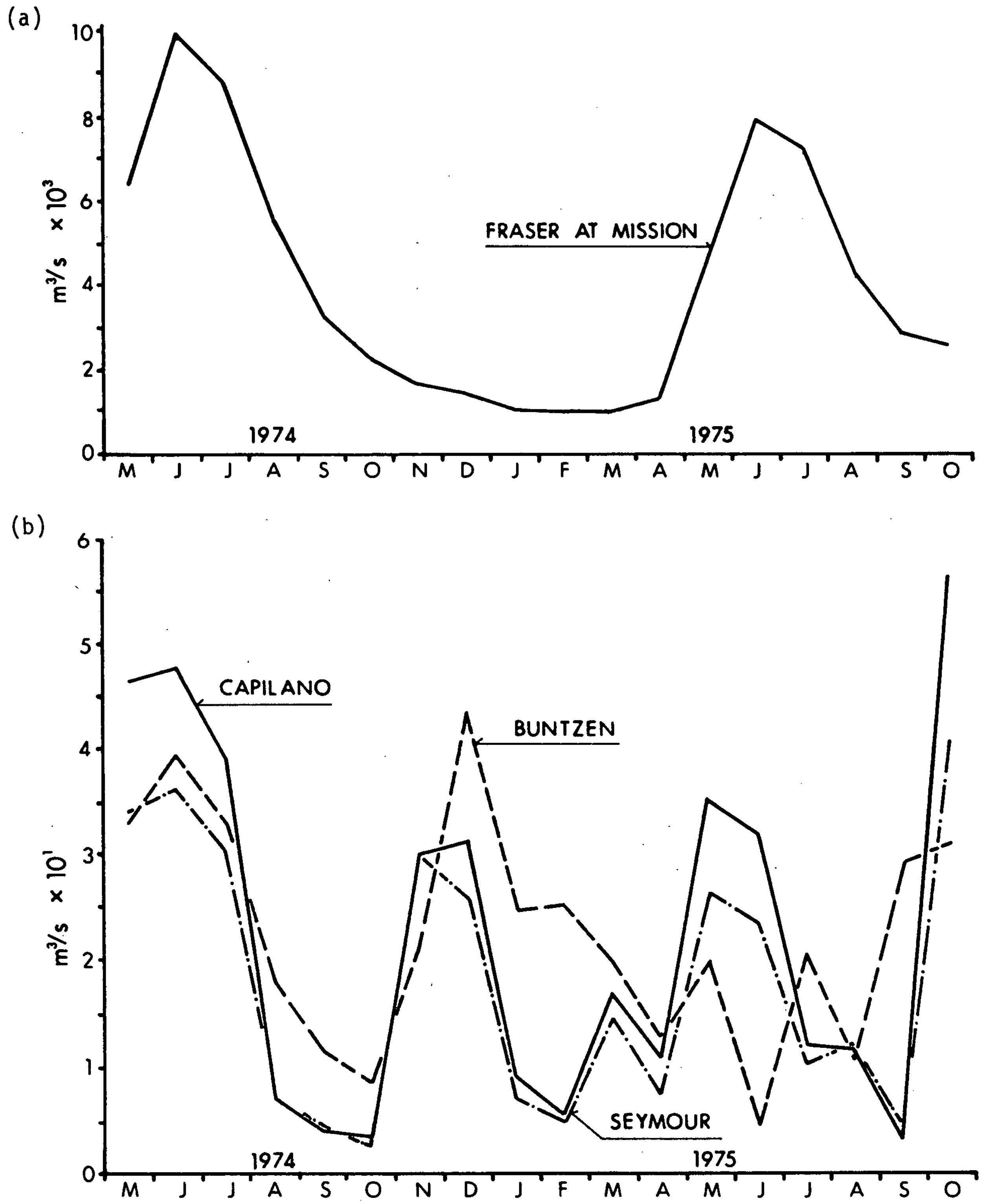


Figure 4.3 Seasonal variation of monthly runoff from (a) Fraser River at Mission and (b) Capilano River, Seymour River and Buntzen Power Houses

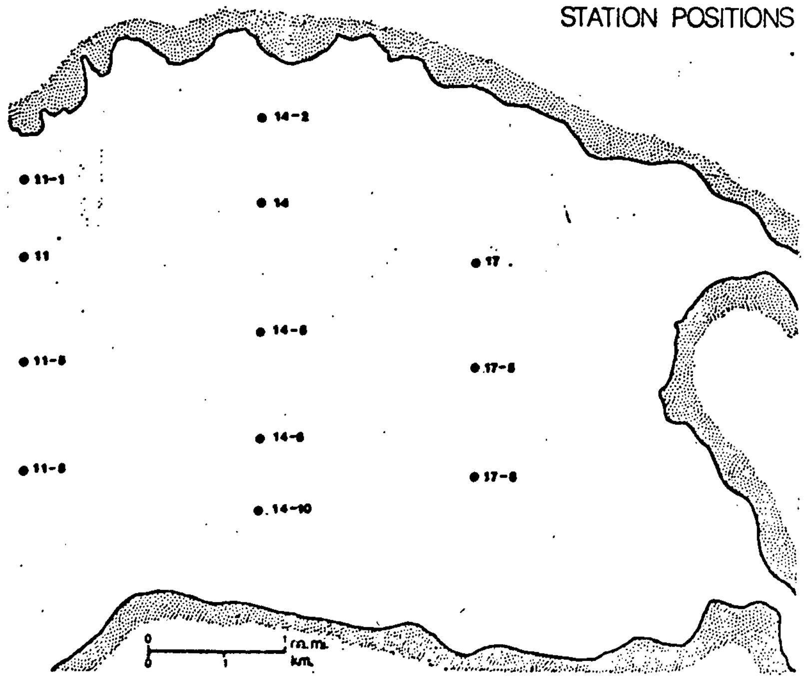


Figure 5.1(a) Station locations in Burrard Inlet Approaches

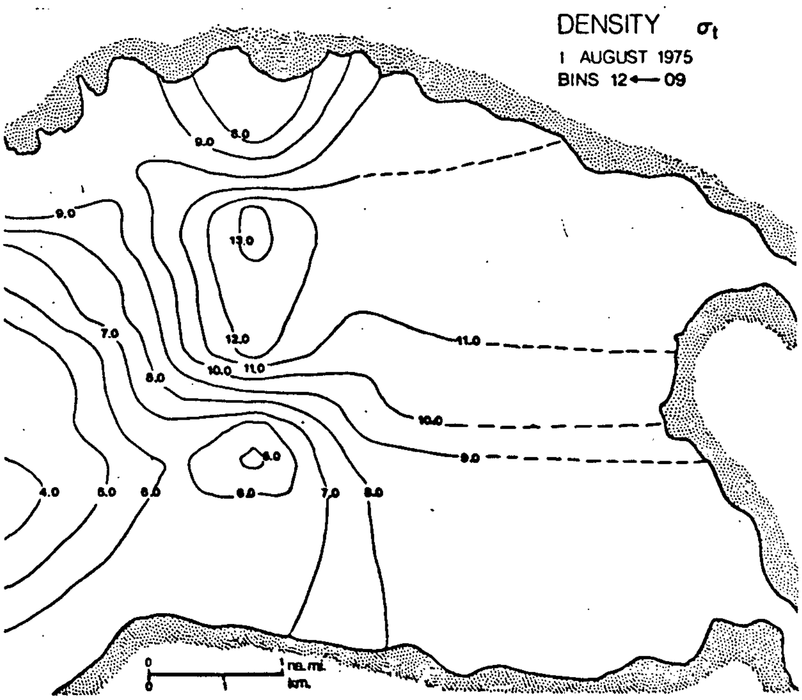
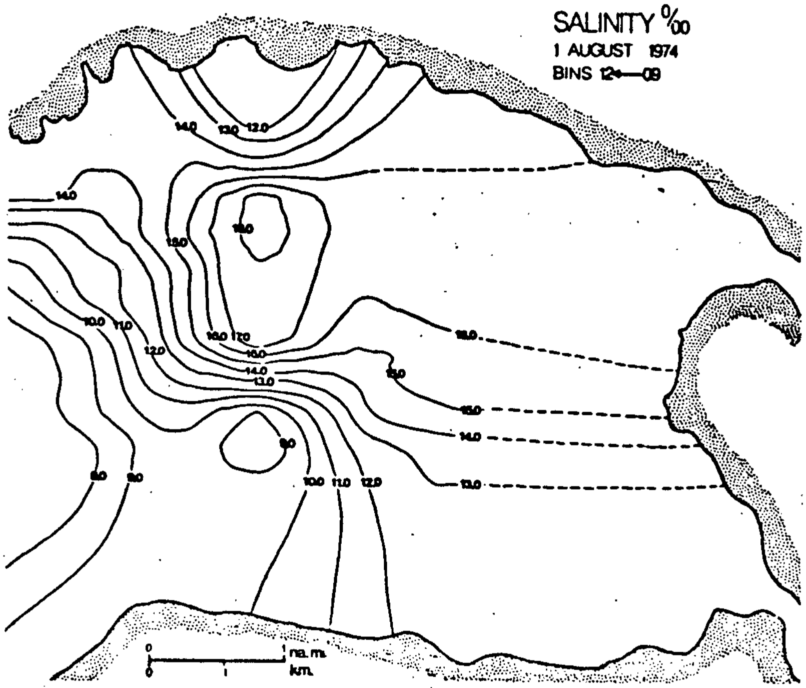


Figure 5.1(b) Surface distribution of density (sigma-t) in Burrard Inlet Approaches, August 1, 1974

(a)



(b)

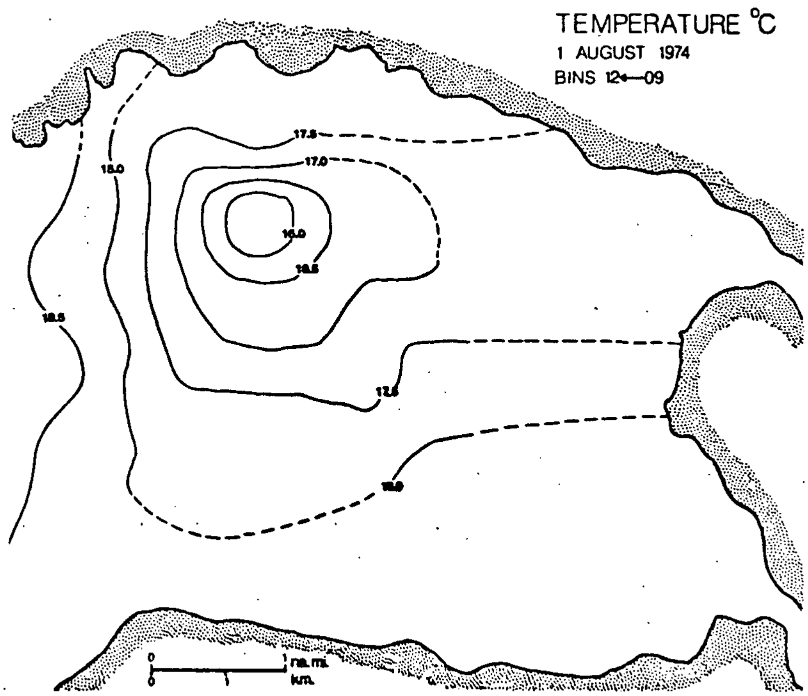


Figure 5.2 Surface distributions of (a) salinity and (b) temperature in Burrard Inlet Approaches, August 1, 1974

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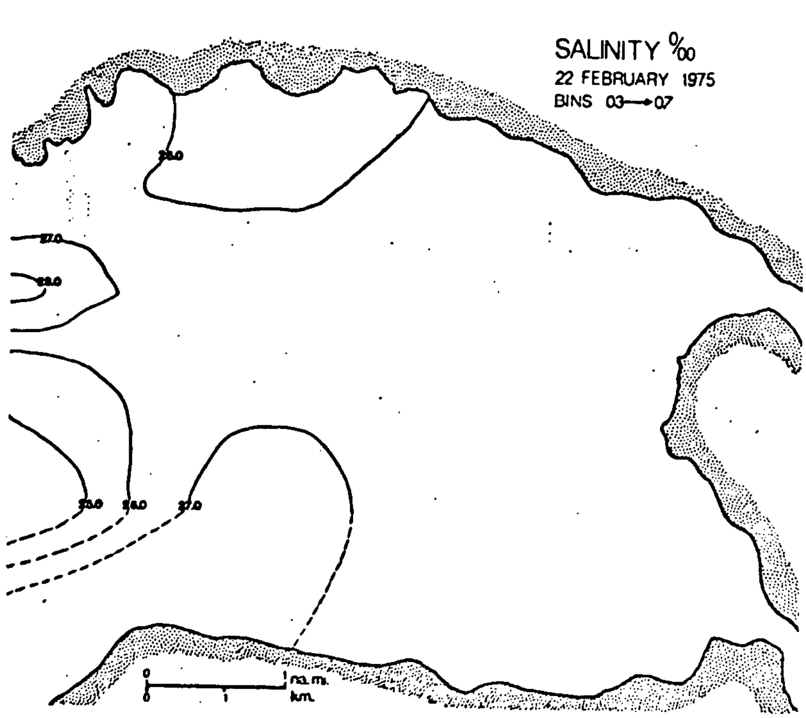
Figs 5.3 & 6

(a)



(b)

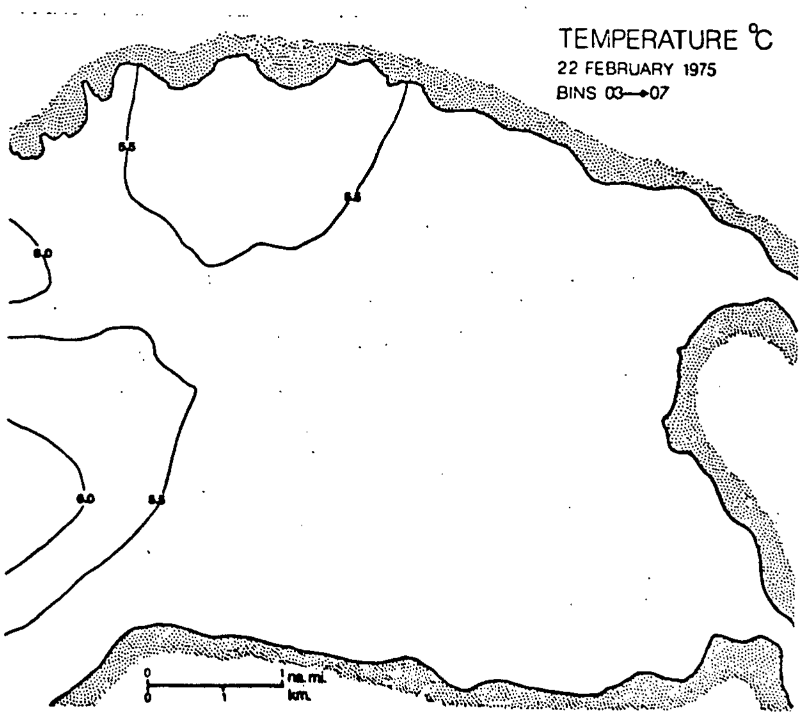
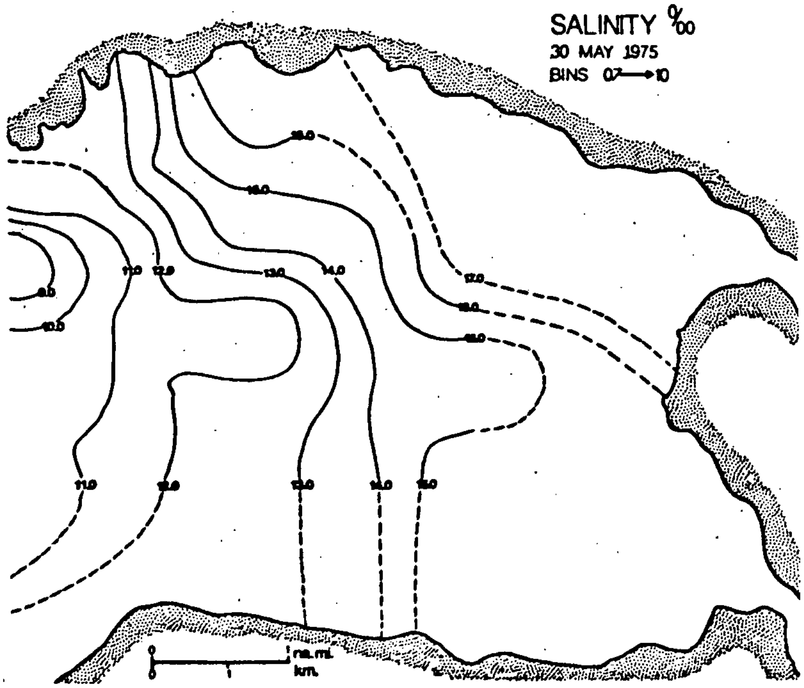


Figure 5.4 Surface distributions of (a) salinity and (b) temperature in Burrard Inlet Approaches, February 22, 1975

(a)



(b)

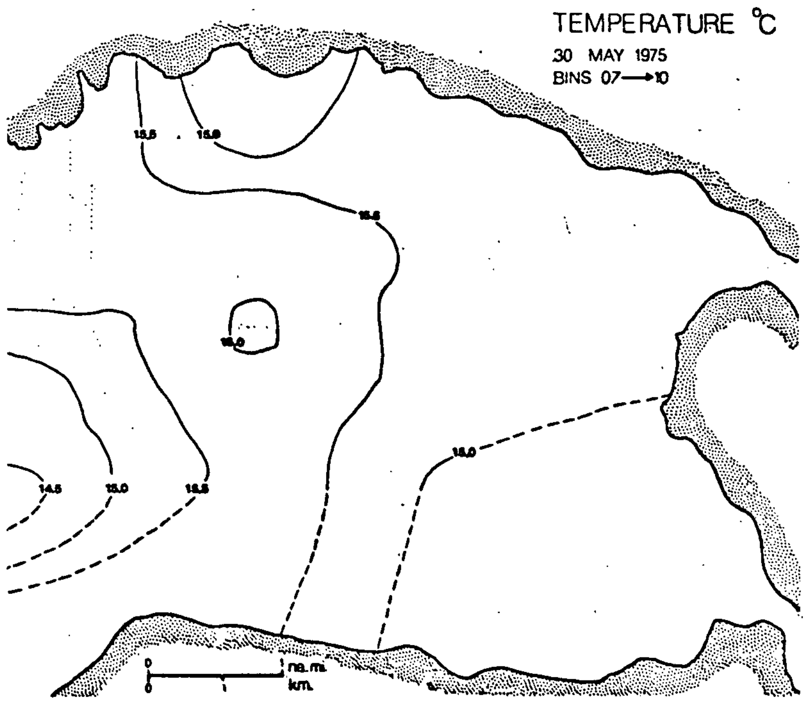
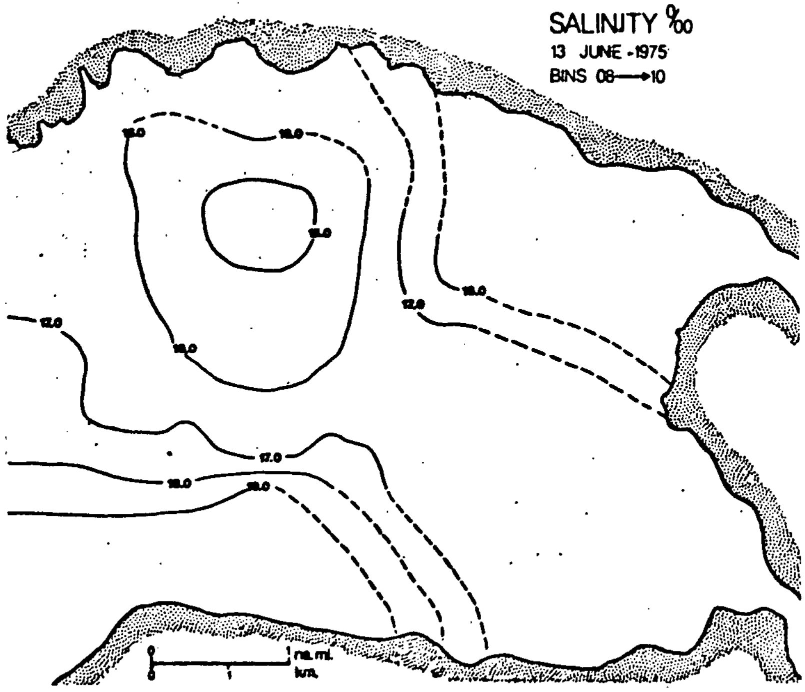


Figure 5.5 Surface distributions of (a) salinity and (b) temperature in Burrard Inlet Approaches, May 30, 1975

(a)



(b)

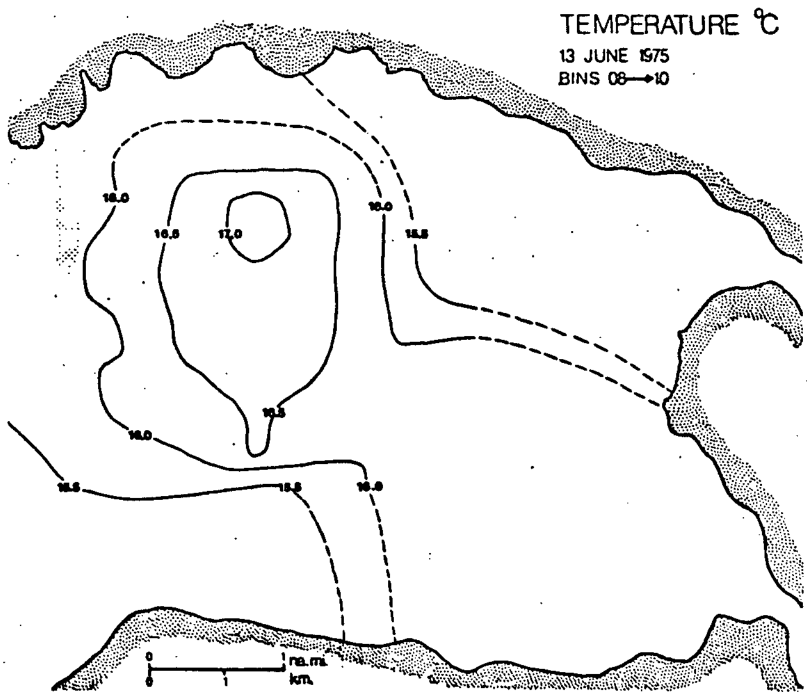
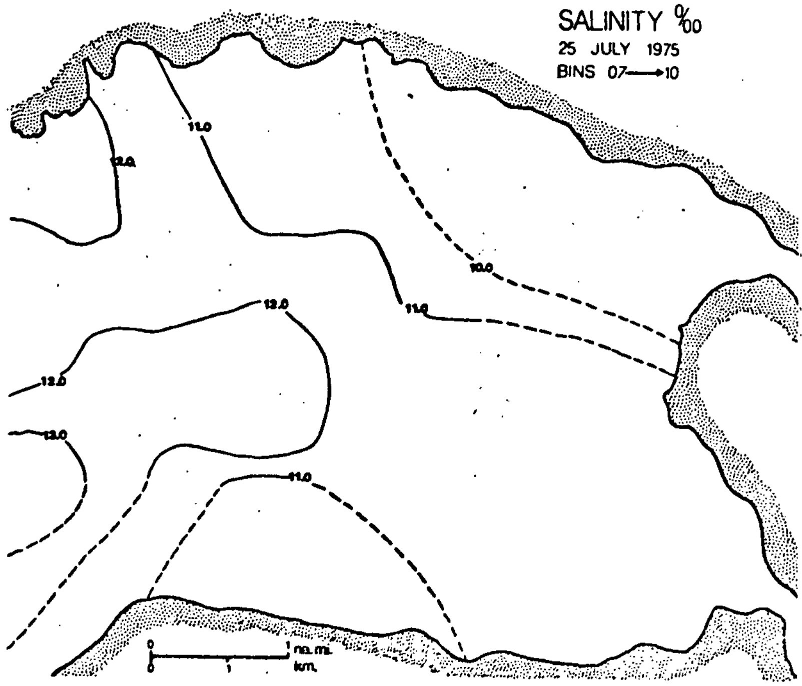


Figure 5.6 Surface distributions of (a) salinity and (b) temperature in Burrard Inlet Approaches, June 13, 1975

(a)



(b)

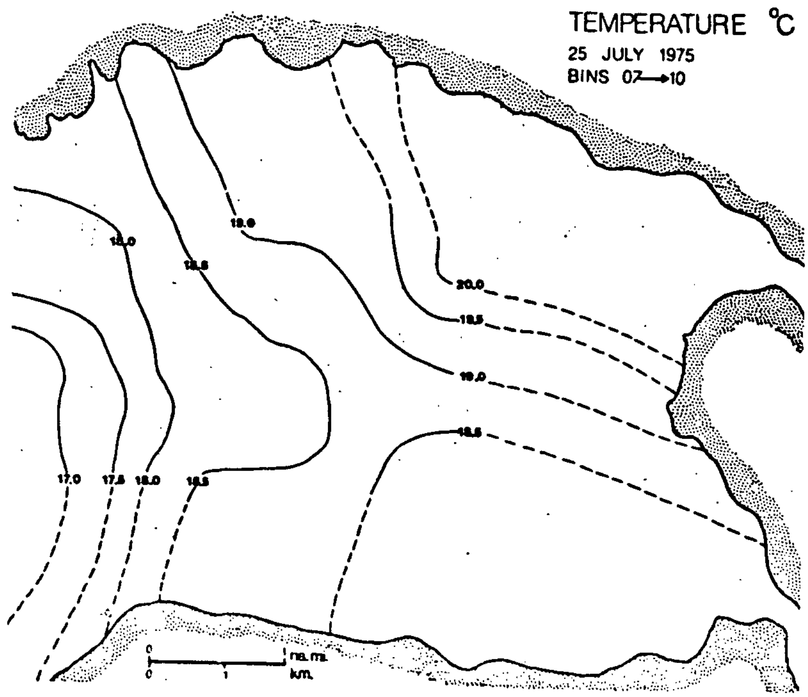
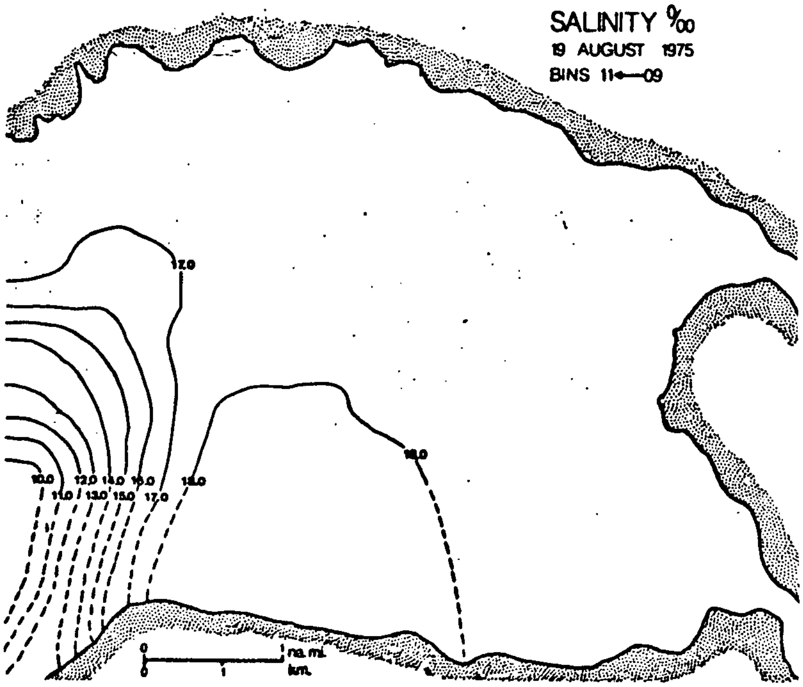


Figure 5.7 Surface distributions of (a) salinity and (b) temperature in Burrard Inlet Approaches, July 25, 1975

(a)



(b)

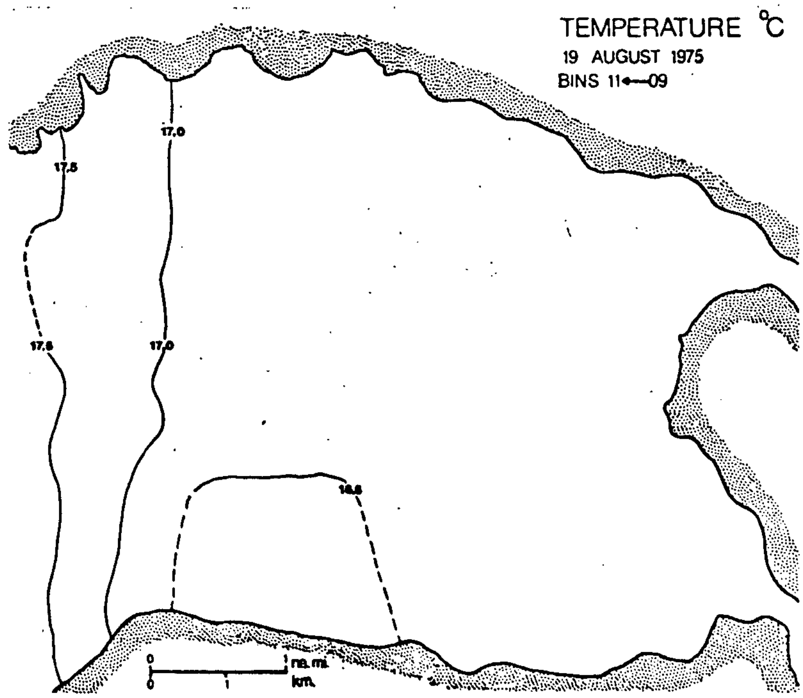


Figure 5.8 Surface distributions of (a) salinity and (b) temperature in Burrard Inlet Approaches, August 19, 1975

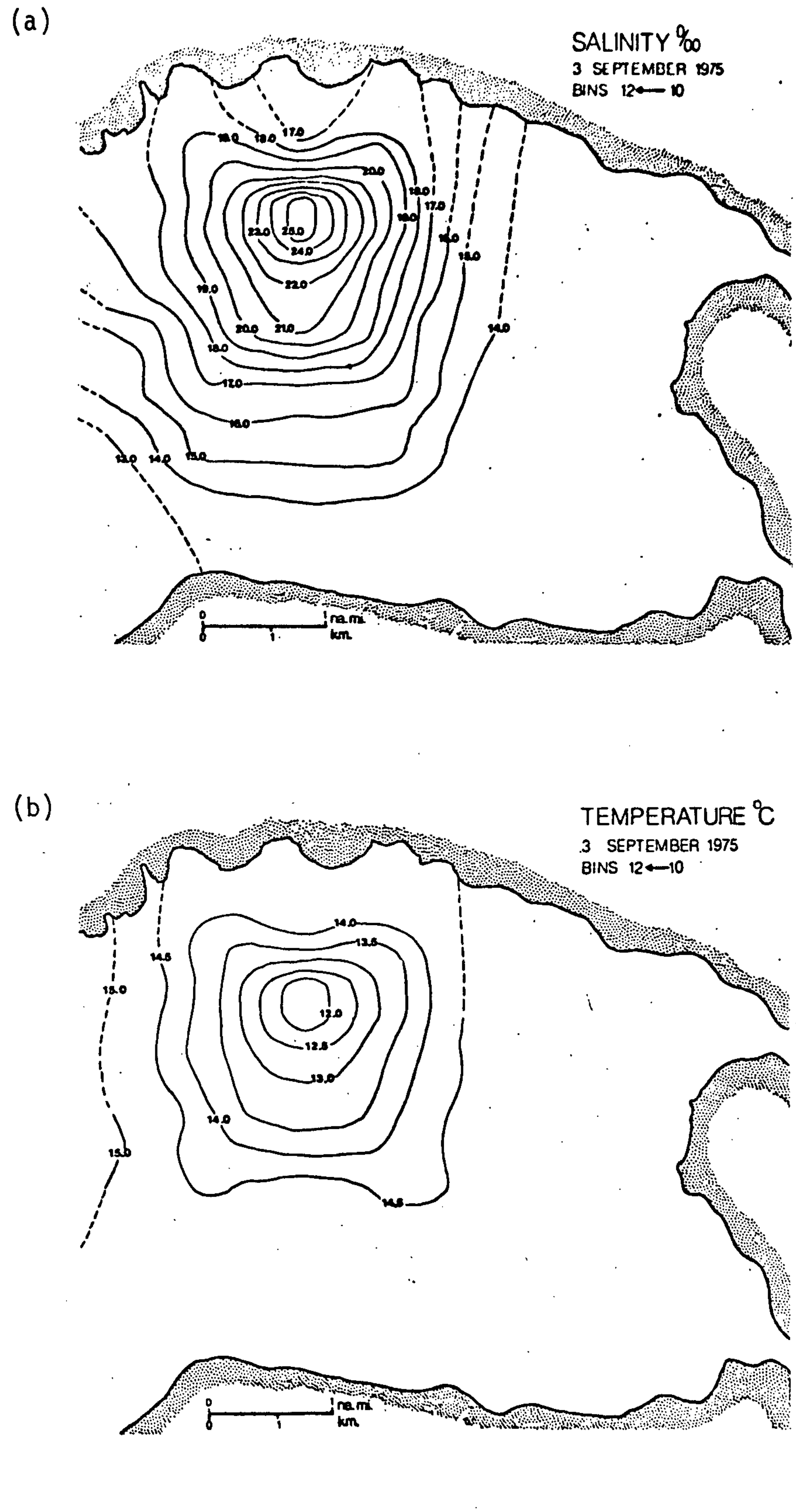


Figure 5.9 Surface distributions of (a) salinity and (b) temperature in Burrard Inlet Approaches, September 3, 1975

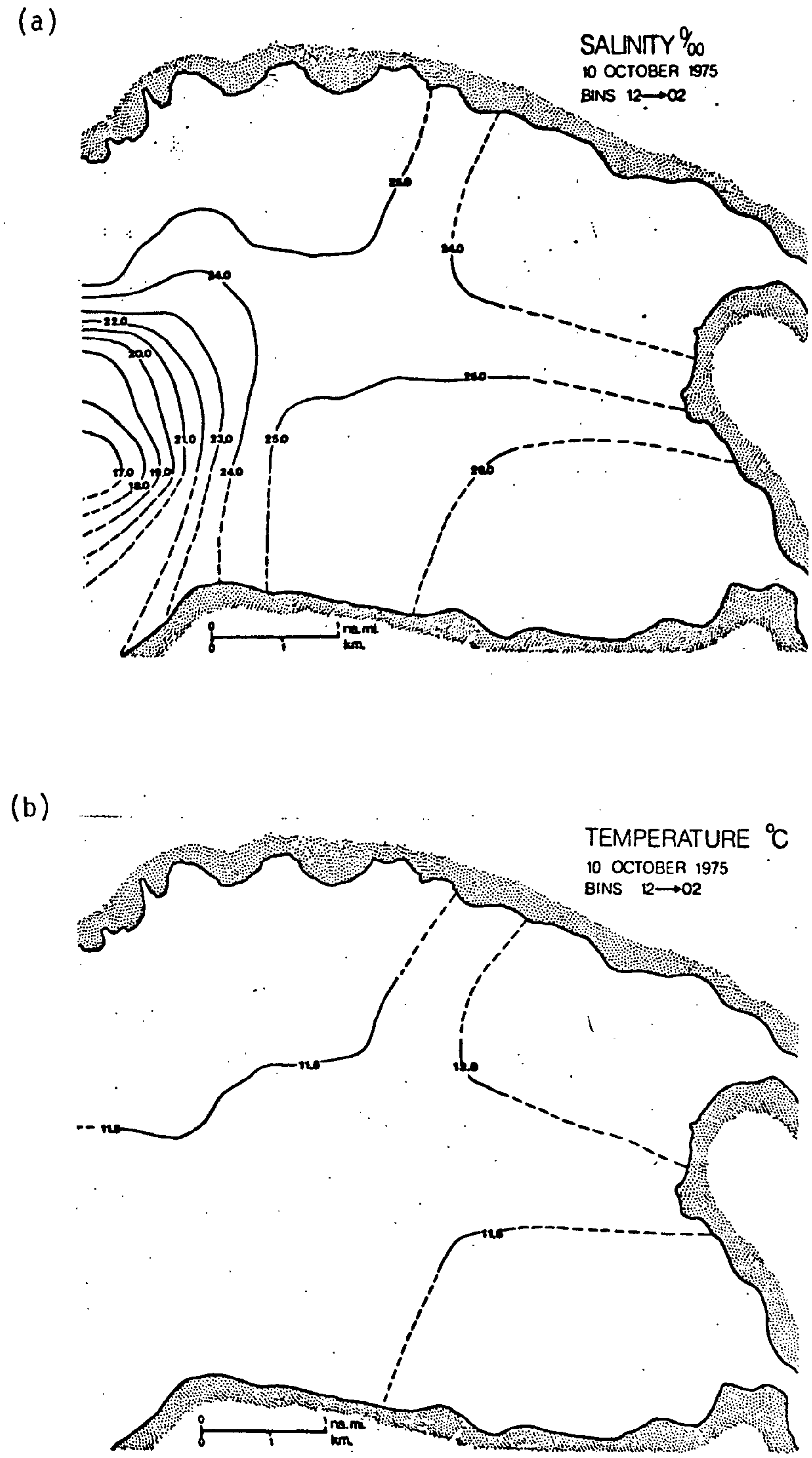


Figure 5.10 Surface distributions of (a) salinity and (b) temperature in Burrard Inlet Approaches, October 10, 1975

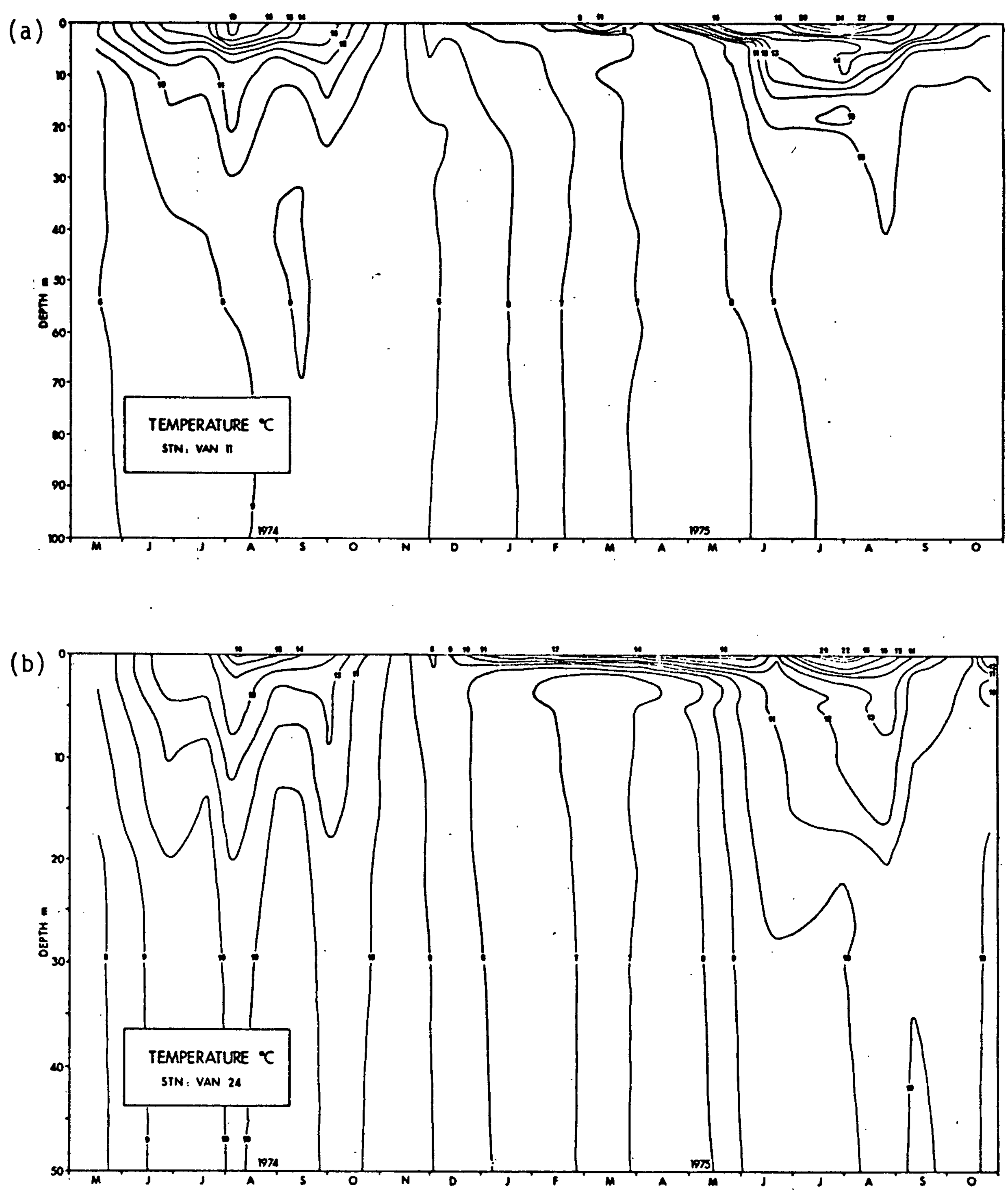
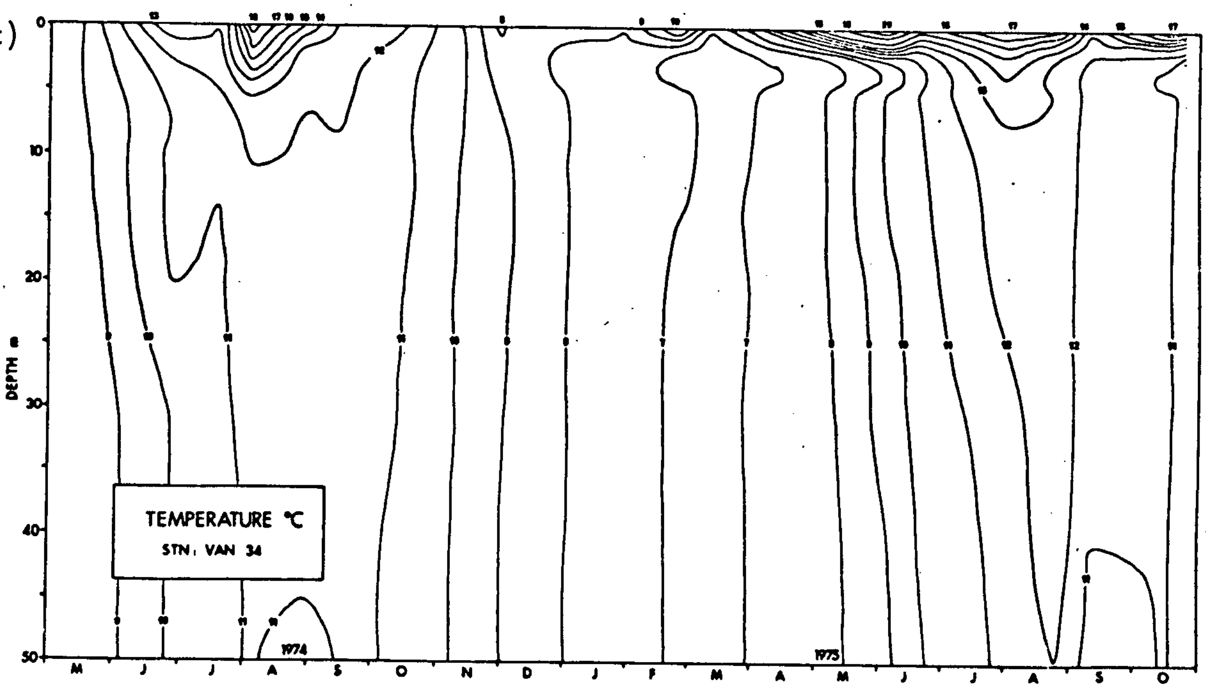
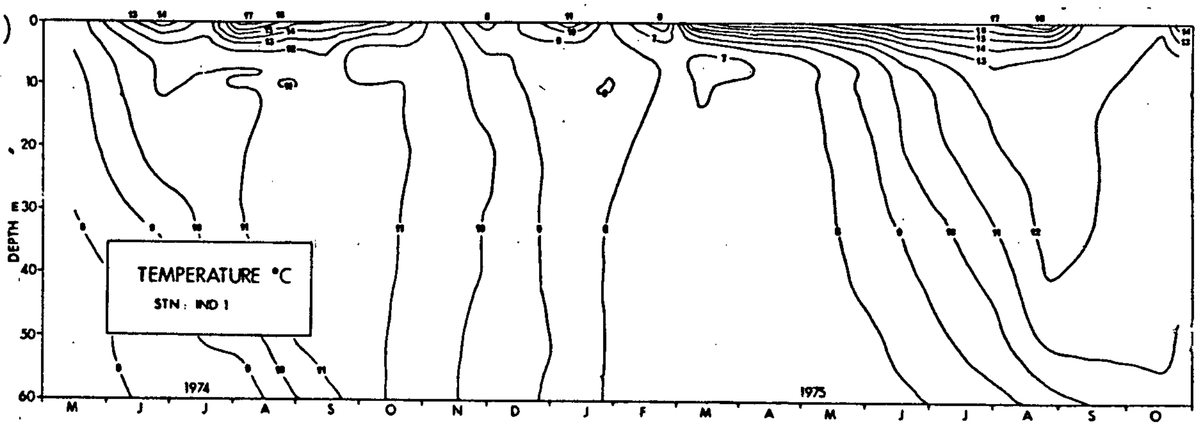


Figure 5.11 Time-depth sections of temperature, May 1974 to October 1975 at stations (a) Van 11 (b) Van 24 (c) Van 34 (d) Ind 1 and (e) Ind 2

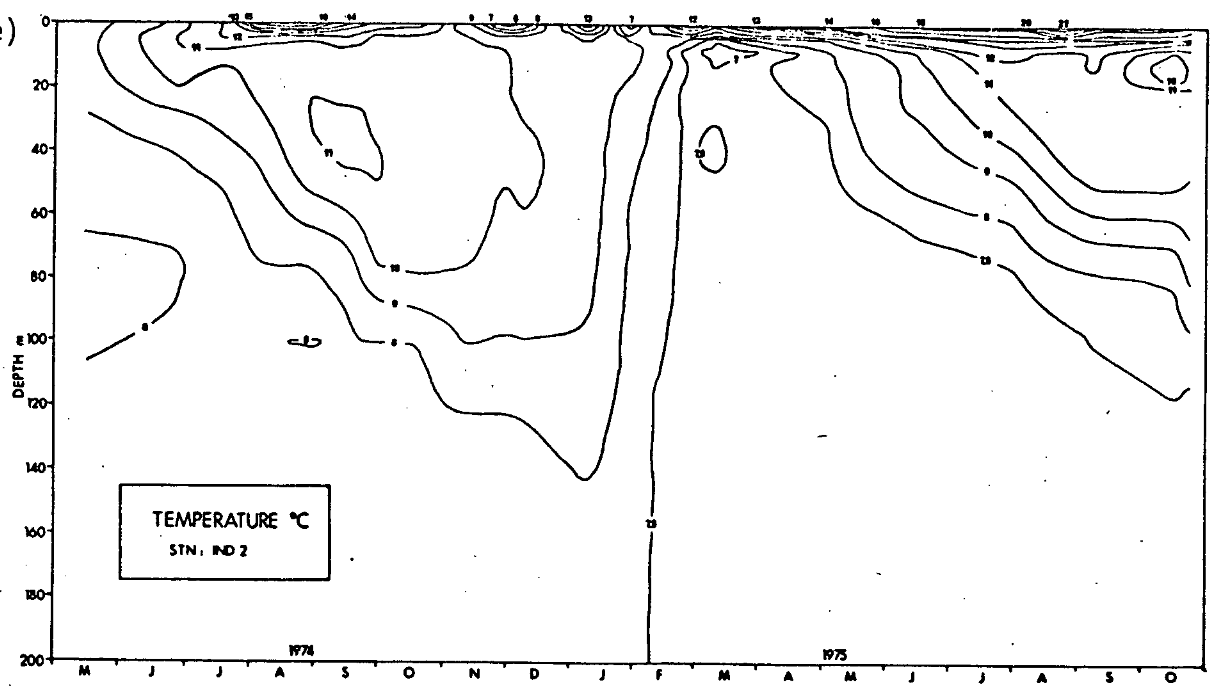
(c)


TEMPERATURE °C
STN: VAN 34
DEPTH m
1974
1975
M J J A S O N D J F M A M J J A S O

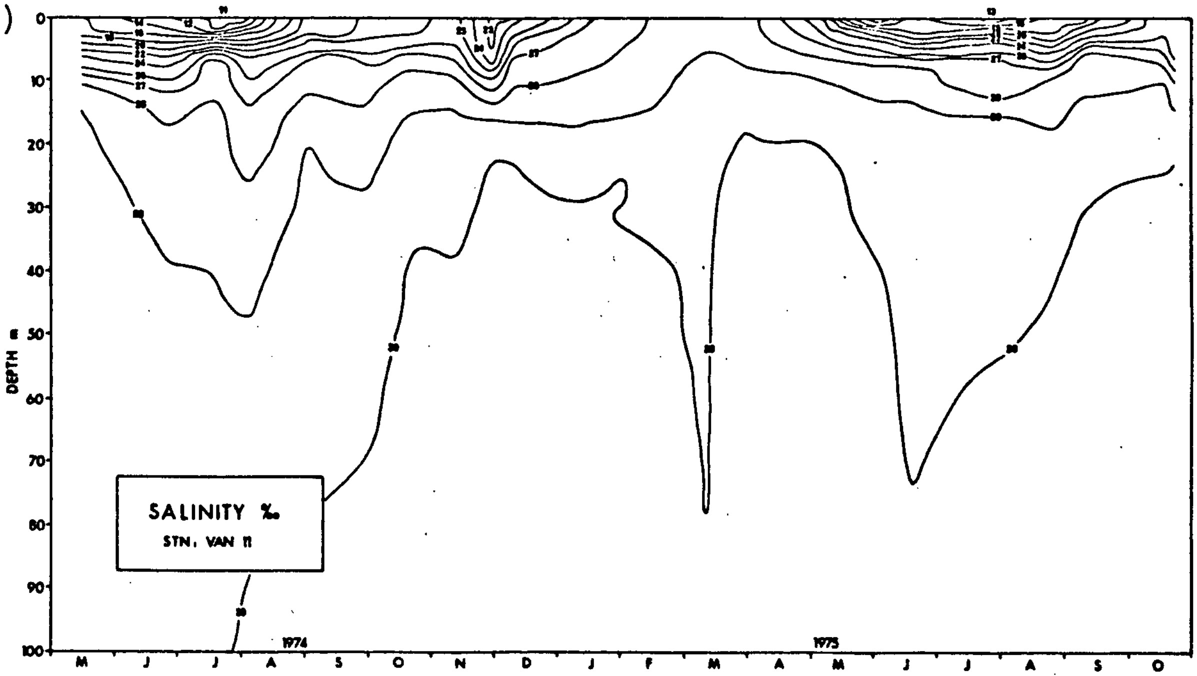
(d)


TEMPERATURE °C
STN: IND 1
DEPTH m
1974
1975
M J J A S O N D J F M A M J J A S O

(e)


TEMPERATURE °C
STN: IND 2
DEPTH m
1974
1975
M J J A S O N D J F M A M J J A S O

(a)



(b)

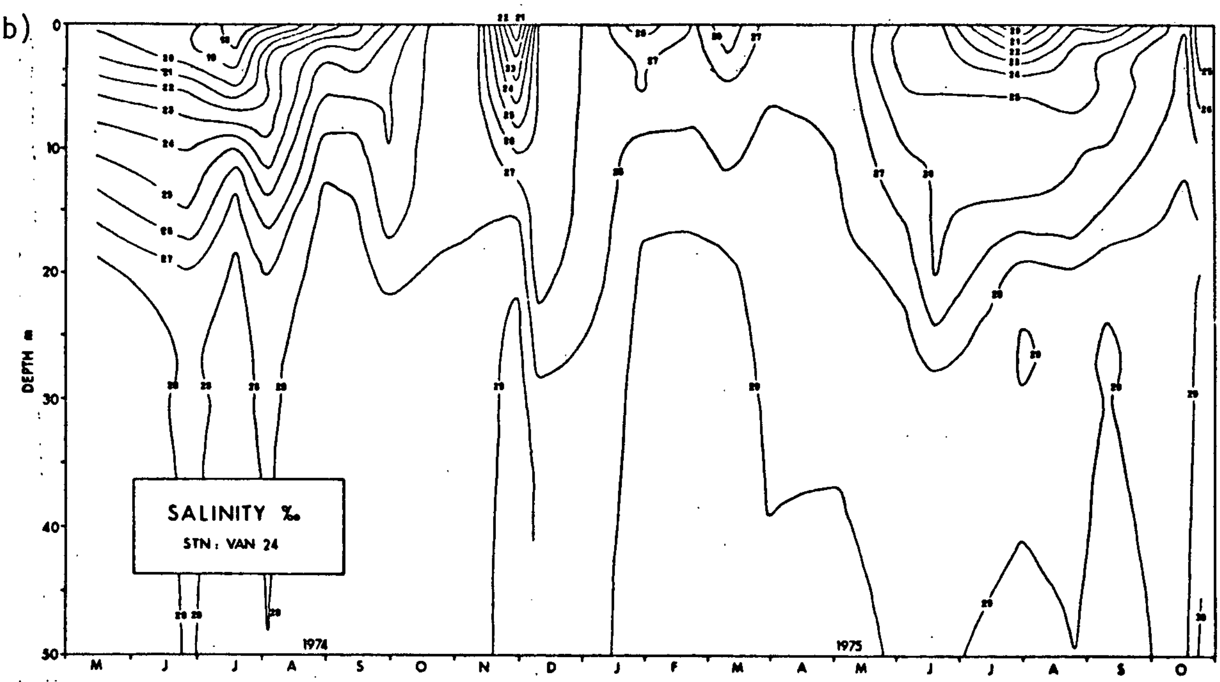
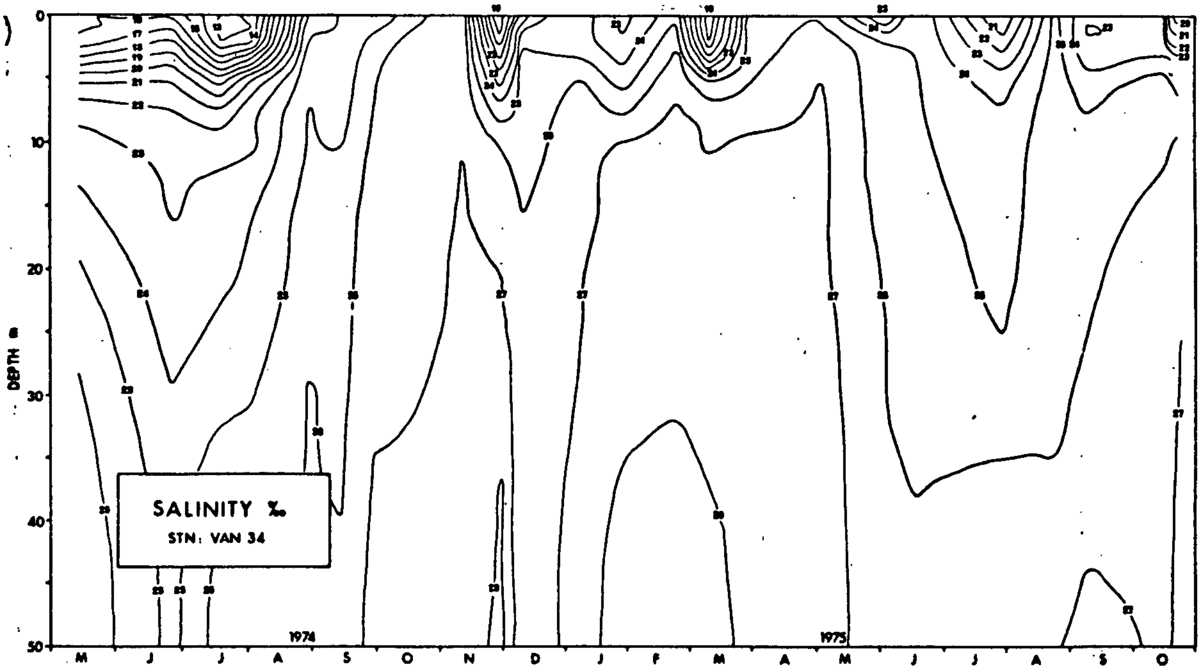
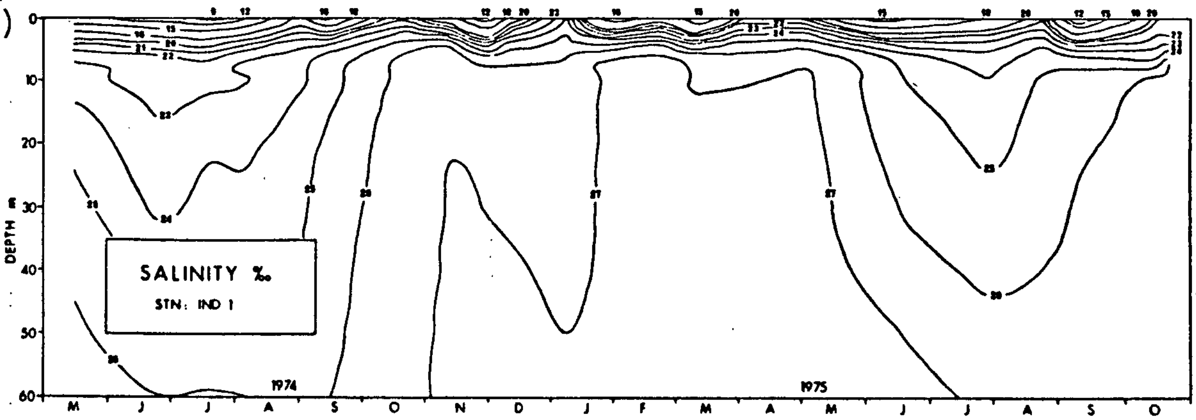


Figure 5.12 Time-depth sections of salinity, May 1974 to October 1975 at stations (a) Van 11 (b) Van 24 (c) Van 34 (d) Ind 1 and (e) Ind 2

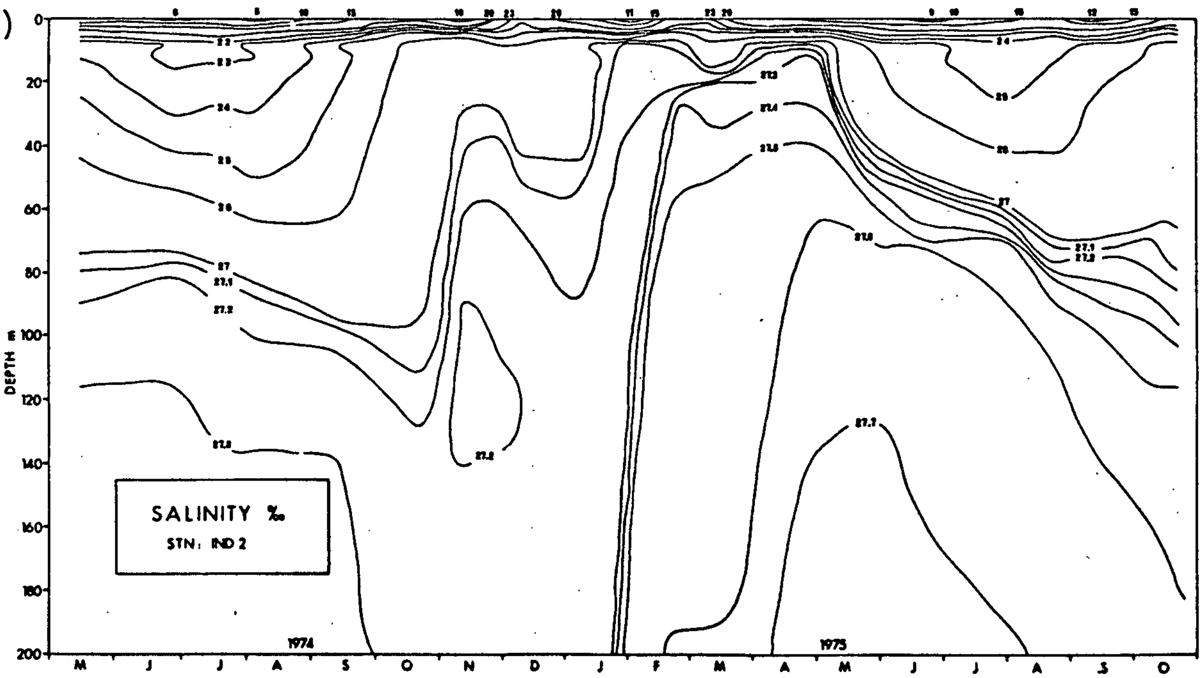
(c)


SALINITY ‰
STN: VAN 34
DEPTH m
1974
1975
M J J A S O N D J F M A M J J A S O

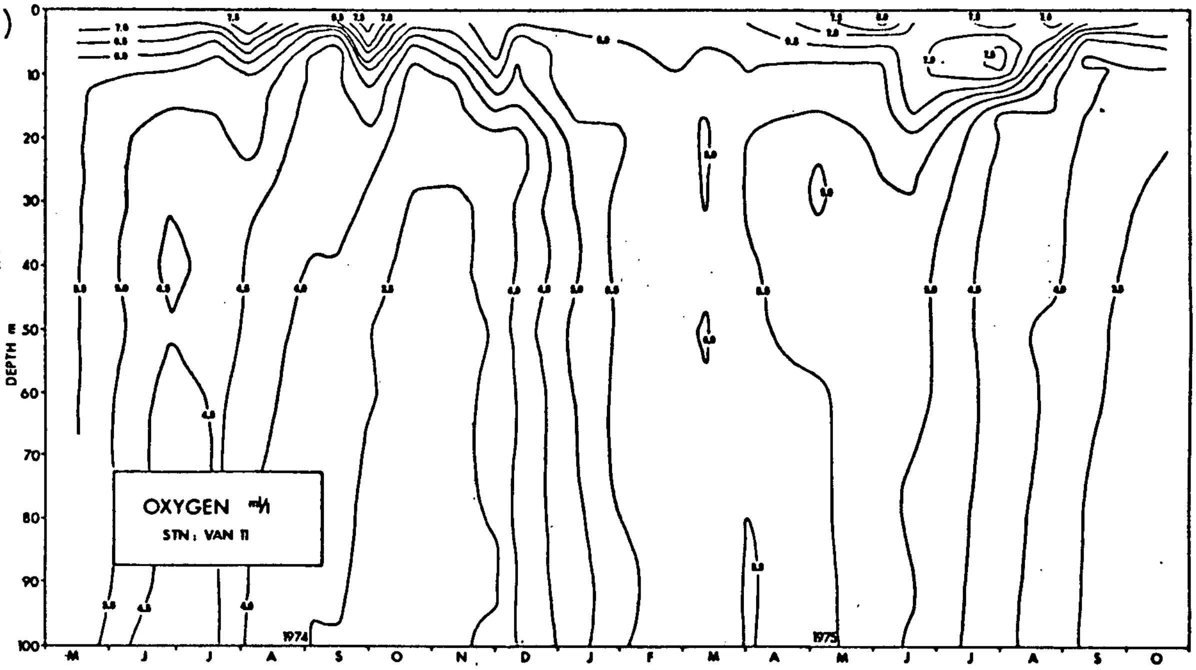
(d)


SALINITY ‰
STN: IND 1
DEPTH m
1974
1975
M J J A S O N D J F M A M J J A S O

(e)


SALINITY ‰
STN: IND 2
DEPTH m
1974
1975
M J J A S O N D J F M A M J J A S O

(a)



(b)

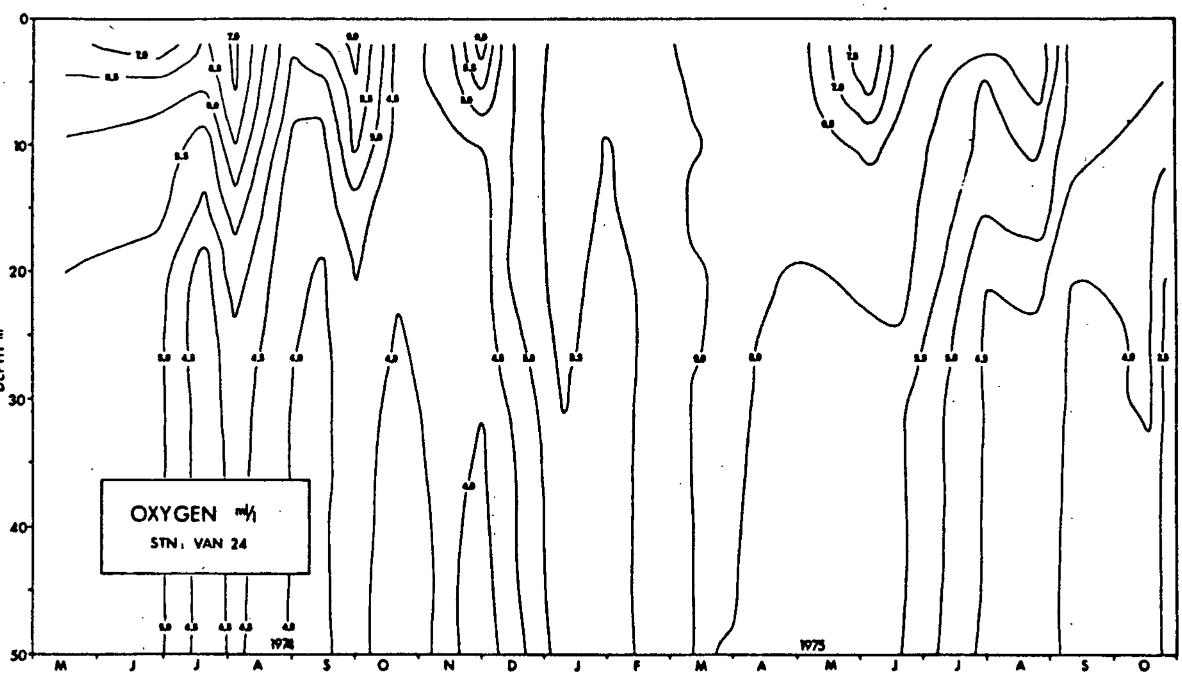
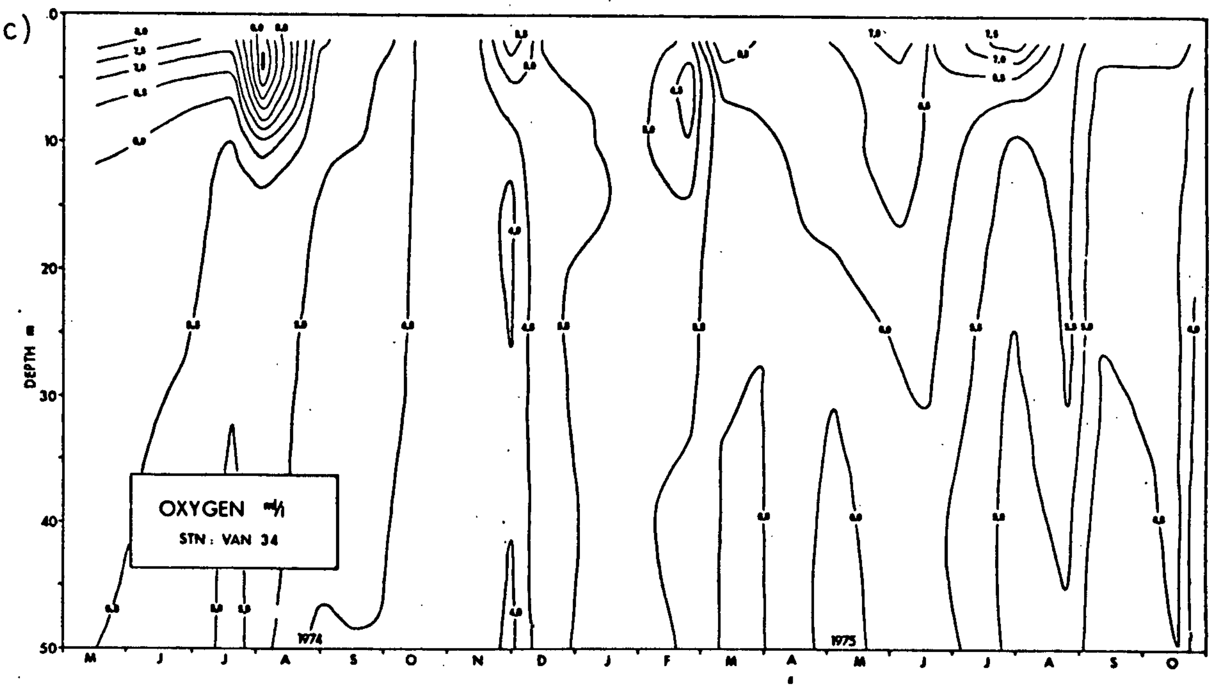
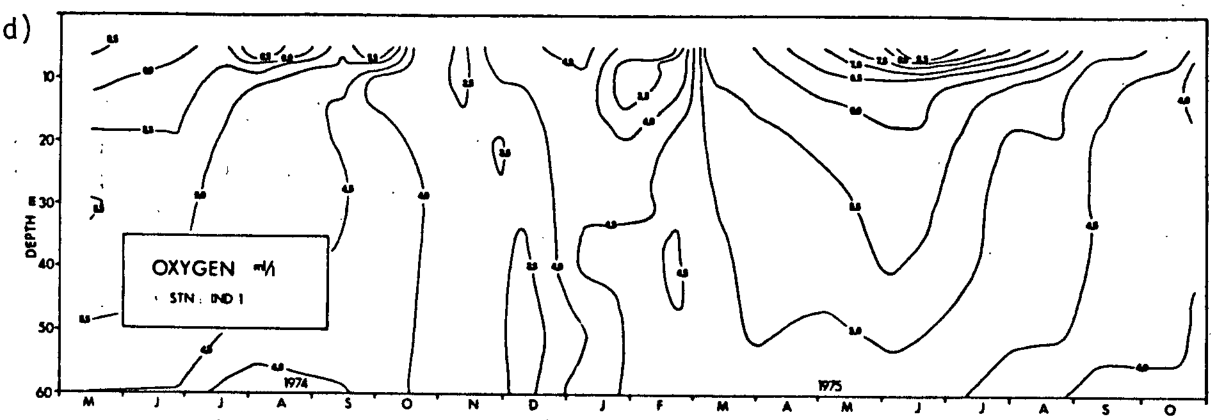


Figure 5.13 Time-depth sections of oxygen, May 1974 to October 1975 at stations (a) Van 11 (b) Van 24 (c) Van 34 (d) Ind 1 and (e) Ind 2

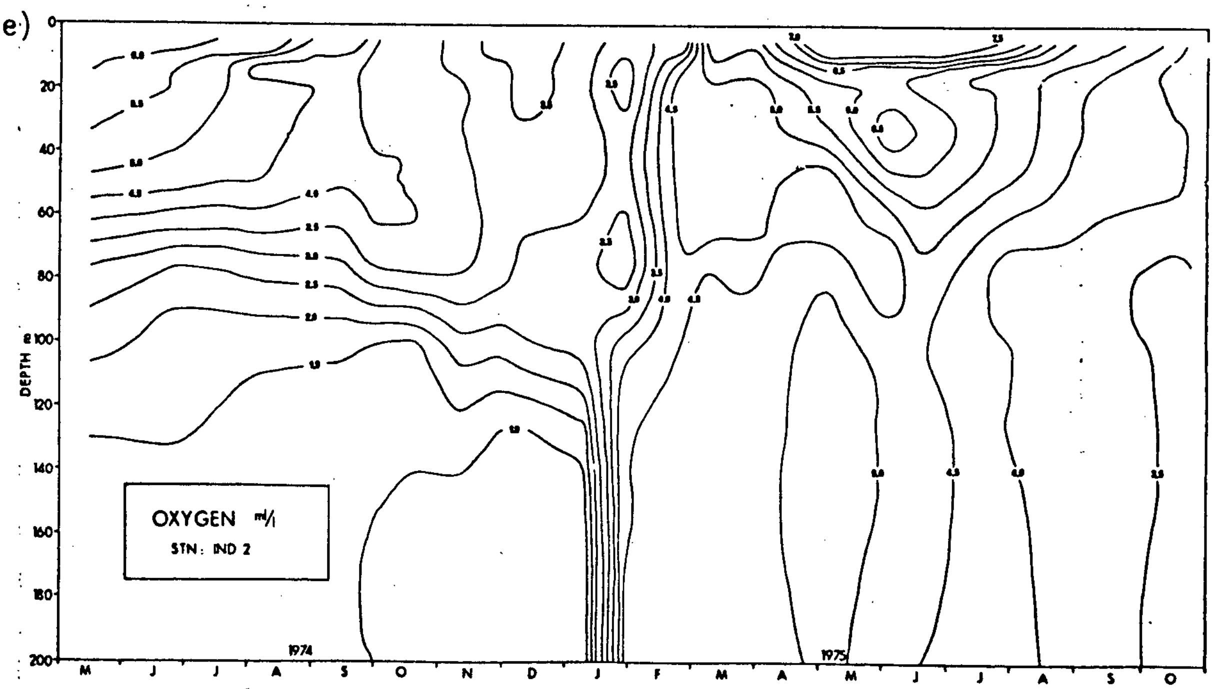
(c)


OXYGEN ml/l
STN: VAN 34
DEPTH m
1974
1975
M J J A S O N D J F M A M J J A S O

(d)


OXYGEN ml/l
STN: IND 1
DEPTH m
1974
1975
M J J A S O N D J F M A M J J A S O

(e)


OXYGEN ml/l
STN: IND 2
DEPTH m
1974
1975
M J J A S O N D J F M A M J J A S O

(a)

(b)

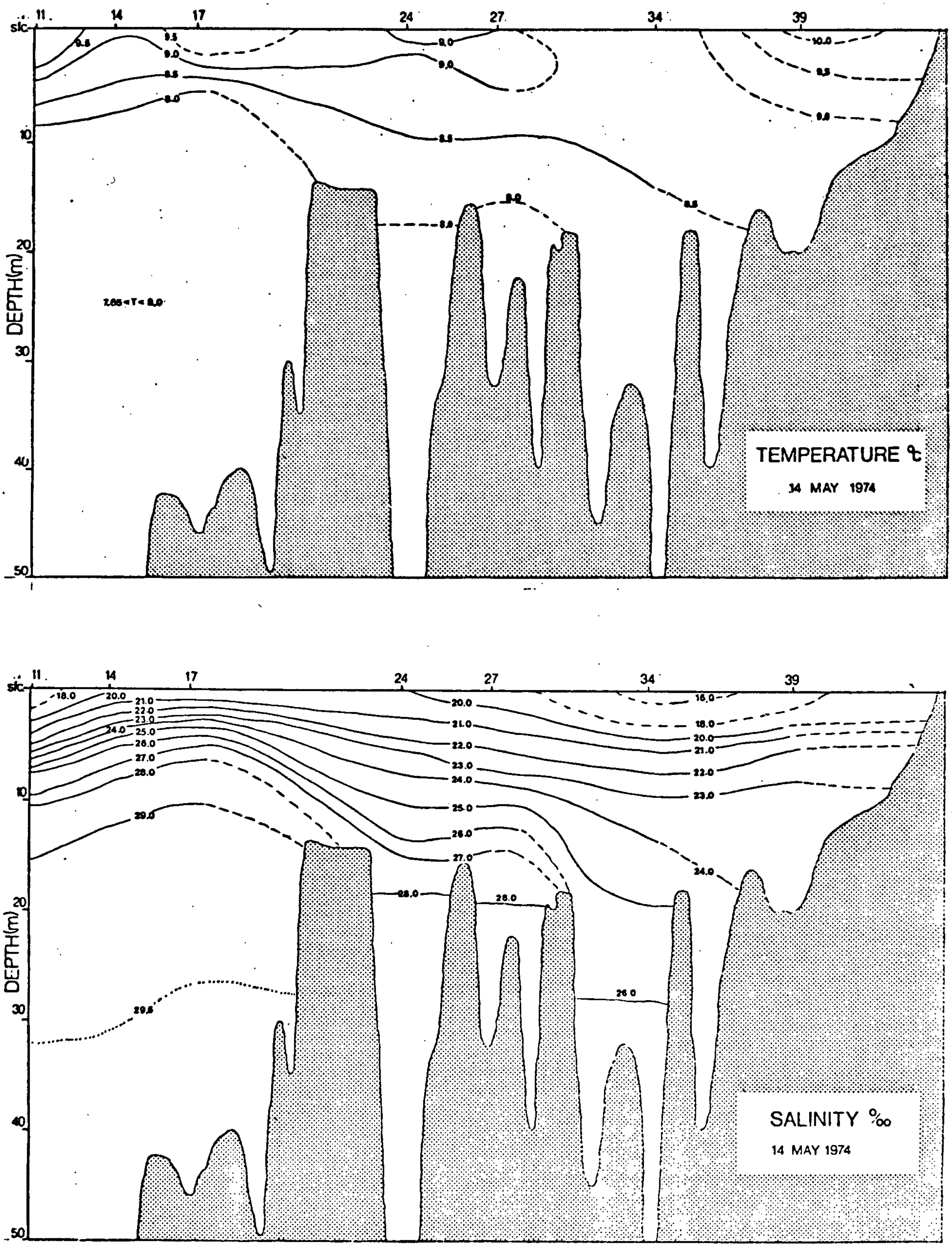
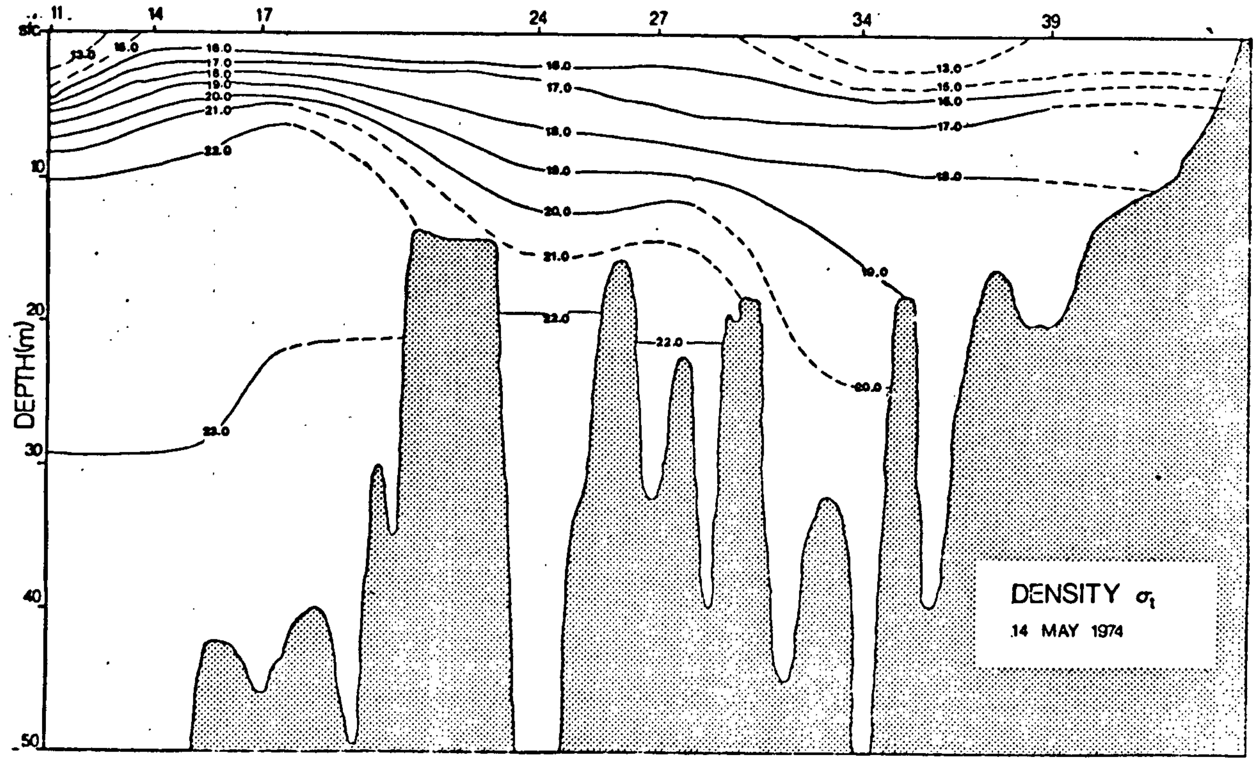
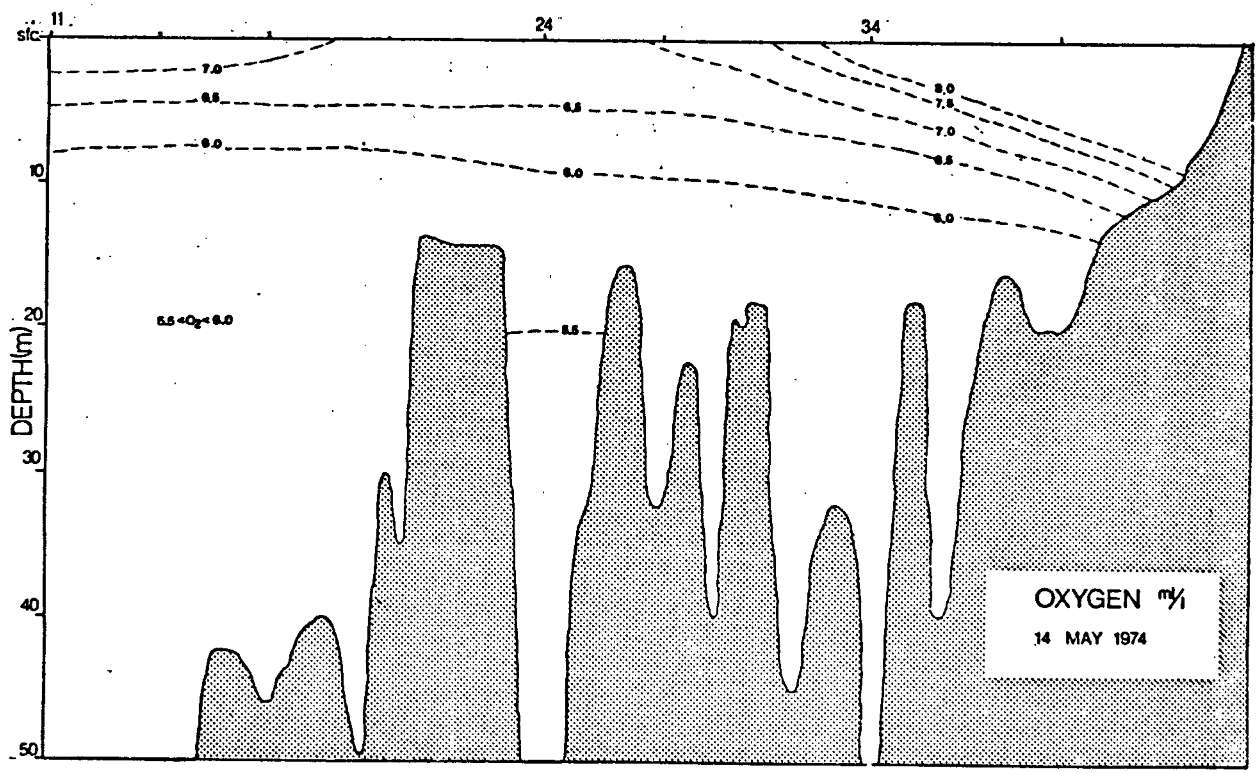


Figure 5.14 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Burrard Inlet, May 14, 1974

(c)


DENSITY σ_t
14 MAY 1974
DEPTH(m)
sfc
10
20
30
40
50
11
14
17
24
27
34
39

(d)


OXYGEN ml/l
14 MAY 1974
DEPTH(m)
sfc
10
20
30
40
50
11
24
34

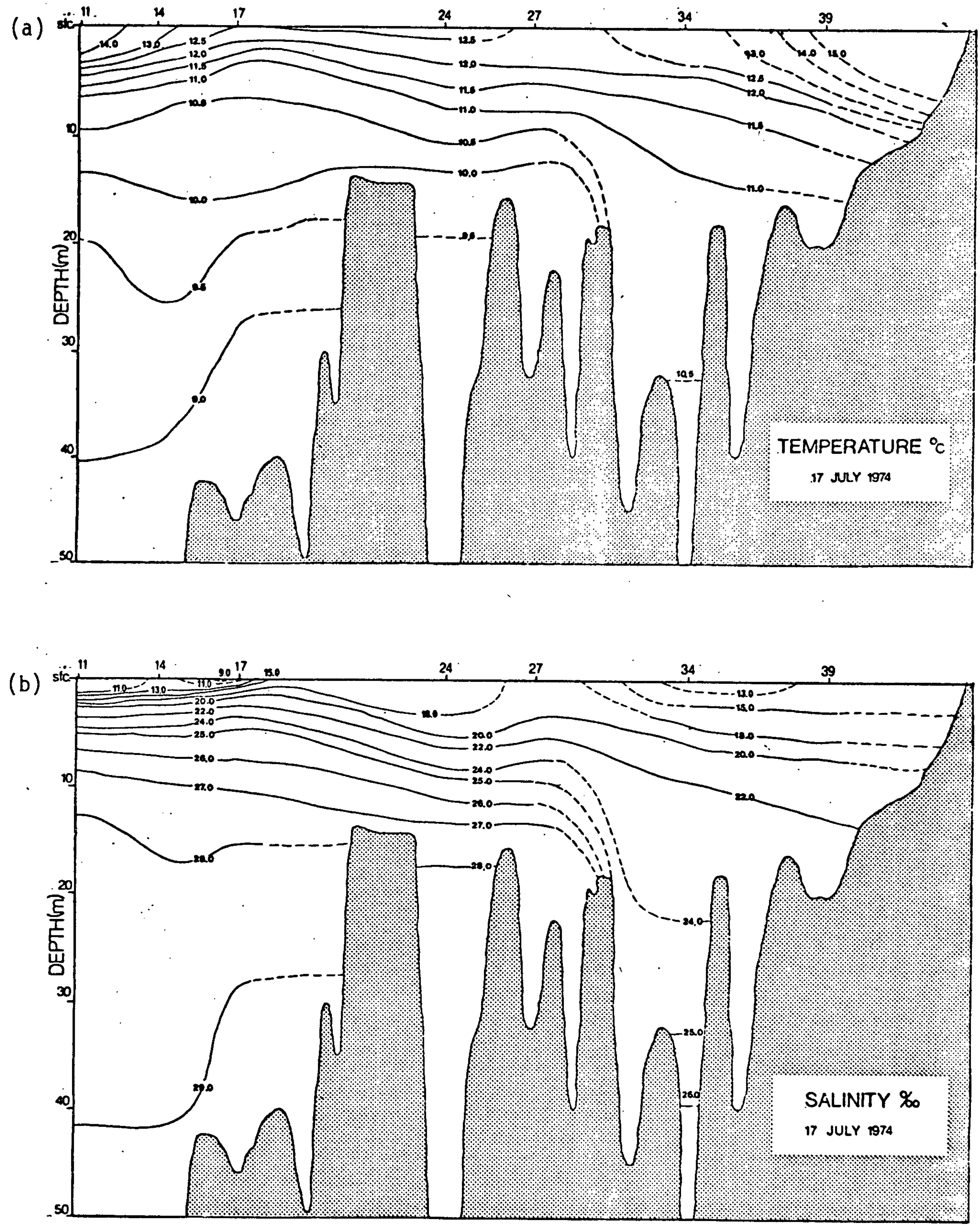
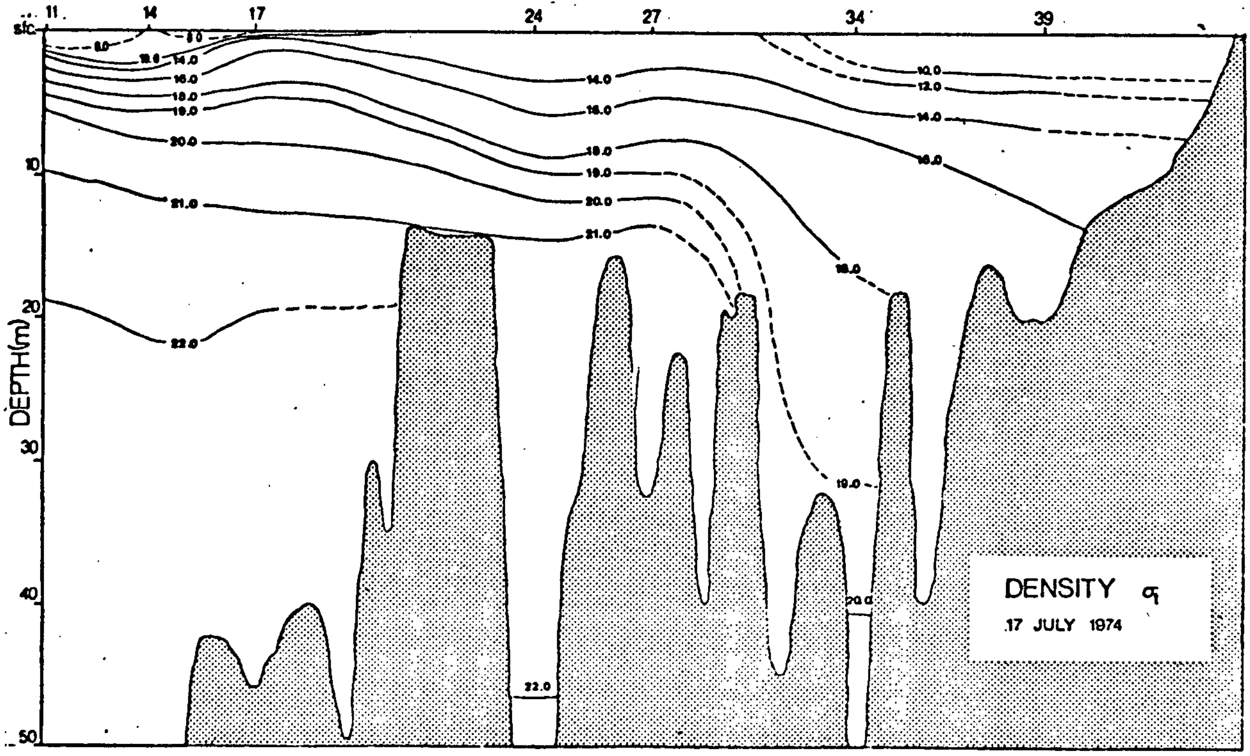
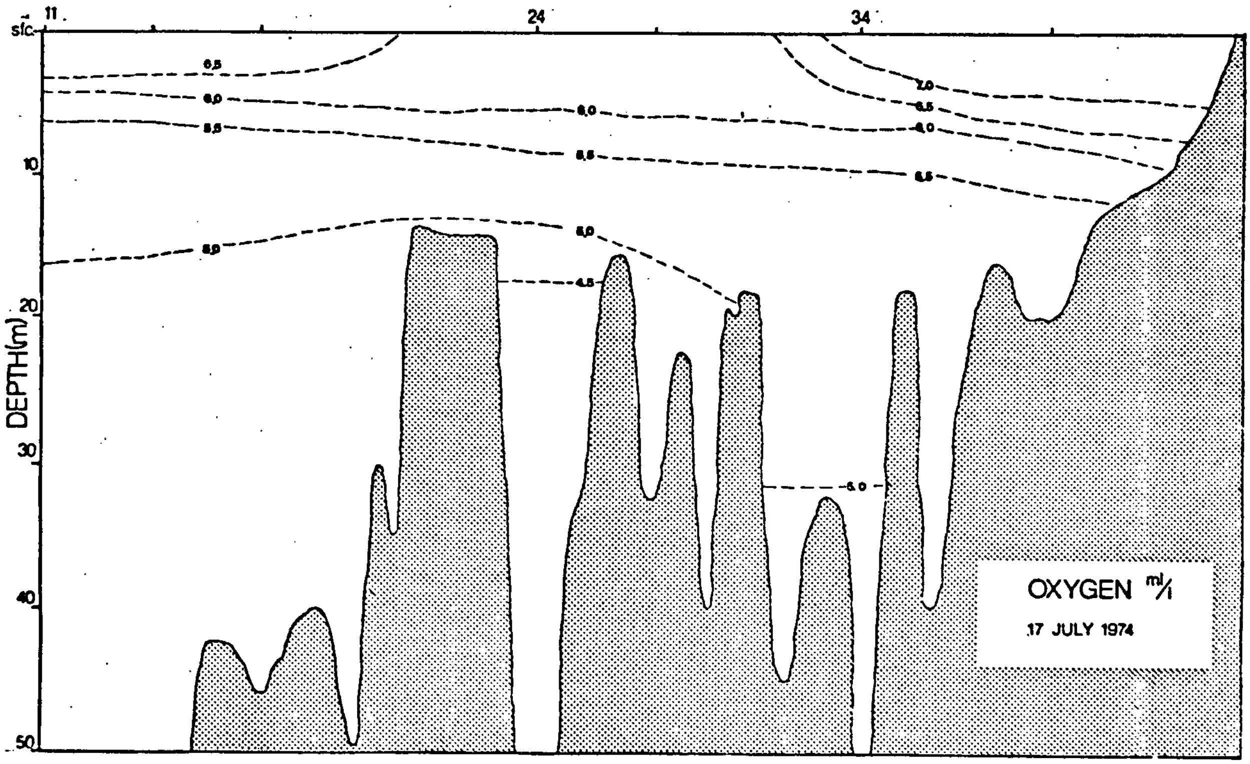


Figure 5.15 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Burrard Inlet, July 17, 1974

(c)


sfc
11
14
17
24
27
34
39
DEPTH(m)
10
20
30
40
50
14.0
16.0
18.0
19.0
20.0
21.0
22.0
10.0
12.0
DENSITY σt
17 JULY 1974

(d)


sfc
11
24
34
DEPTH(m)
10
20
30
40
50
6.5
6.0
5.5
5.0
4.5
7.0
OXYGEN ml/l
17 JULY 1974

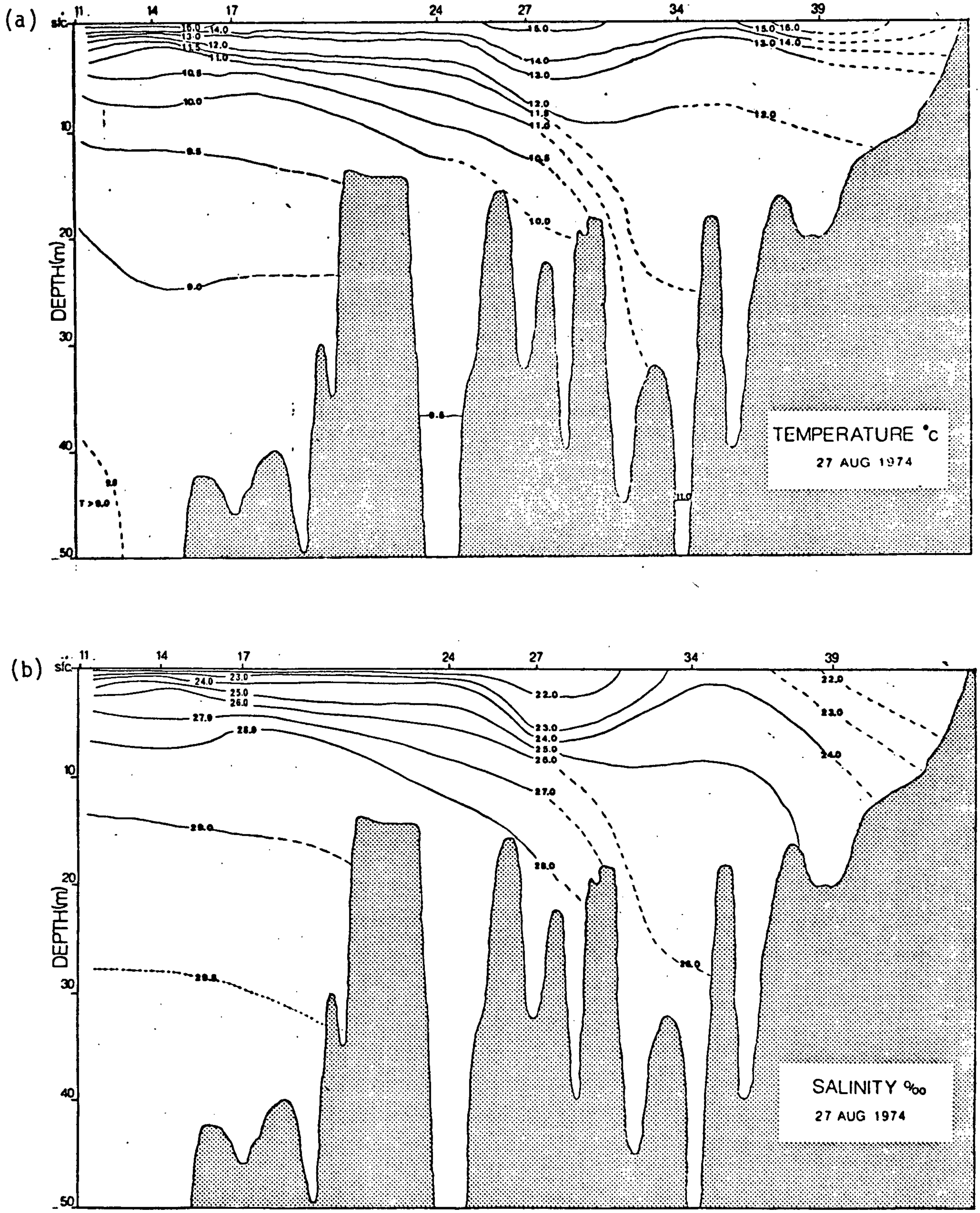
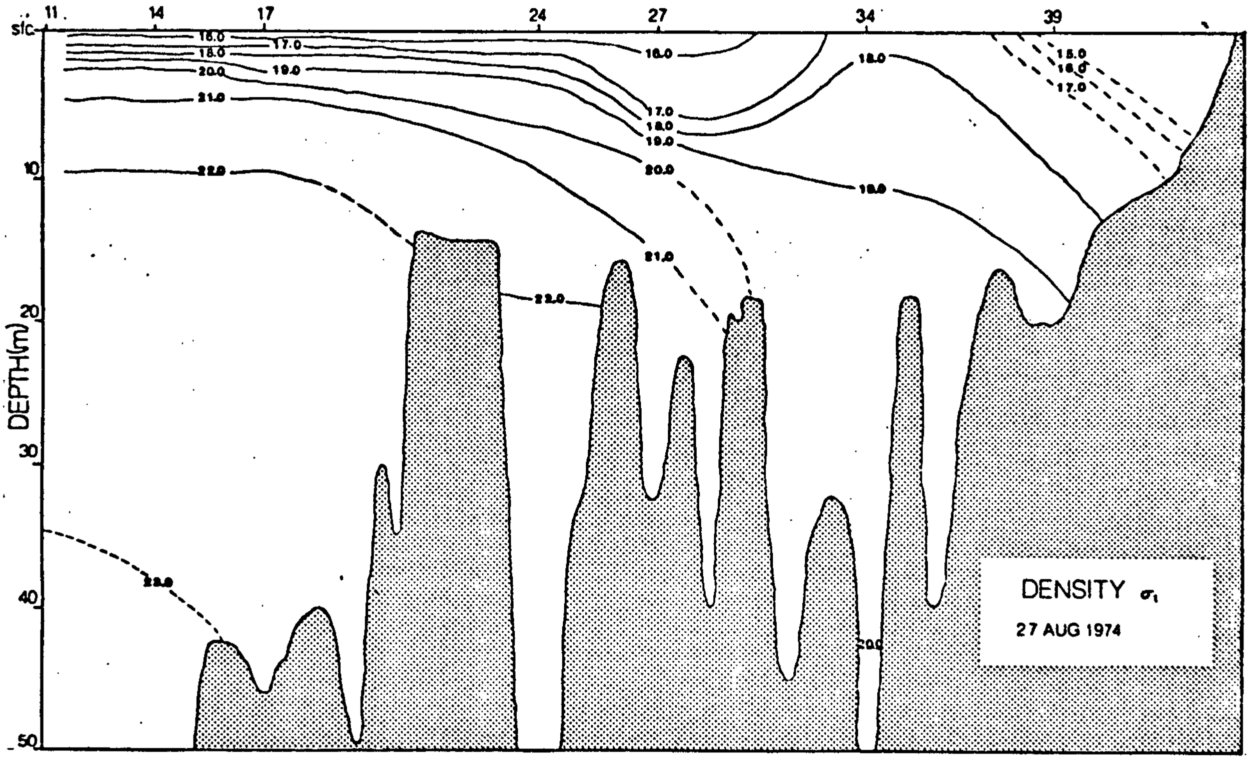
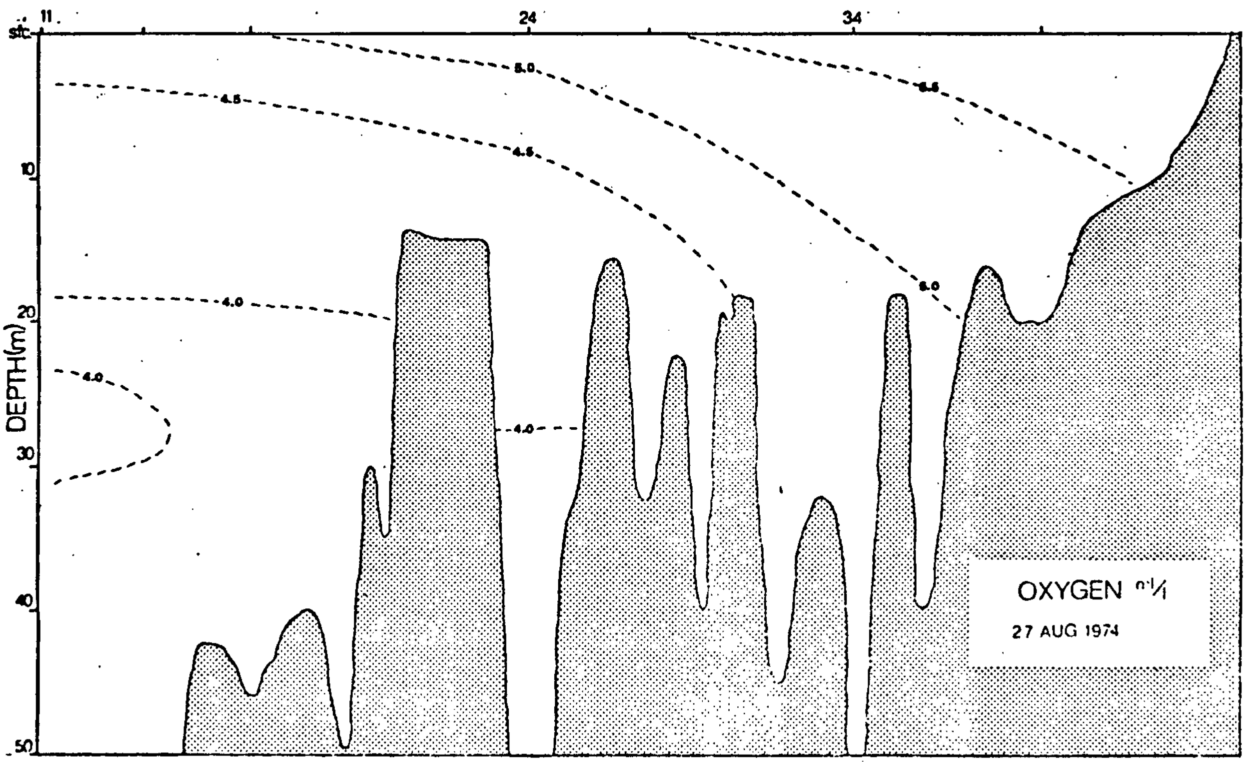


Figure 5.16 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Burrard Inlet, August 27, 1974

(c)


11
14
17
24
27
34
39
sfc
10
20
30
40
50
DEPTH(m)
16.0
17.0
18.0
19.0
20.0
21.0
22.0
15.0
DENSITY σ_t
27 AUG 1974

(d)


11
24
34
sfc
10
20
30
40
50
DEPTH(m)
5.0
5.5
4.5
4.0
OXYGEN ml/l
27 AUG 1974

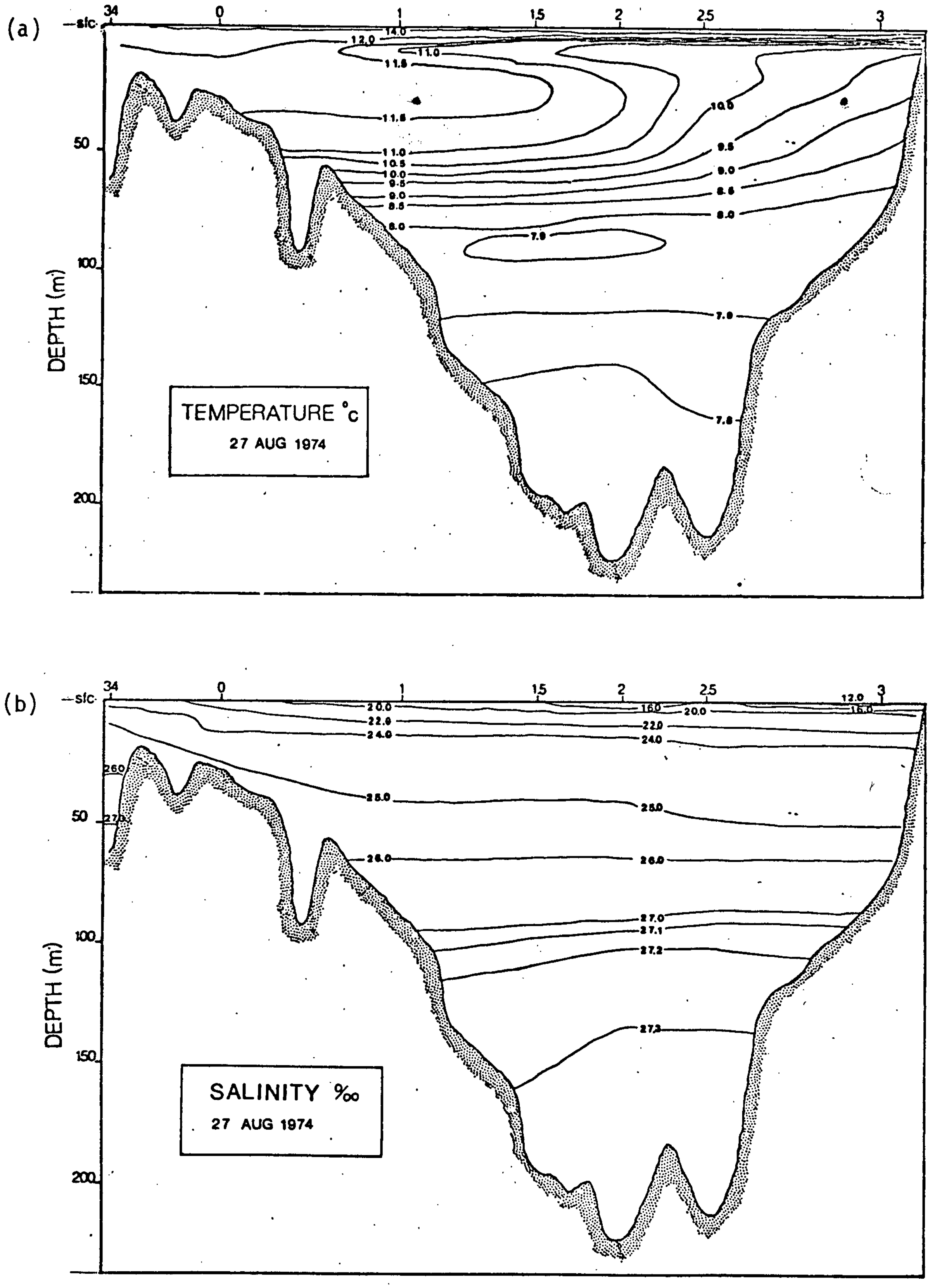
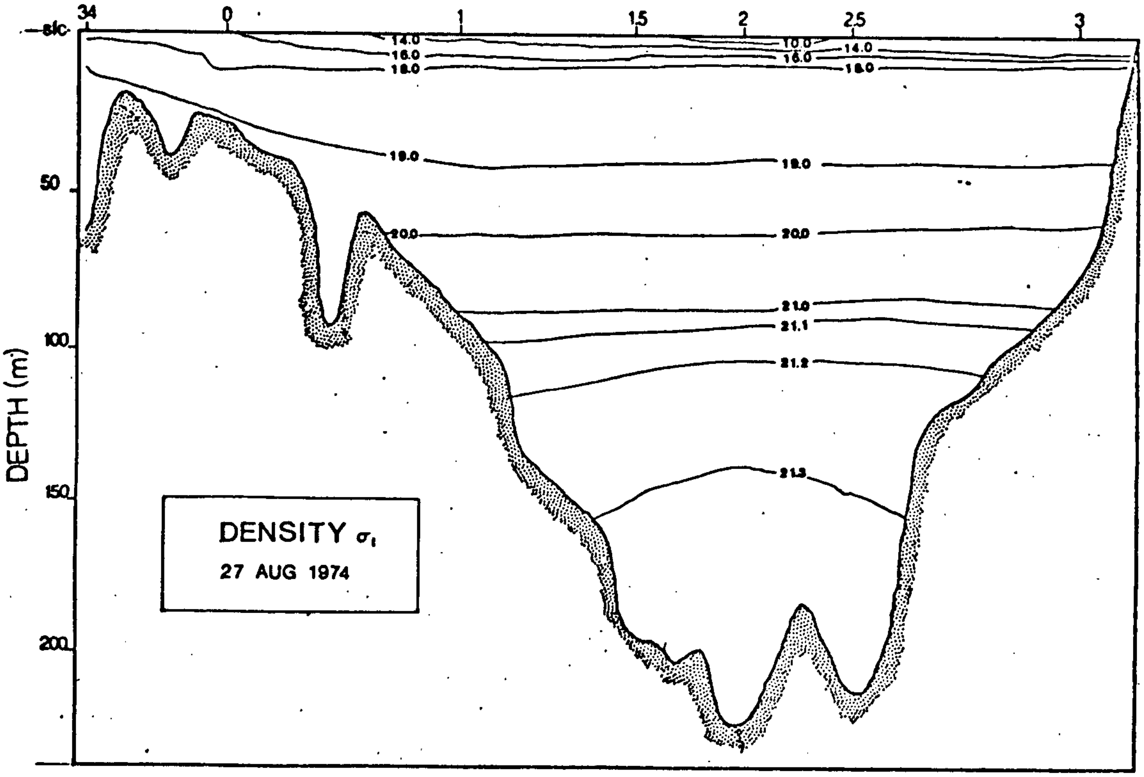
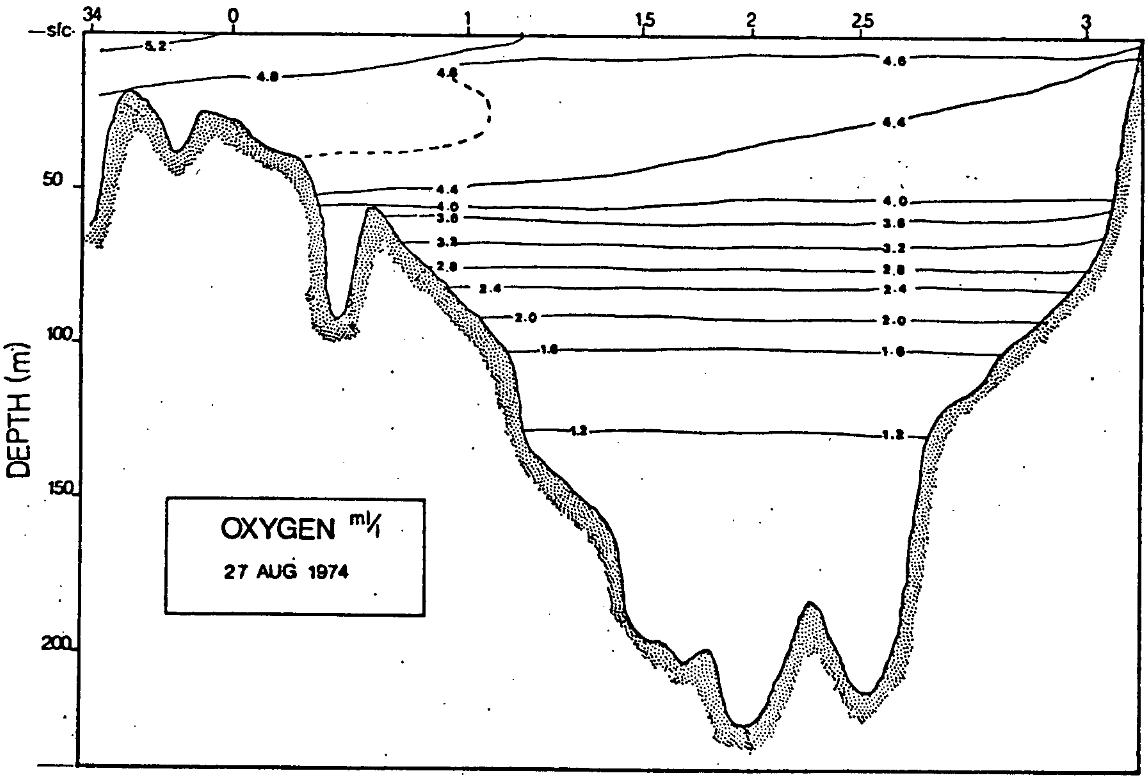


Figure 5.17 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Indian Arm, August 27, 1974

(c)


DENSITY σ_t
27 AUG 1974
DEPTH (m)
sfc
50
100
150
200
34
0
1
1.5
2
2.5
3
14.0
16.0
18.0
19.0
20.0
21.0
21.1
21.2
21.3

(d)


OXYGEN ml/l
27 AUG 1974
DEPTH (m)
sfc
50
100
150
200
34
0
1
1.5
2
2.5
3
5.2
4.8
4.6
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2

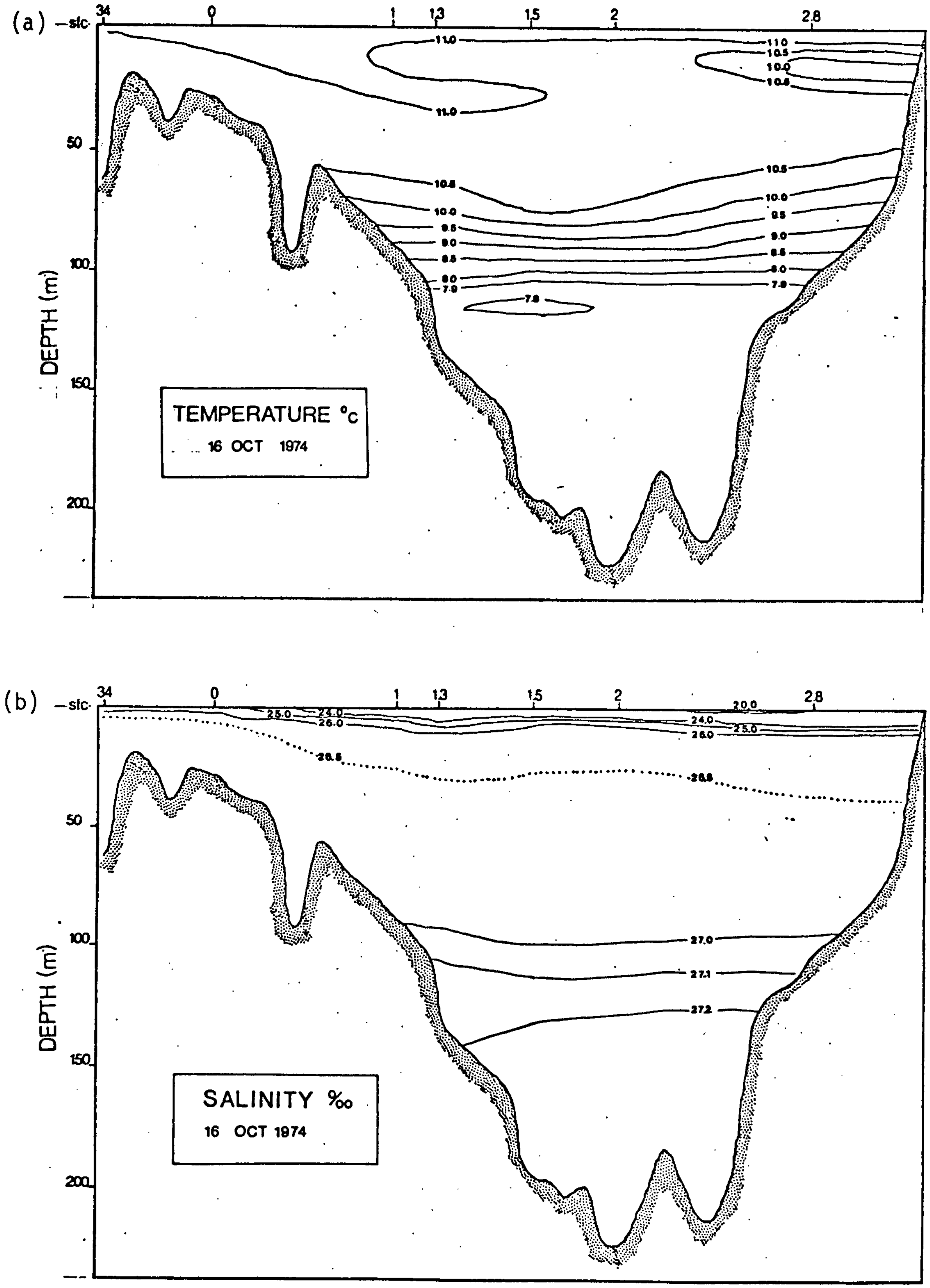
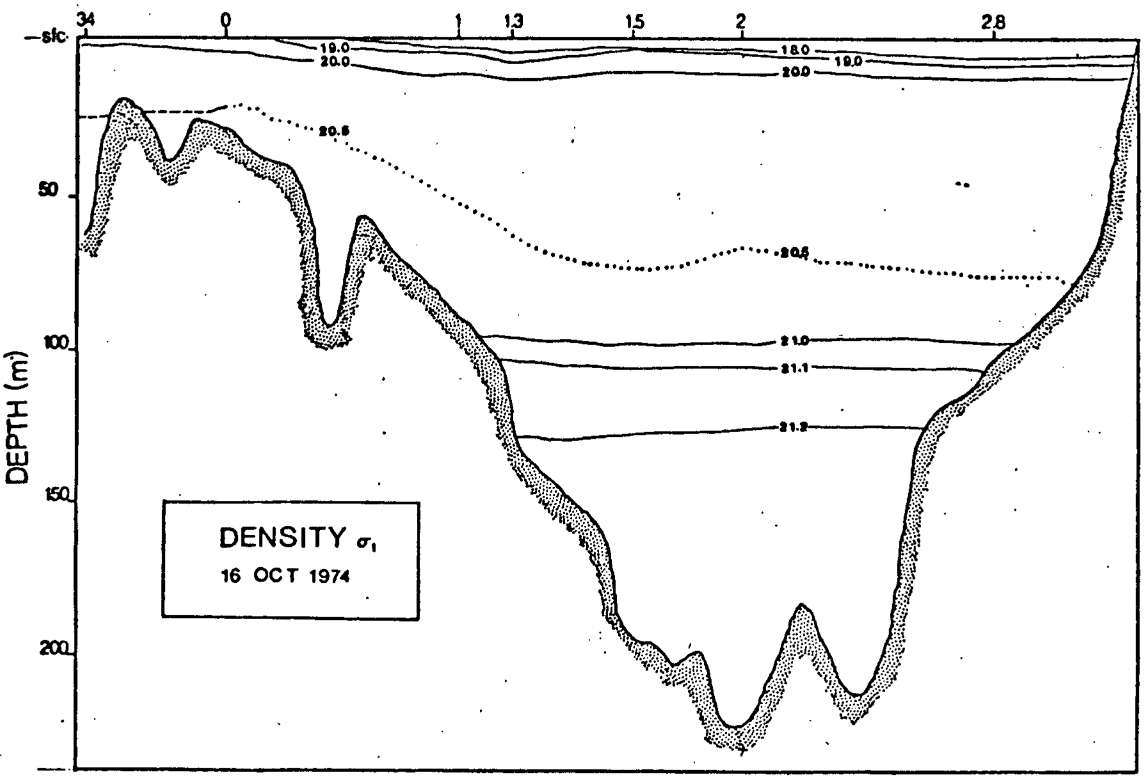
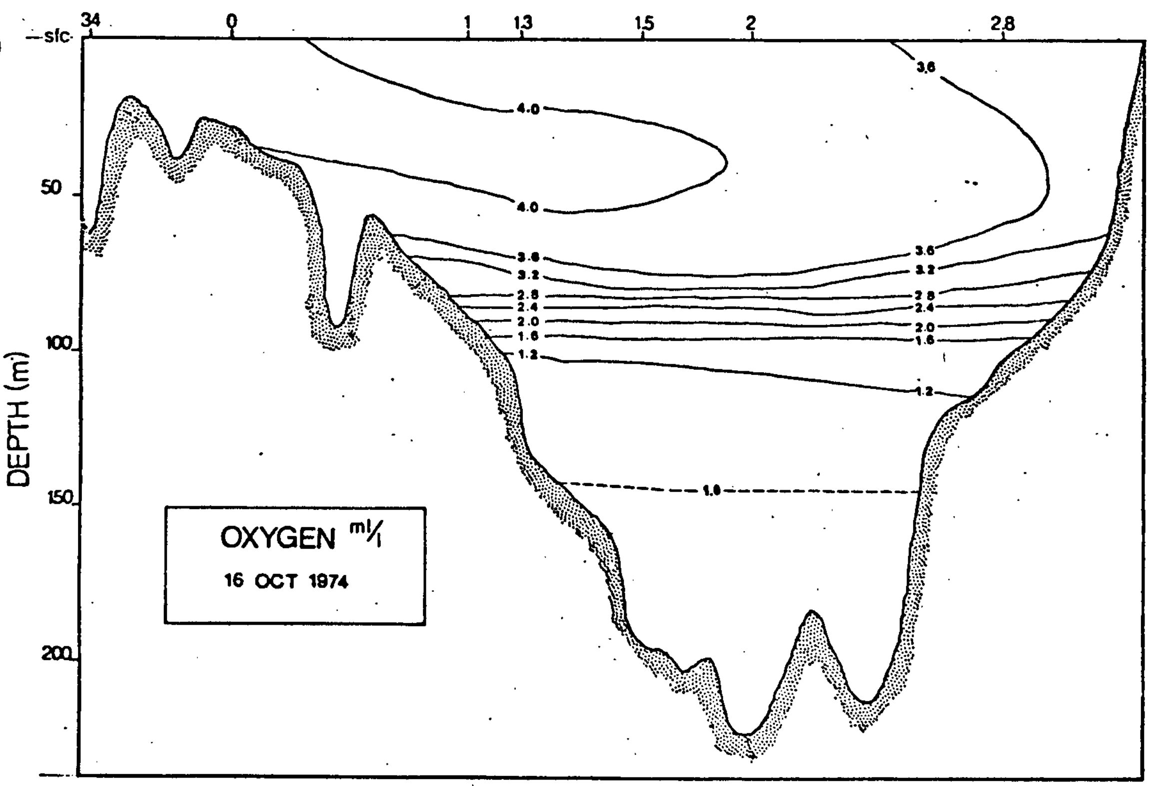


Figure 5.18 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Indian Arm, October 16, 1974

(c)


34
0
1
1.3
1.5
2
2.8
sfc
50
100
150
200
DEPTH (m)
19.0
20.0
18.0
19.0
20.0
20.5
20.5
21.0
21.1
21.2
DENSITY σ_t
16 OCT 1974

(d)


34
0
1
1.3
1.5
2
2.8
sfc
50
100
150
200
DEPTH (m)
4.0
4.0
3.6
3.6
3.2
2.8
2.4
2.0
1.6
1.2
1.0
OXYGEN ml/l
16 OCT 1974

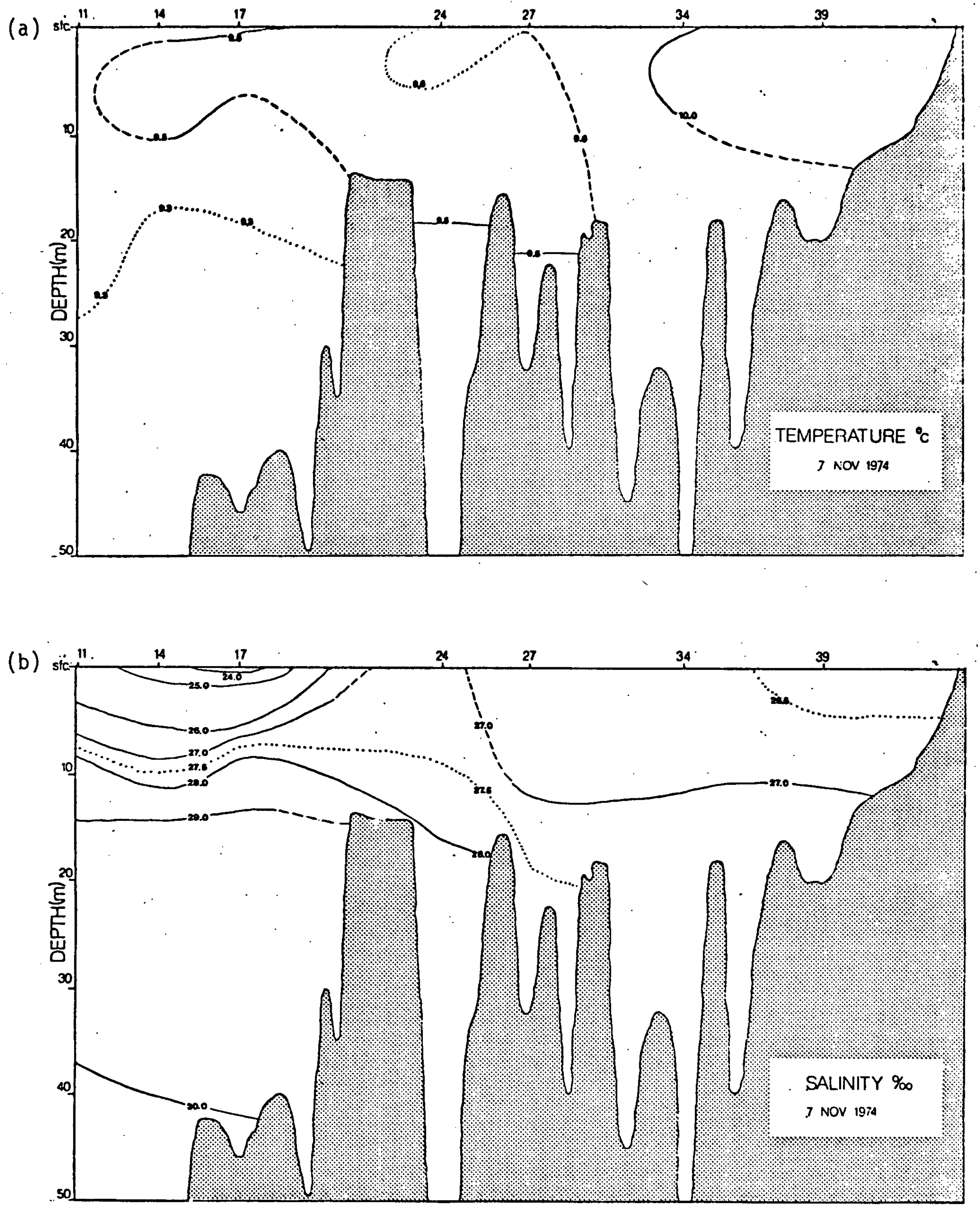
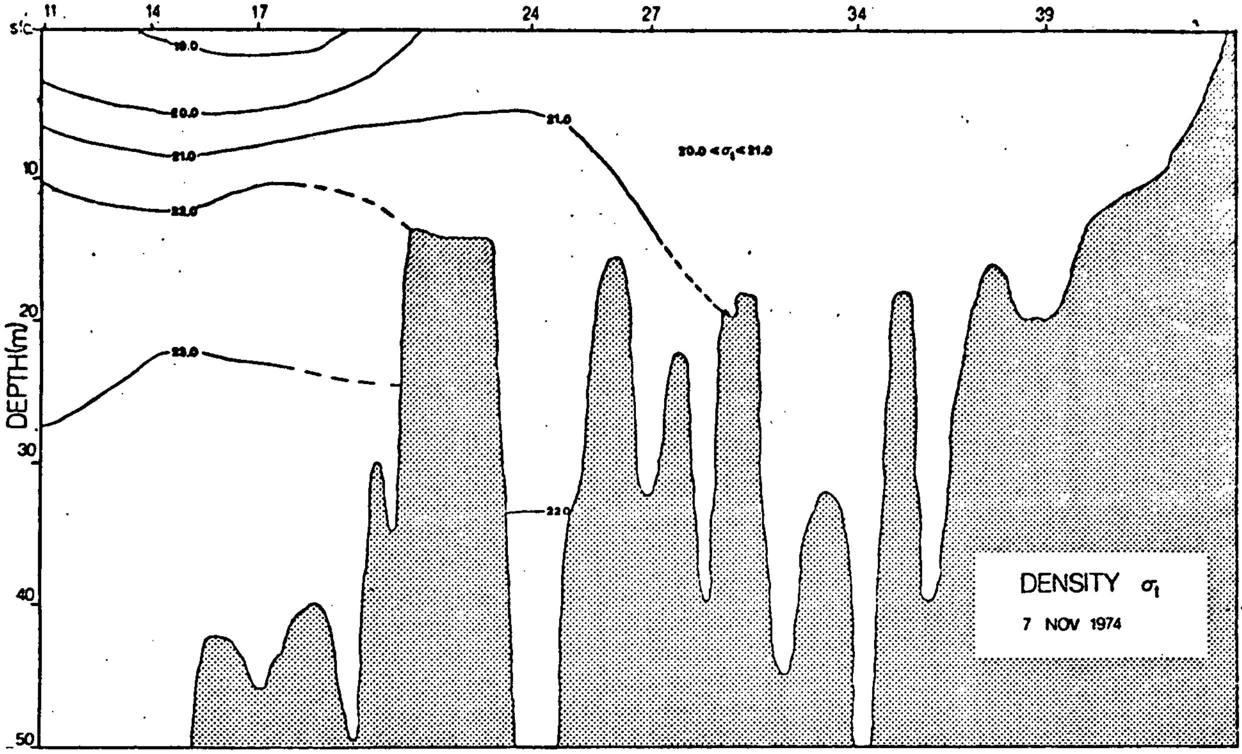
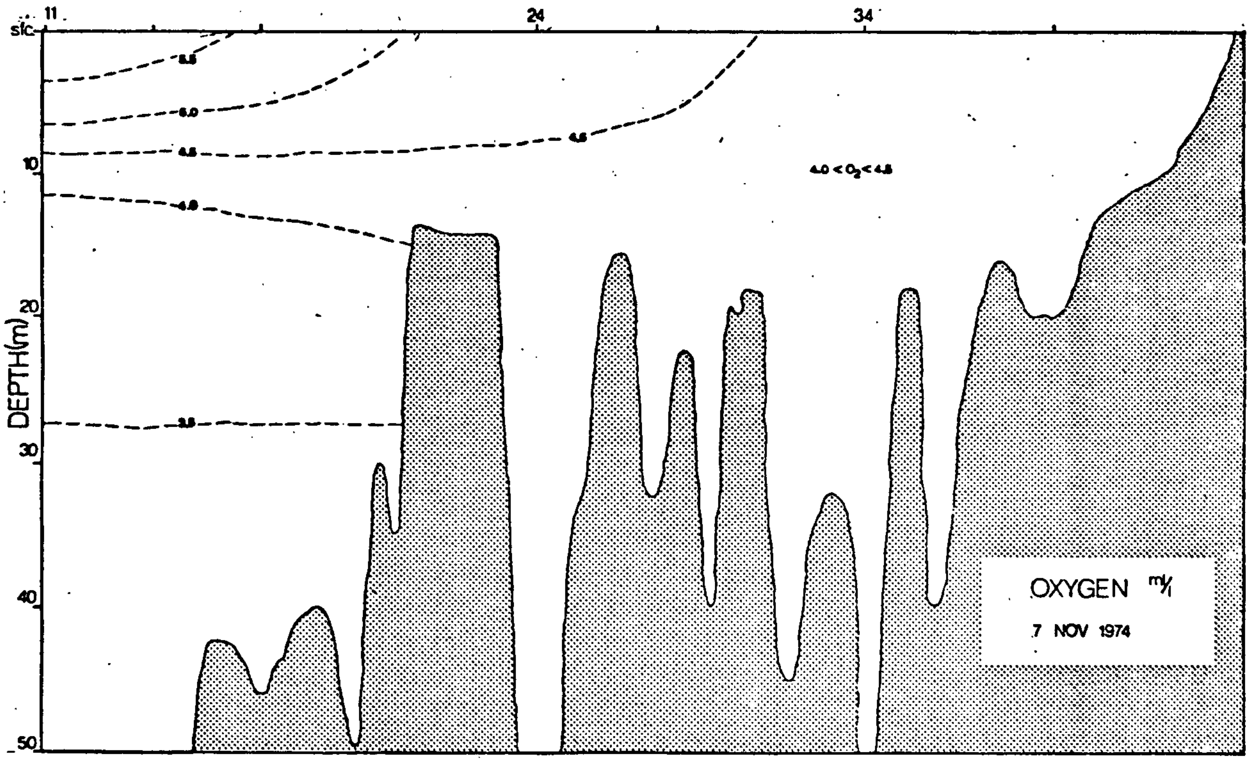


Figure 5.19 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Burrard Inlet, November 7, 1974

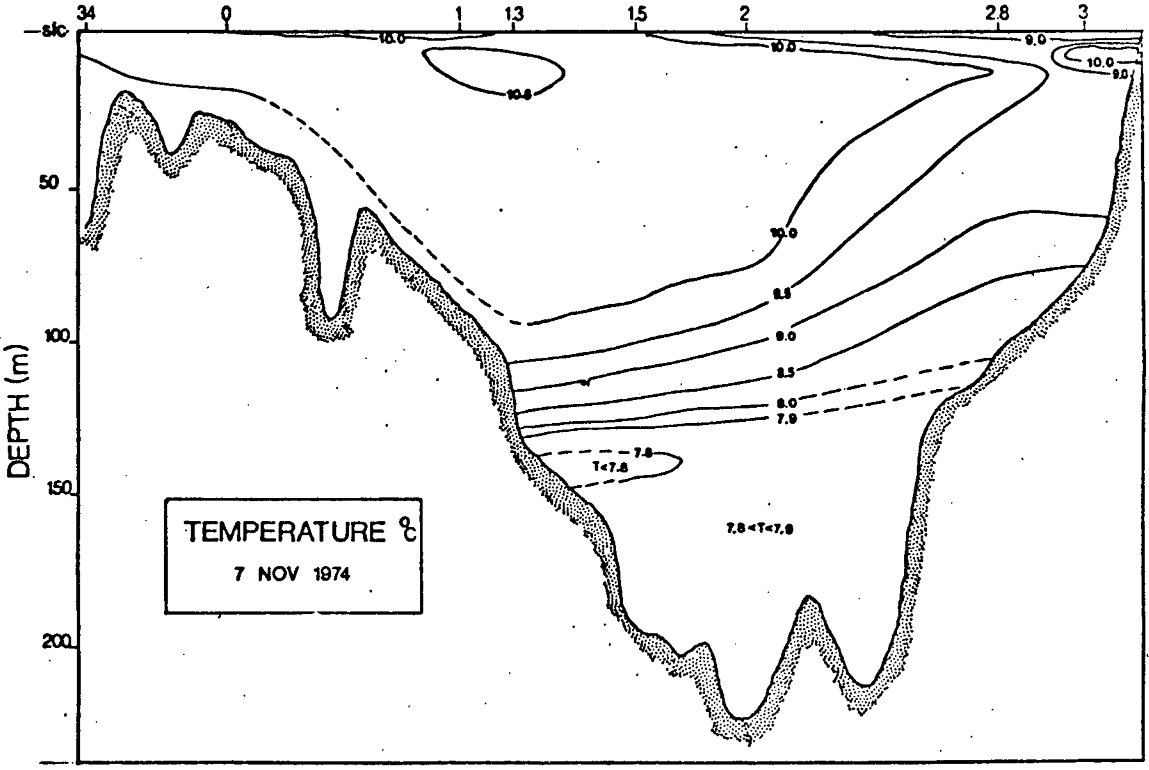
(c)


11
14
17
24
27
34
39
s/c
10
20
30
40
50
DEPTH(m)
DENSITY σ_t
7 NOV 1974

(d)


11
24
34
s/c
10
20
30
40
50
DEPTH(m)
OXYGEN ml/l
7 NOV 1974

(a)



(b)

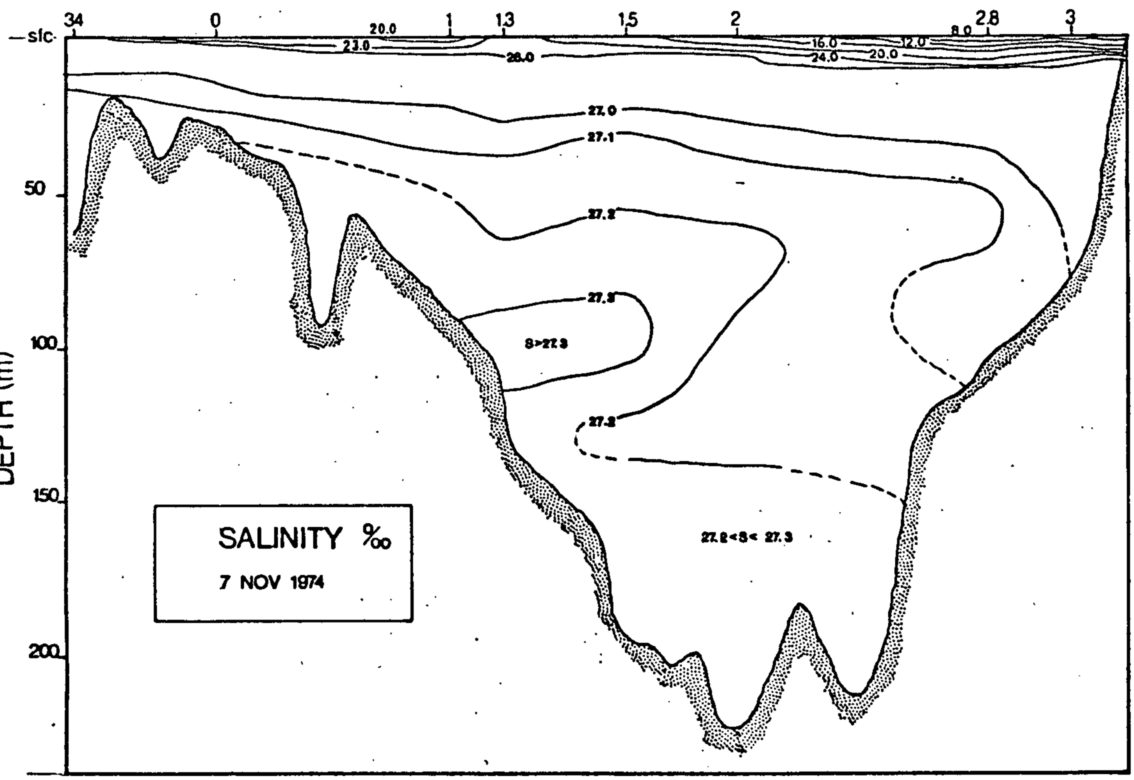
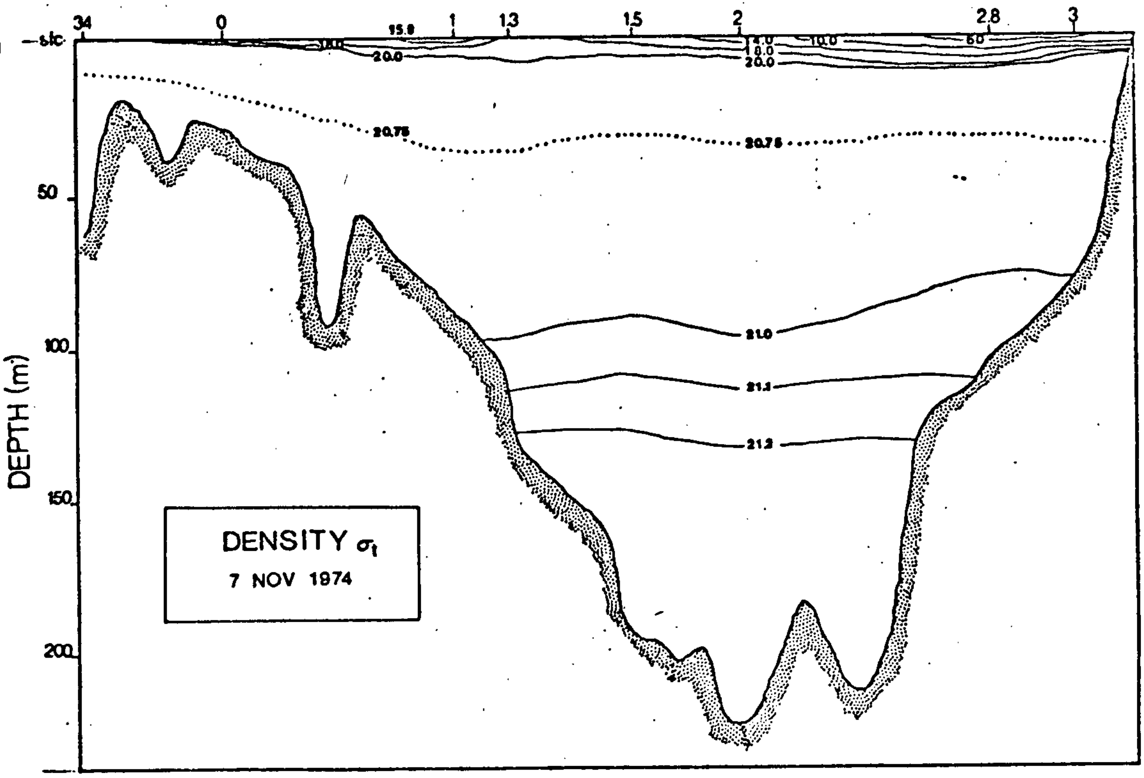
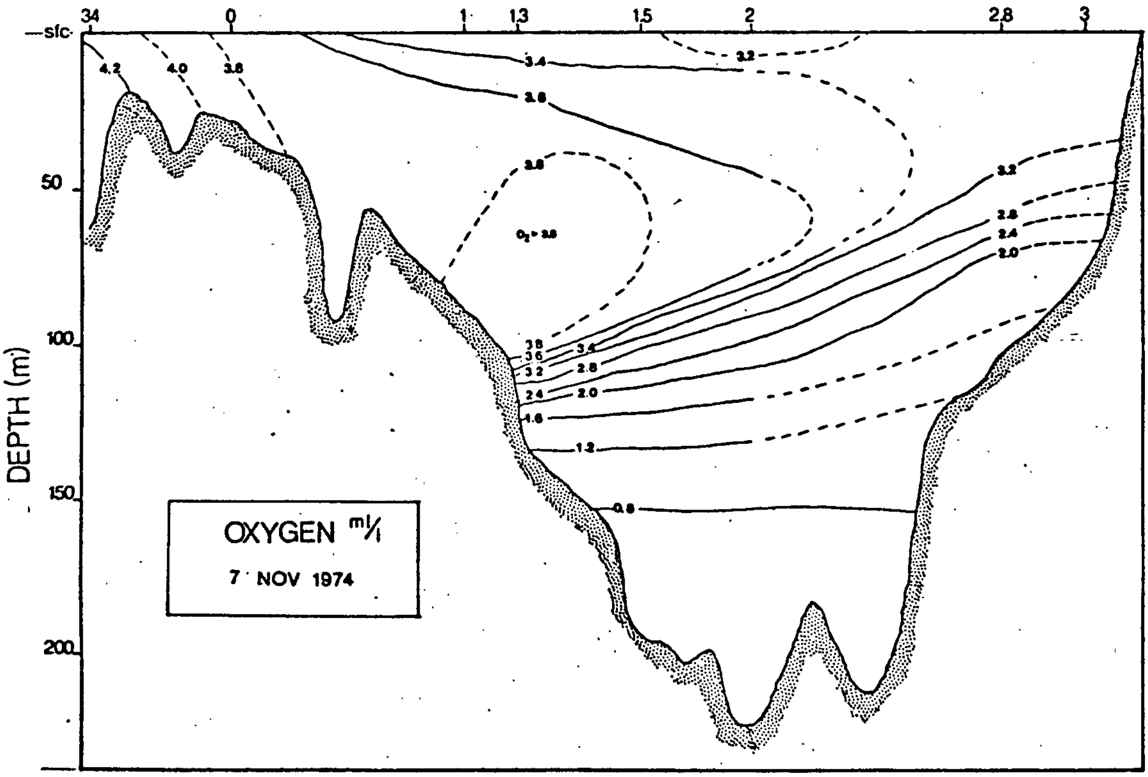


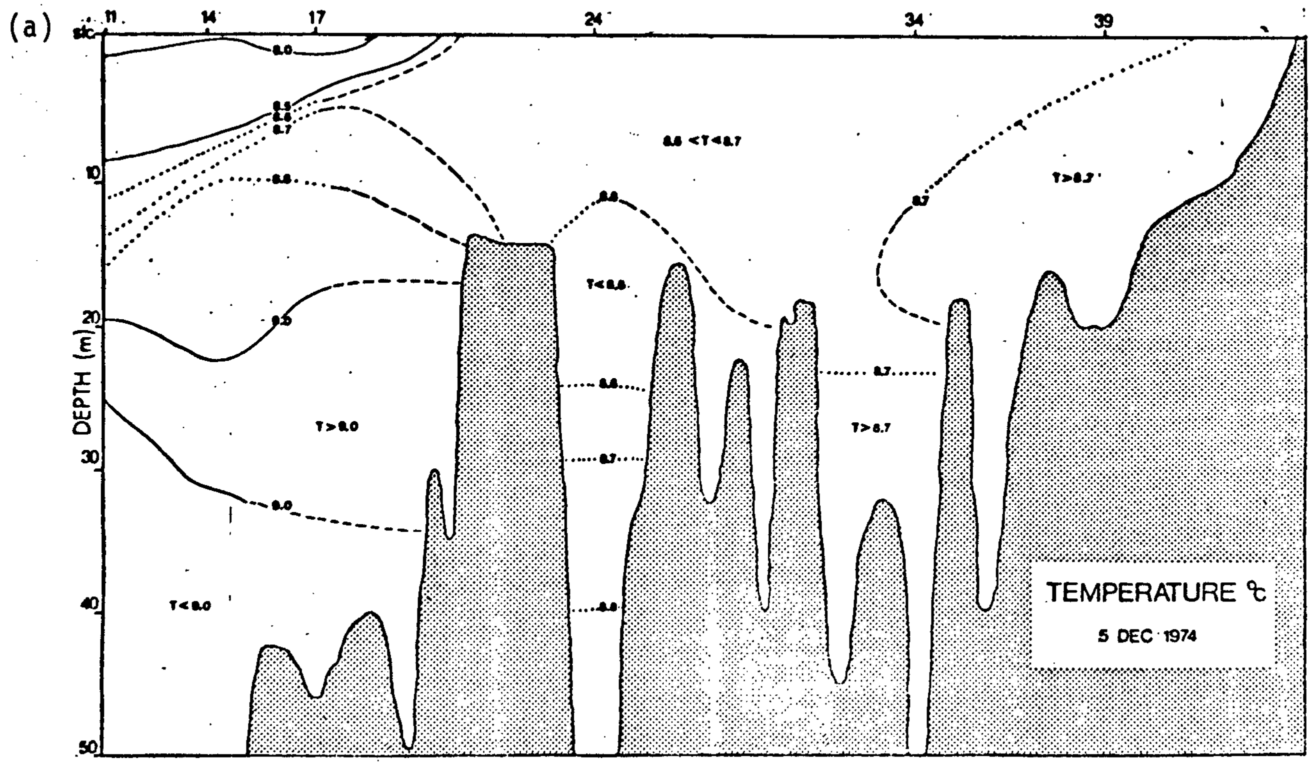
Figure 5.20 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Indian Arm, November 7, 1974

(c)


DENSITY σ_t
7 NOV 1974
DEPTH (m)
sfc
50
100
150
200
34
0
1
1.3
1.5
2
2.8
3
15.8
18.0
20.0
14.0
16.0
10.0
6.0
20.75
21.0
21.1
21.2

(d)


OXYGEN ml/l
7 NOV 1974
DEPTH (m)
sfc
50
100
150
200
34
0
1
1.3
1.5
2
2.8
3
4.2
4.0
3.8
3.4
3.6
3.2
O_2 > 3.8
2.8
2.4
2.0
1.6
1.2
0.8



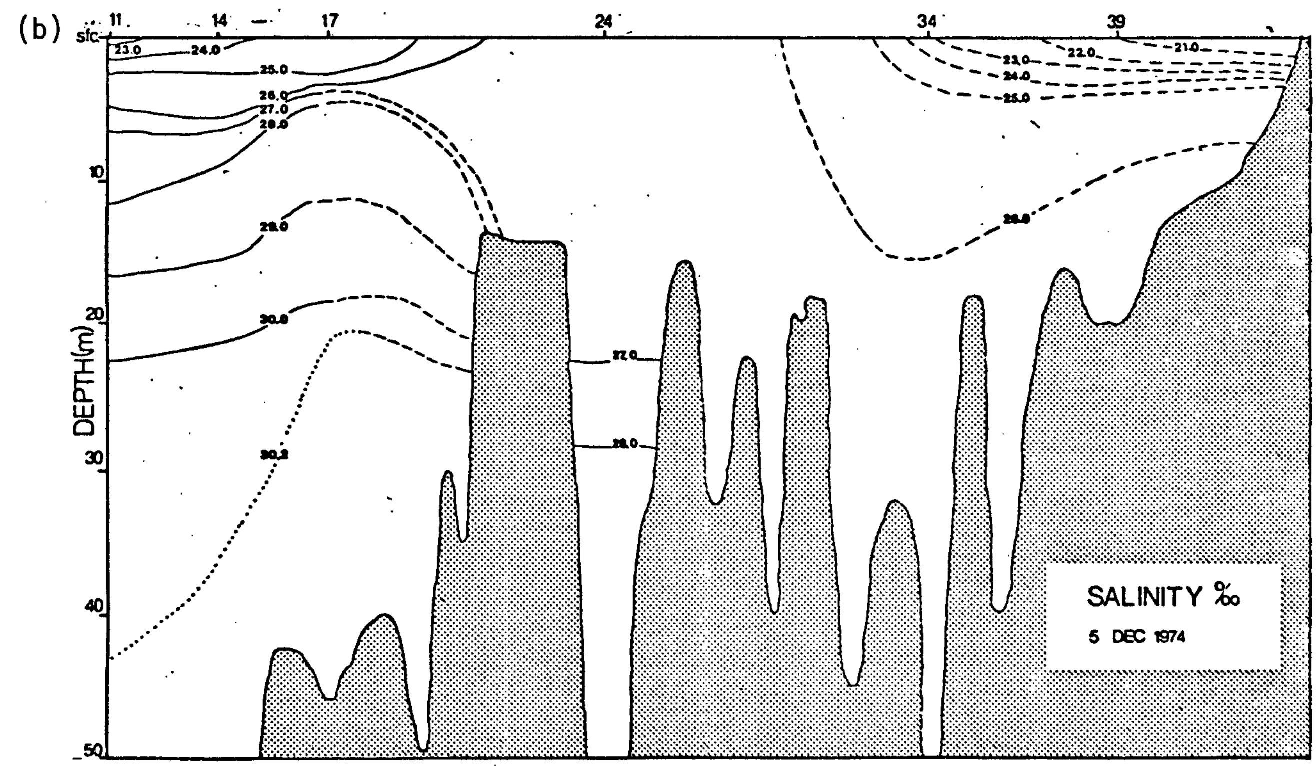
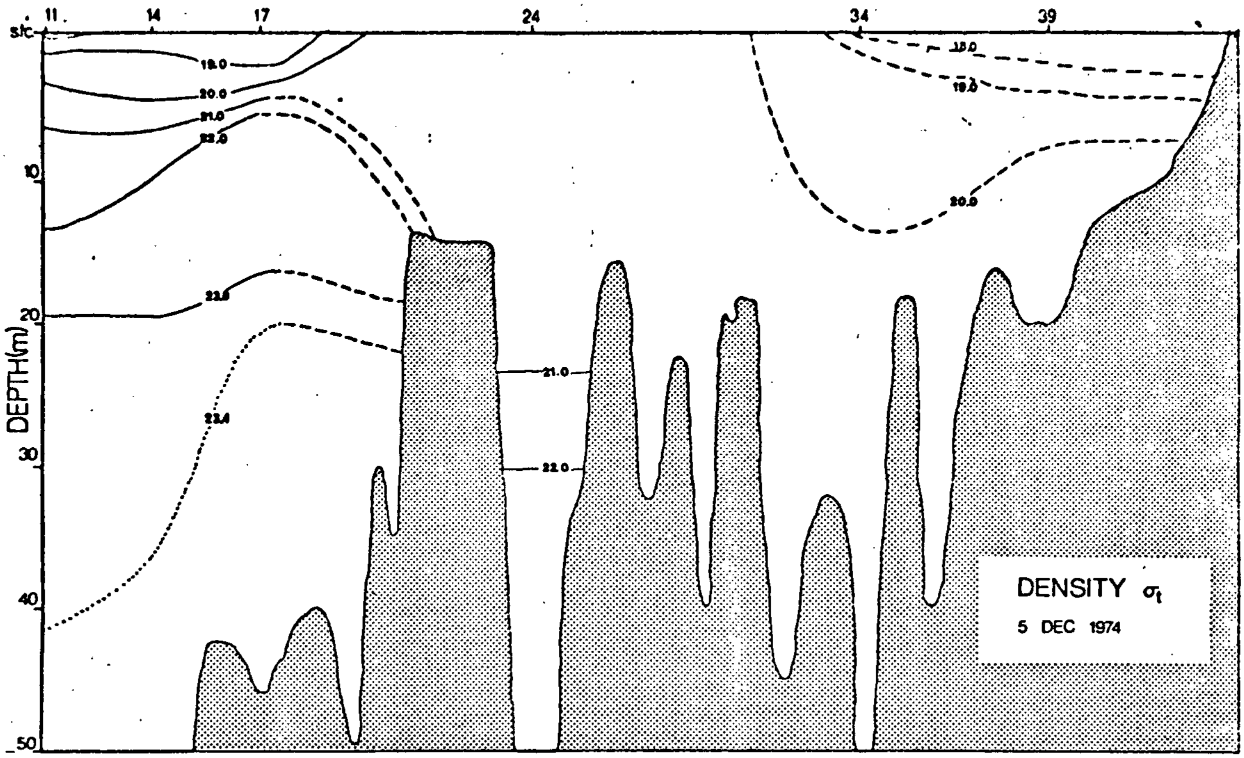
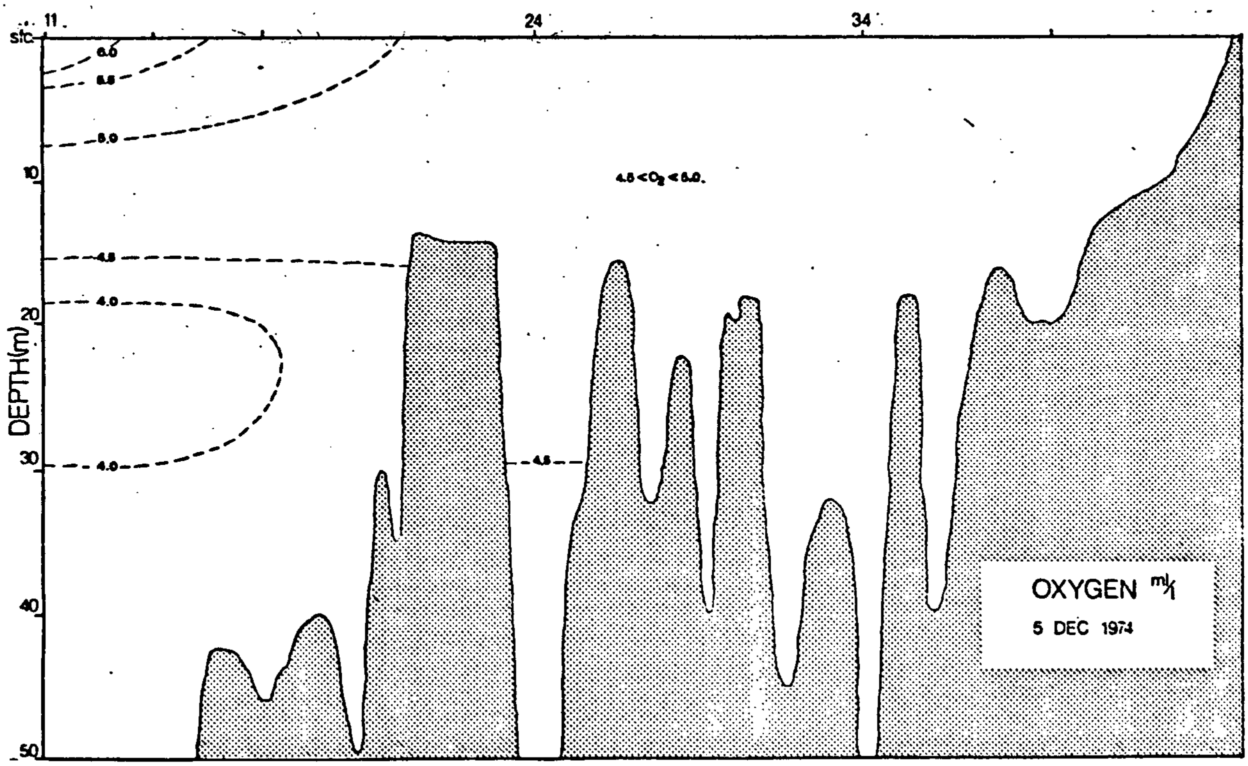


Figure 5.21 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Burrard Inlet, December 5, 1974

(c)


11
14
17
24
34
39
sfc
19.0
20.0
21.0
22.0
22.8
23.4
21.0
22.0
20.0
10
20
30
40
50
DEPTH(m)
DENSITY σ_t
5 DEC 1974

(d)


11
24
34
sfc
6.0
5.5
5.0
4.5 < O_2 < 5.0.
4.5
4.0
4.0
4.5
10
20
30
40
50
DEPTH(m)
OXYGEN ml/l
5 DEC 1974

(a)

(b)

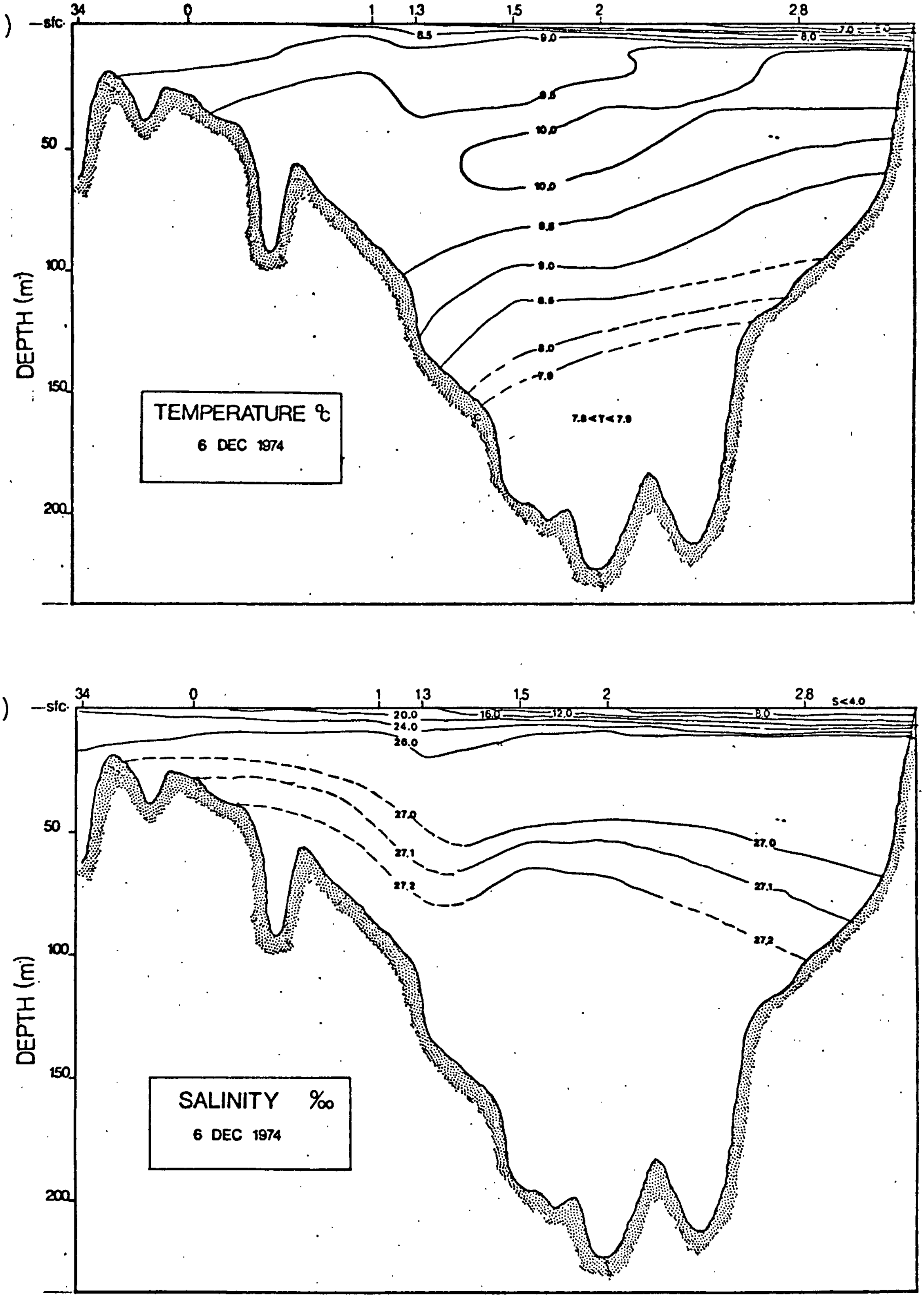
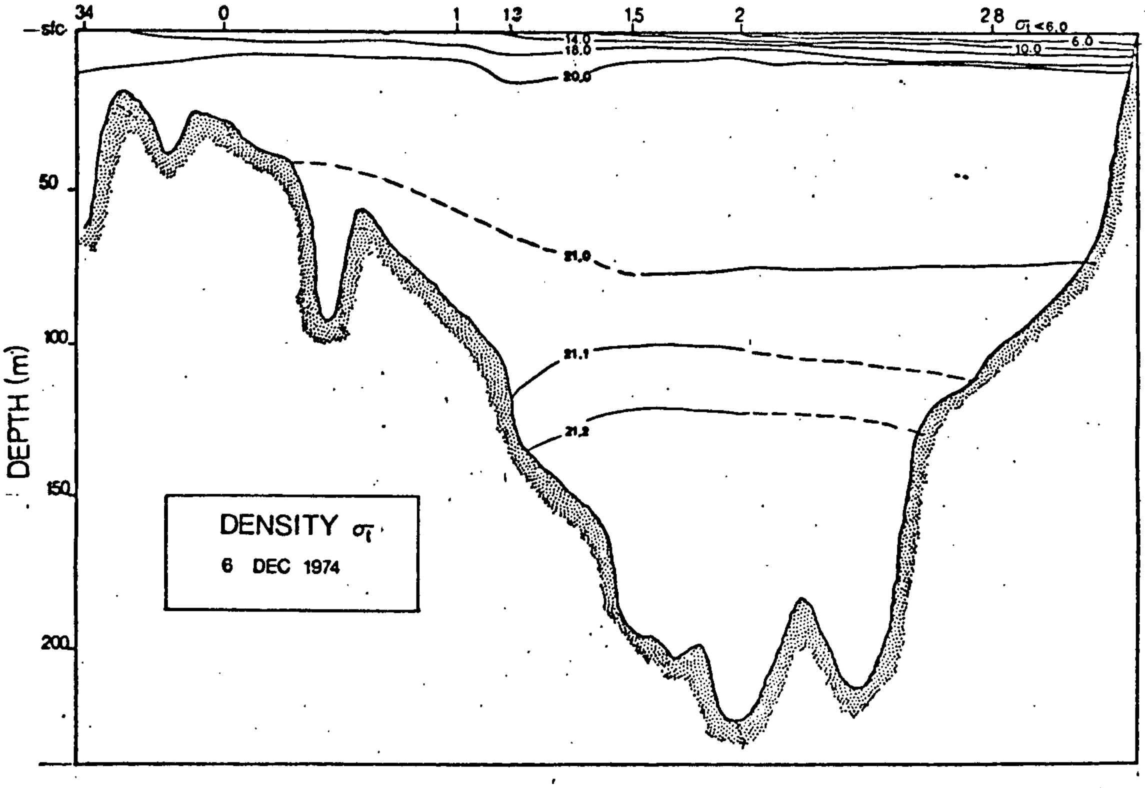
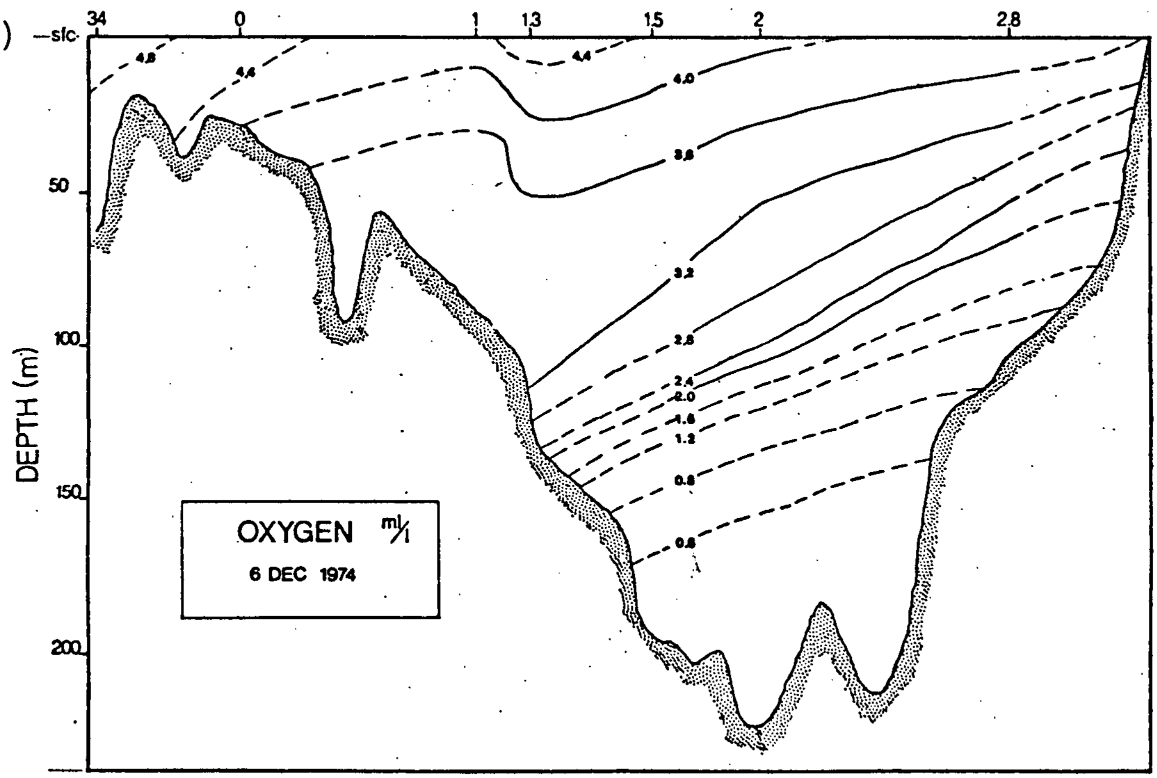


Figure 5.22 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Indian Arm, December 6, 1974

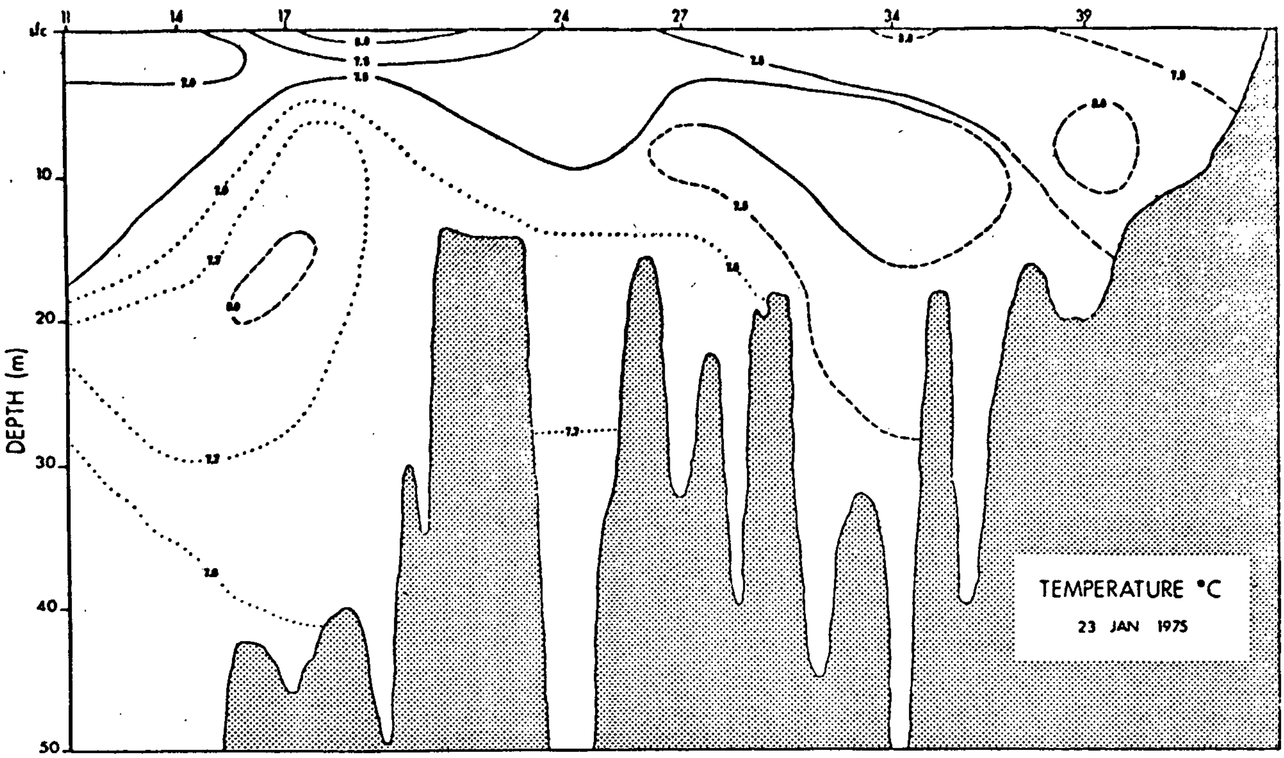
(c)


34
0
1
1.3
1.5
2
2.8
σt<6.0
6.0
10.0
14.0
18.0
20.0
21.0
21.1
21.2
DEPTH (m)
50
100
150
200
DENSITY σt
6 DEC 1974

(d)


34
0
1
1.3
1.5
2
2.8
4.8
4.4
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.8
DEPTH (m)
50
100
150
200
OXYGEN ml/l
6 DEC 1974

(a)



(b)

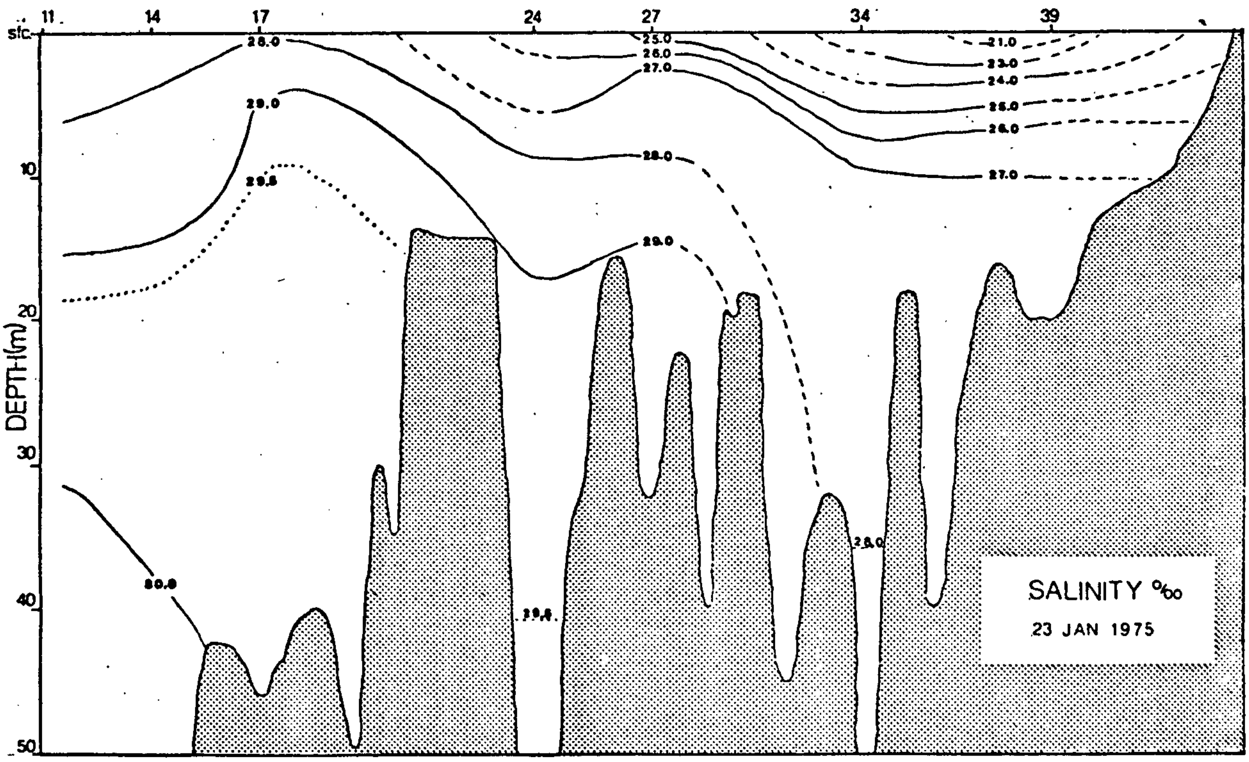
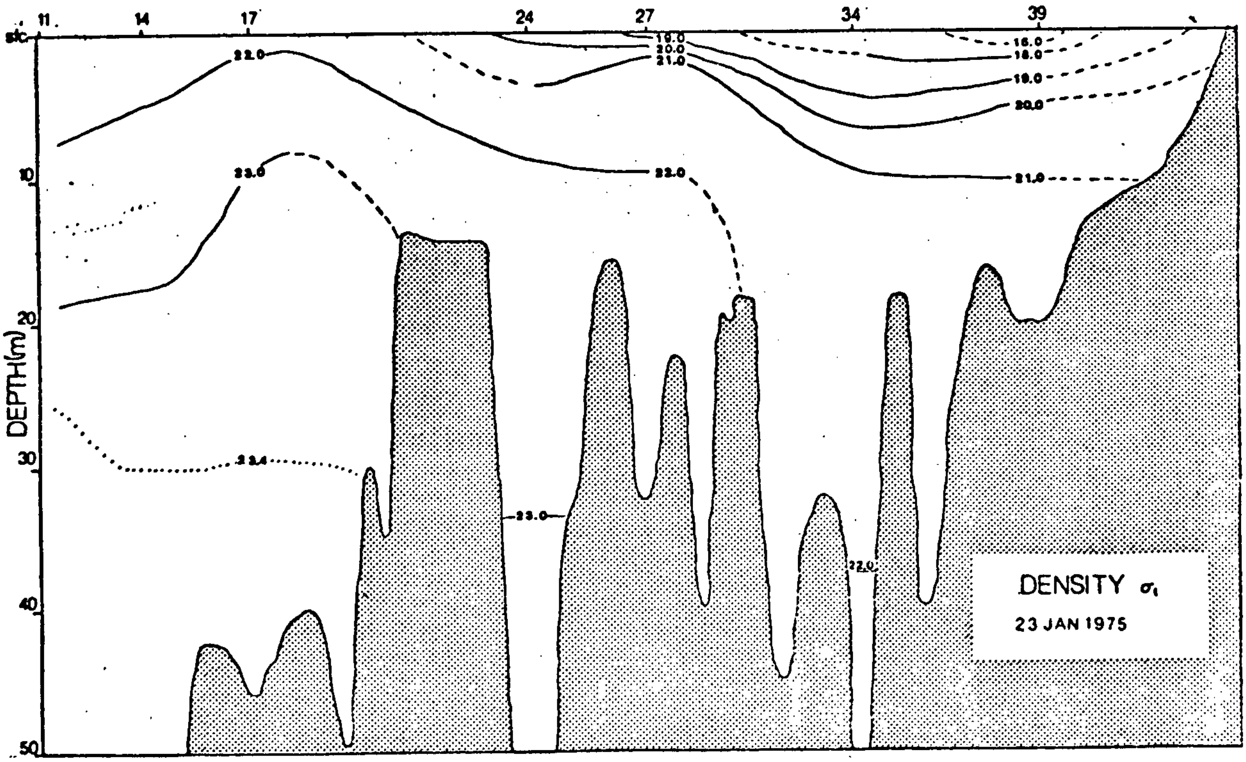
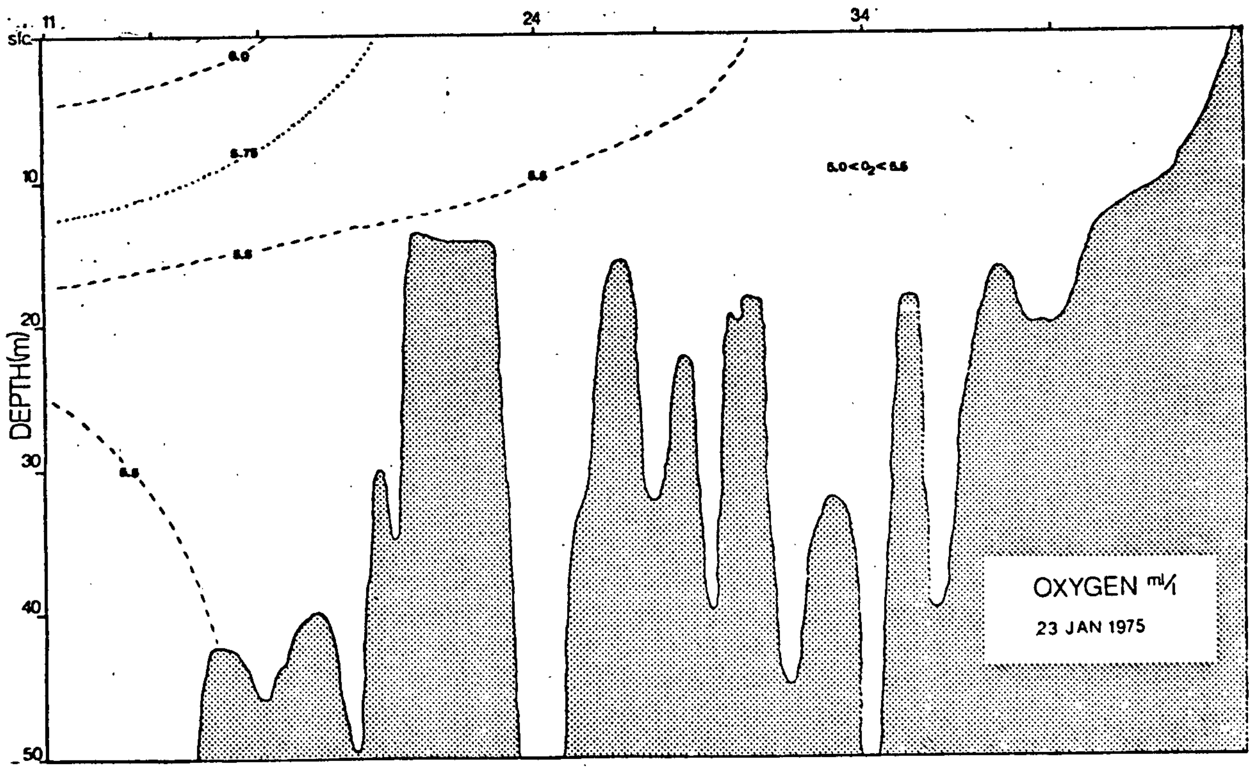


Figure 5.23 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Burrard Inlet January 23, 1975

(c)


11
14
17
24
27
34
39
s/c
10
20
30
40
50
DEPTH(m)
22.0
23.0
23.4
23.0
22.0
21.0
20.0
19.0
18.0
DENSITY σ_t
23 JAN 1975

(d)


11
24
34
s/c
10
20
30
40
50
DEPTH(m)
6.75
5.5
$5.0 < O_2 < 5.5$
OXYGEN ml/l
23 JAN 1975

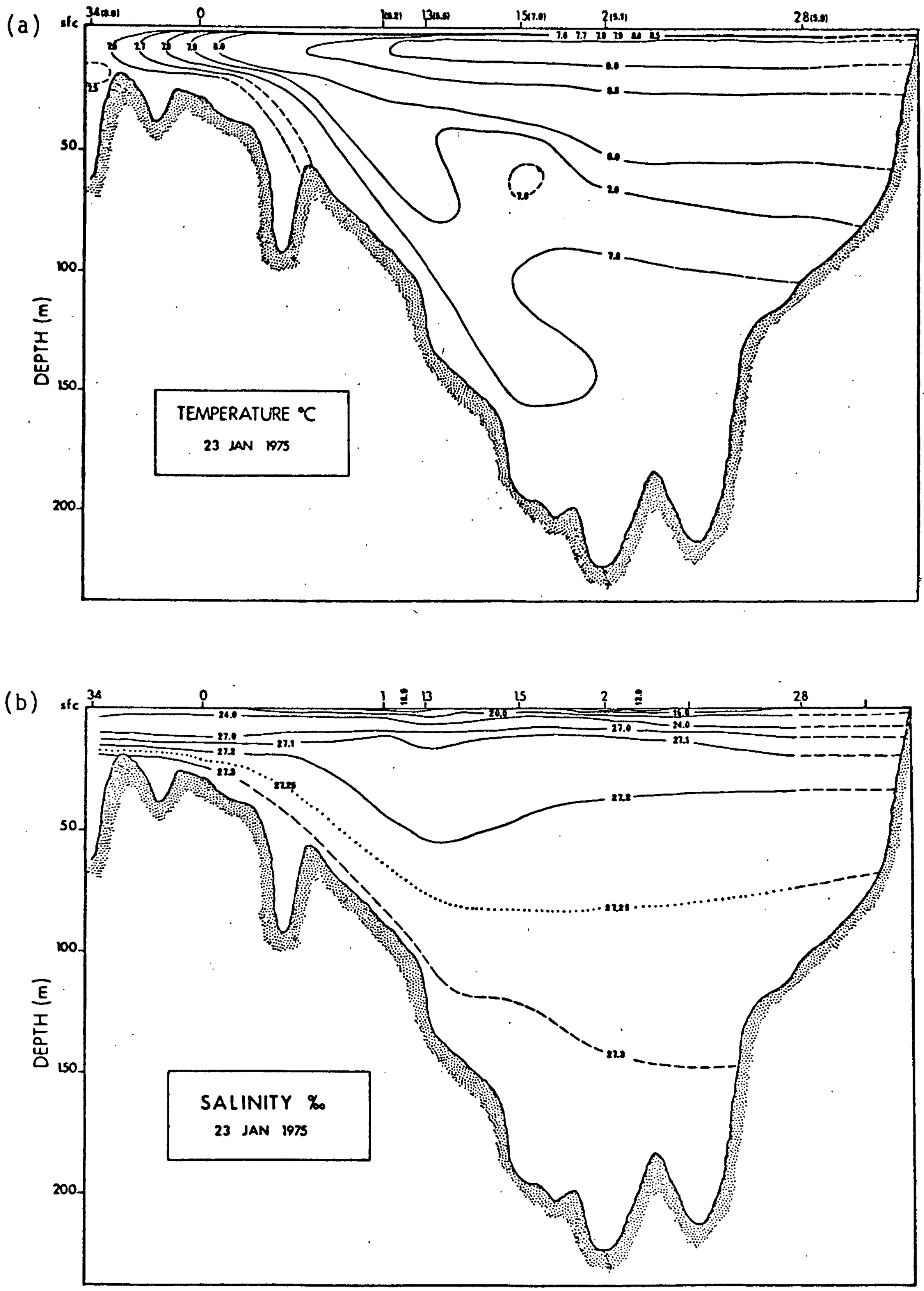
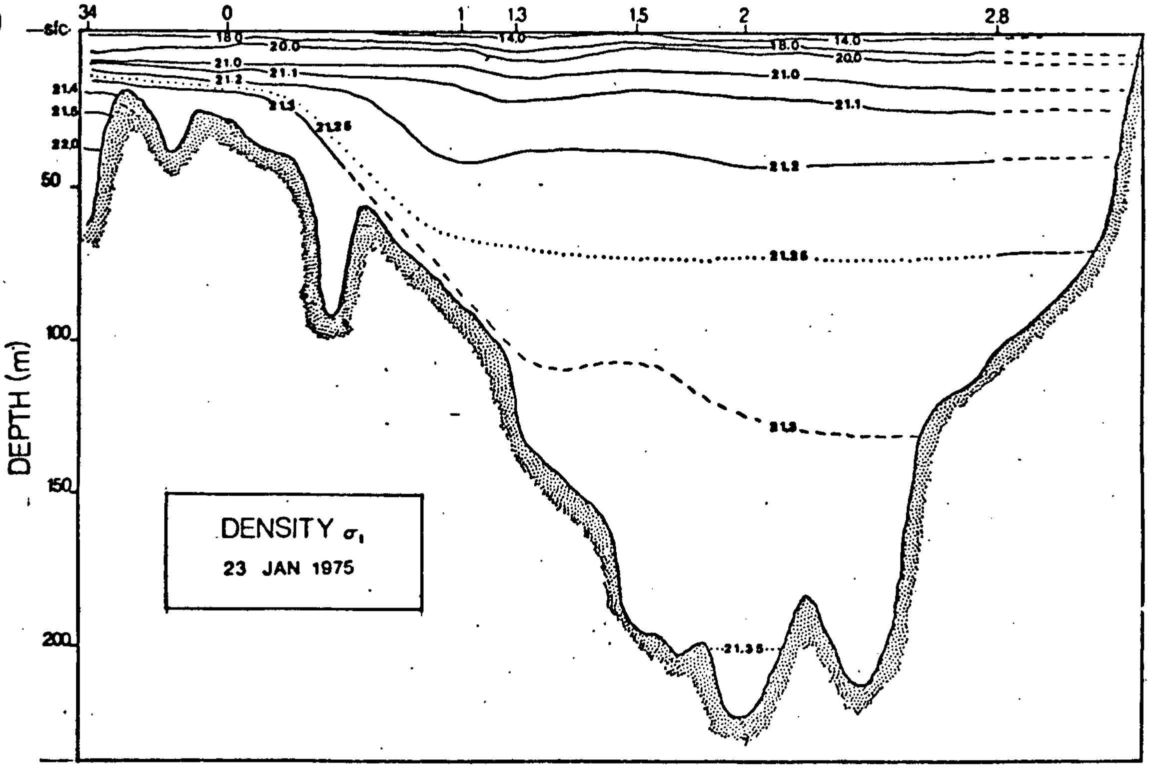
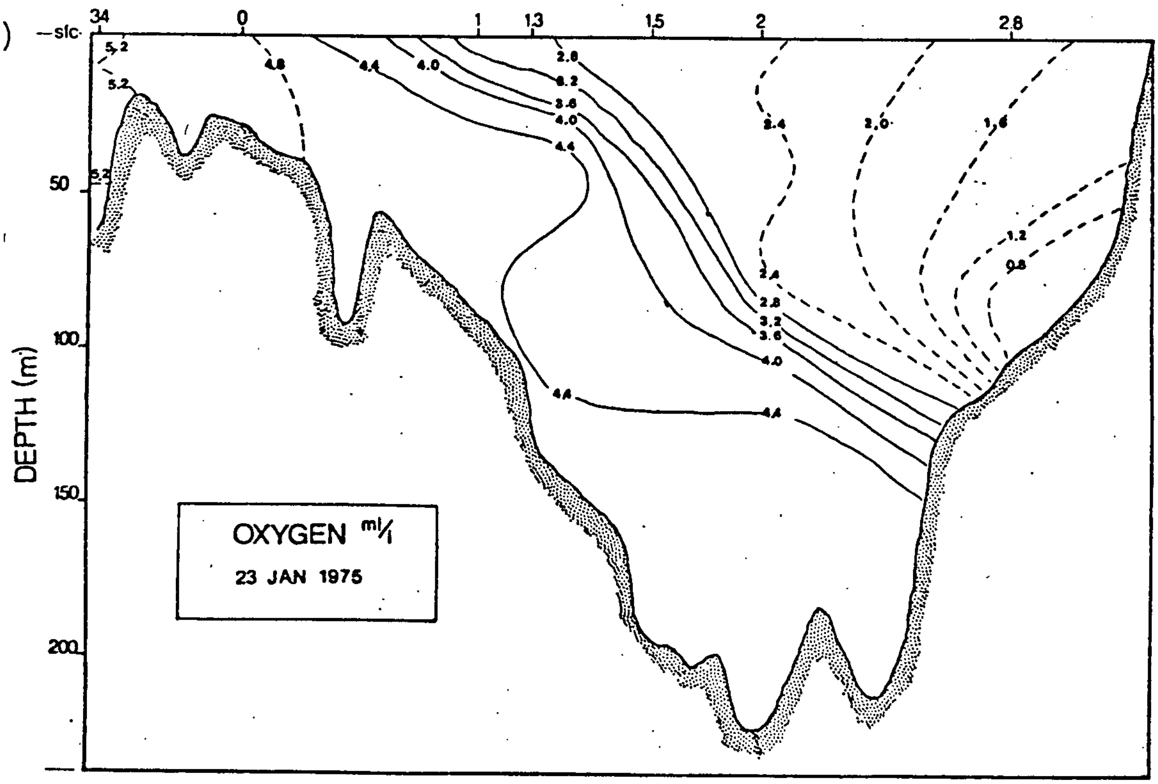


Figure 5.24 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Indian Arm, January 23, 1975

(c)


34
0
1
1.3
1.5
2
2.8
sfc
50
100
150
200
DEPTH (m)
DENSITY σ_t
23 JAN 1975

(d)


34
0
1
1.3
1.5
2
2.8
sfc
50
100
150
200
DEPTH (m)
OXYGEN ml/l
23 JAN 1975

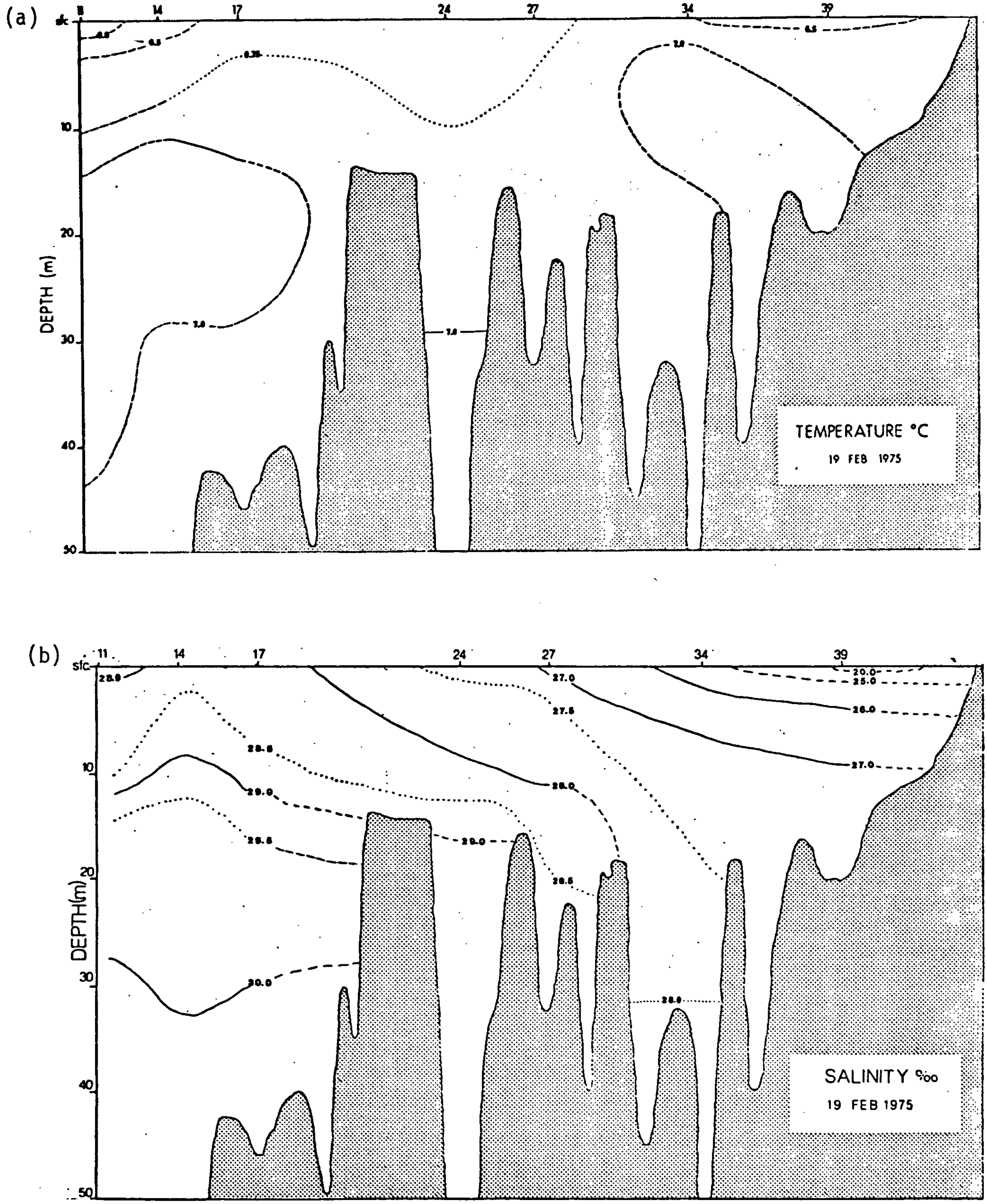
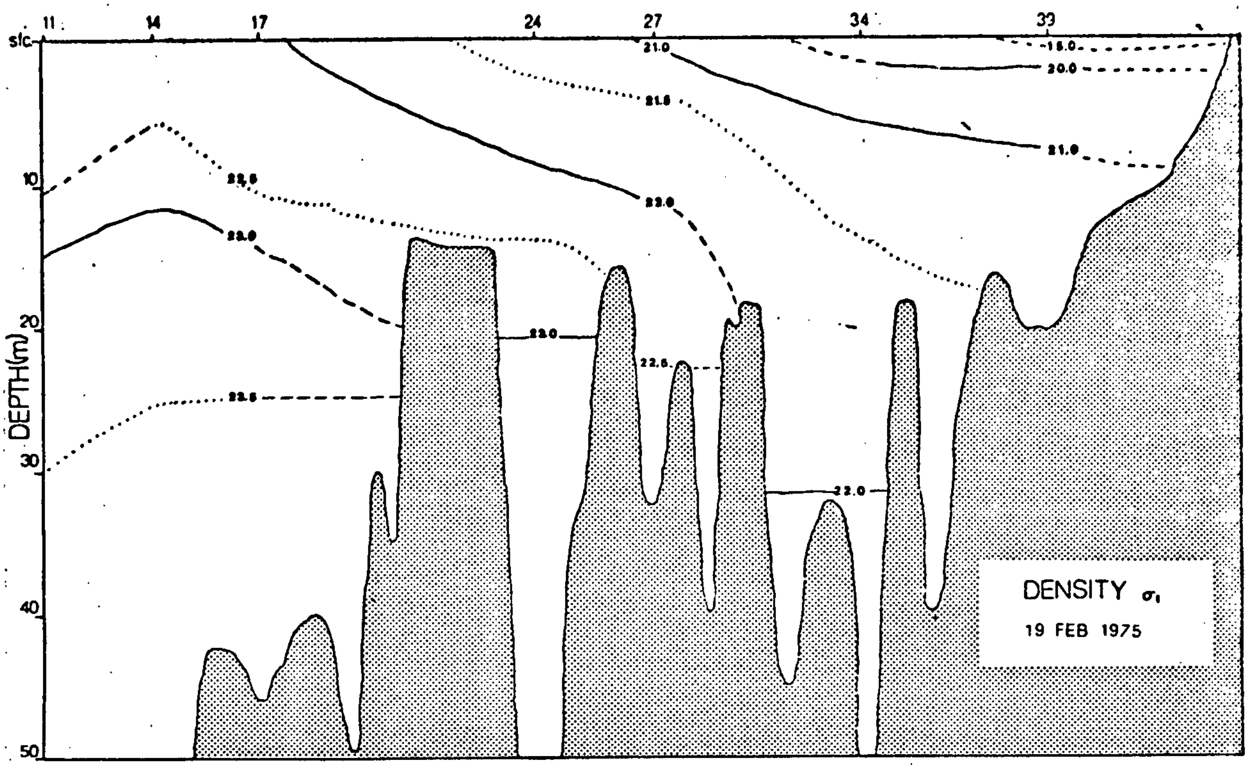
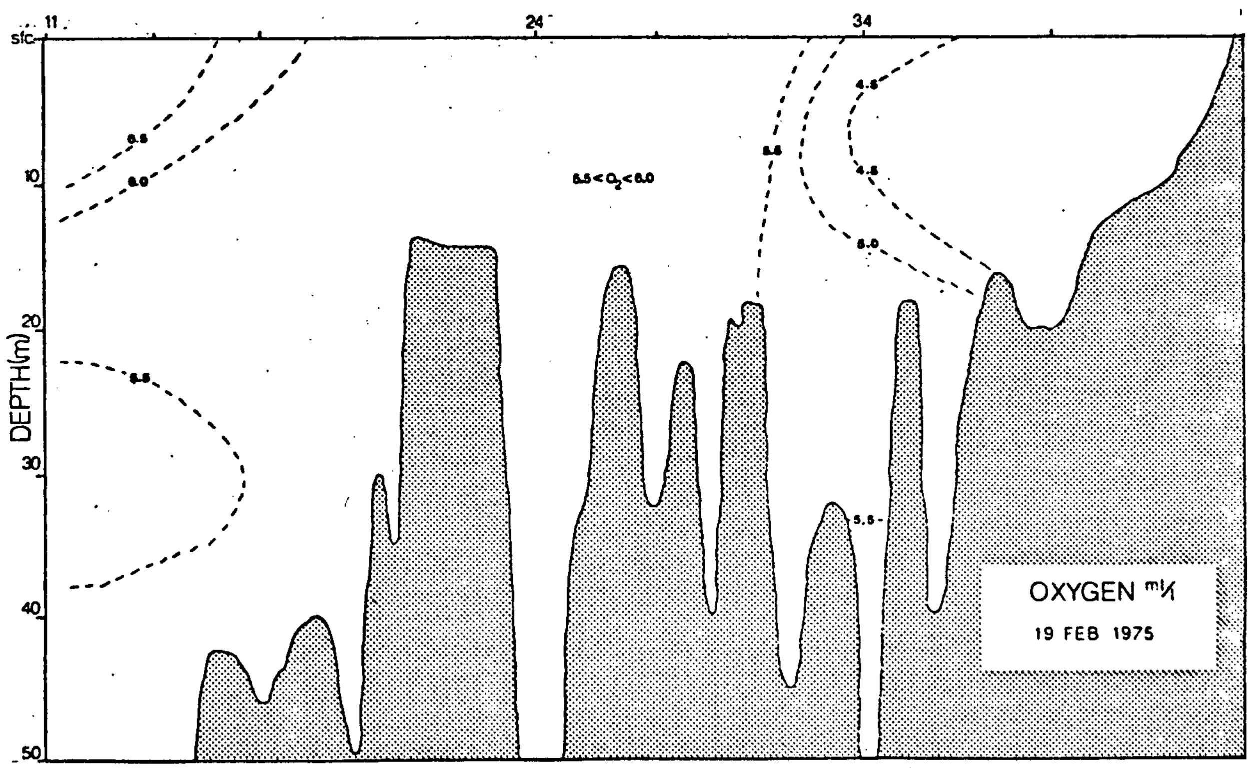


Figure 5.25 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Burrard Inlet, February 19, 1975

(c)


DENSITY σ_t
19 FEB 1975
DEPTH(m)

(d)


OXYGEN ml/l
19 FEB 1975
DEPTH(m)

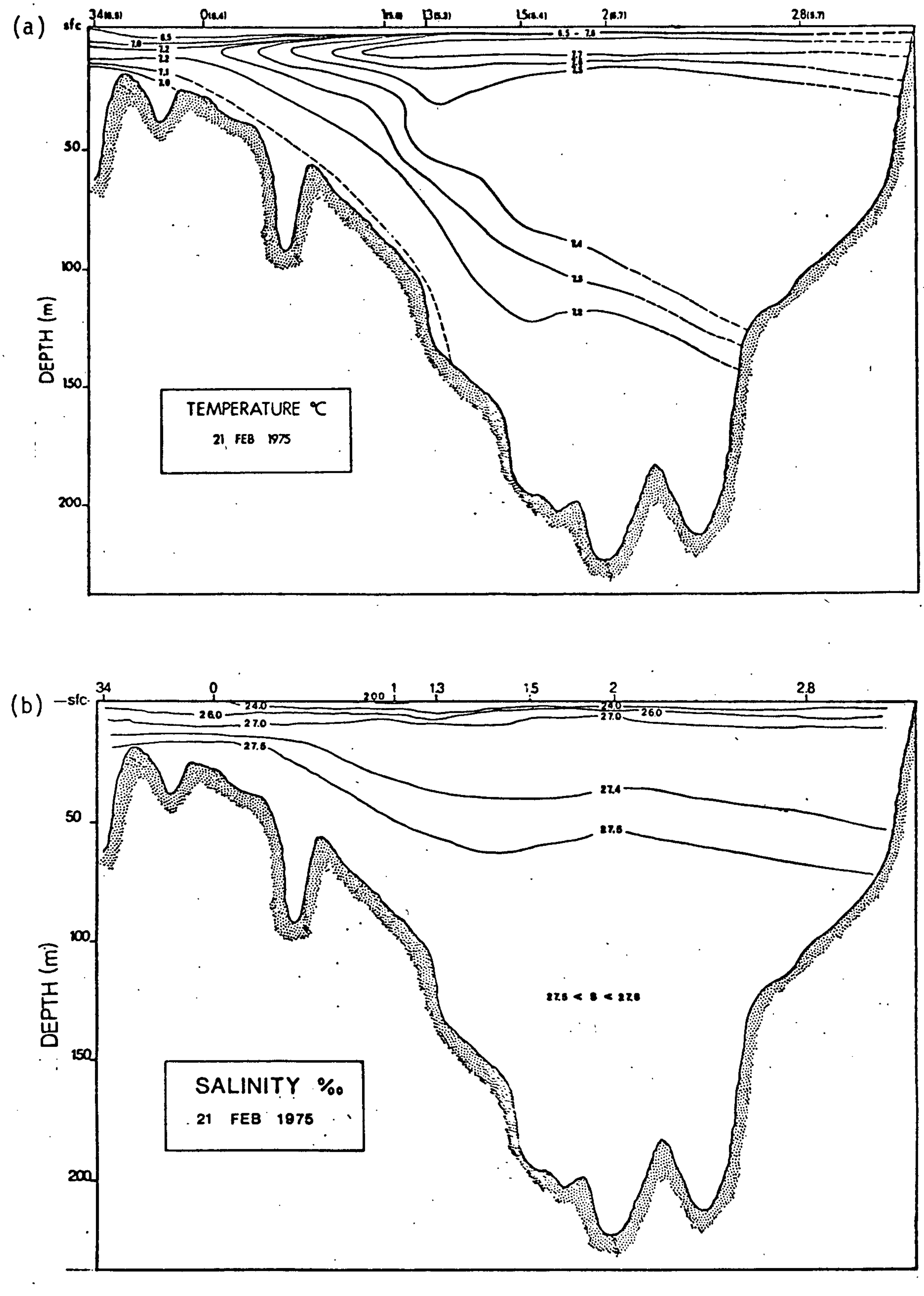
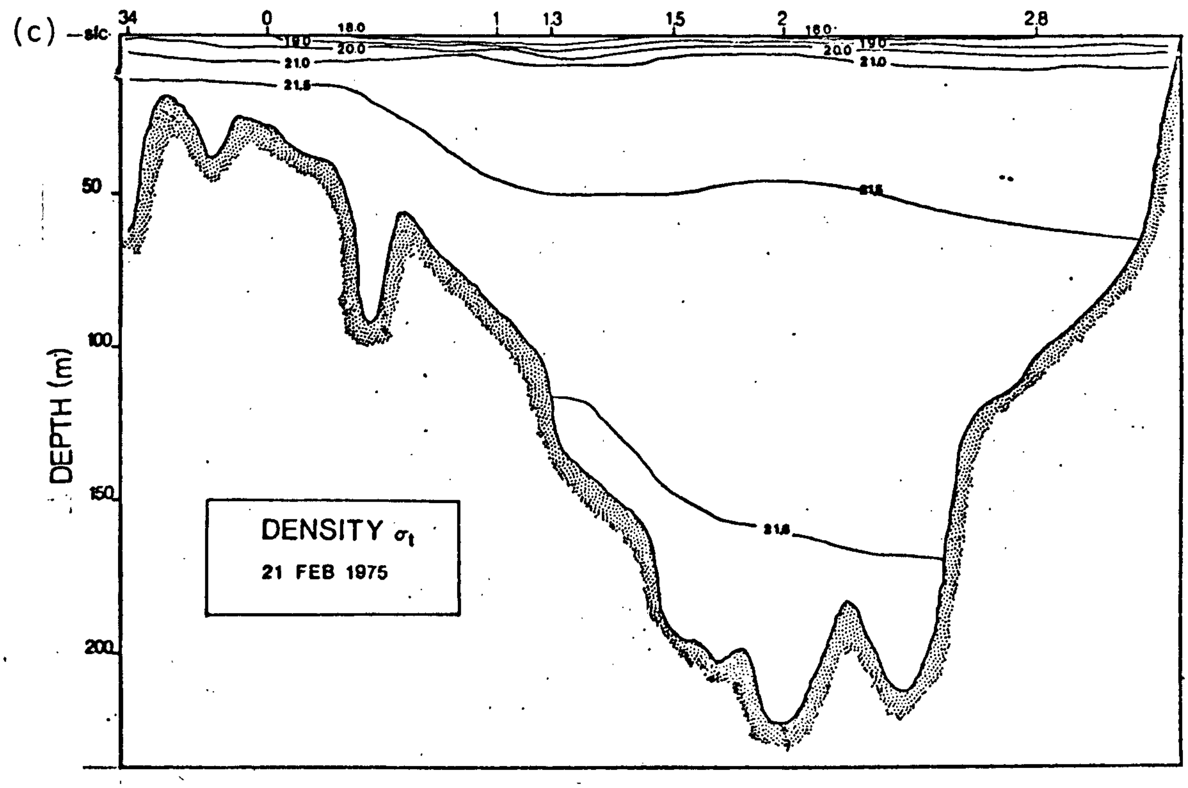
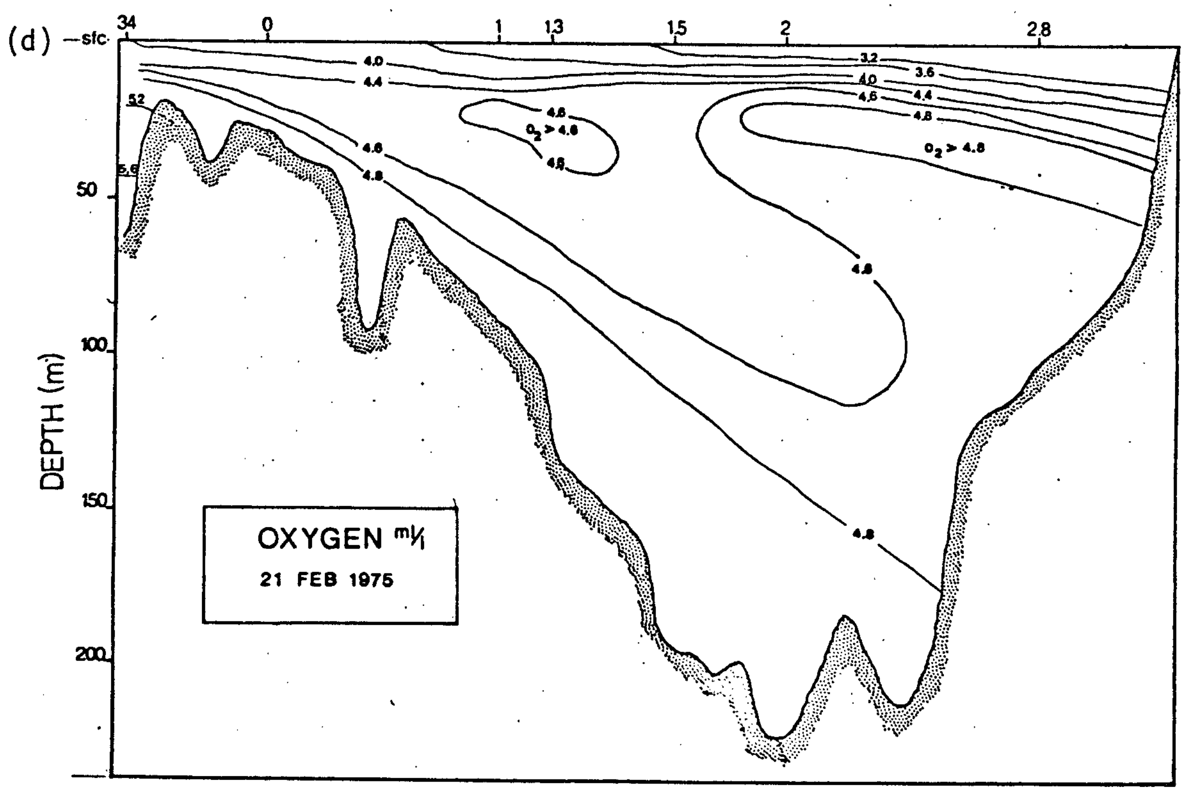


Figure 5.26 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Indian Arm, February 21, 1975


(c)
sfc
34
0
1
1.3
1.5
2
2.8
18.0
19.0
20.0
21.0
21.5
50
100
150
200
DEPTH (m)
DENSITY σ_t
21 FEB 1975


(d)
sfc
34
0
1
1.3
1.5
2
2.8
3.2
3.6
4.0
4.4
4.6
4.8
5.2
5.6
$O_2 > 4.8$
50
100
150
200
DEPTH (m)
OXYGEN ml/l
21 FEB 1975

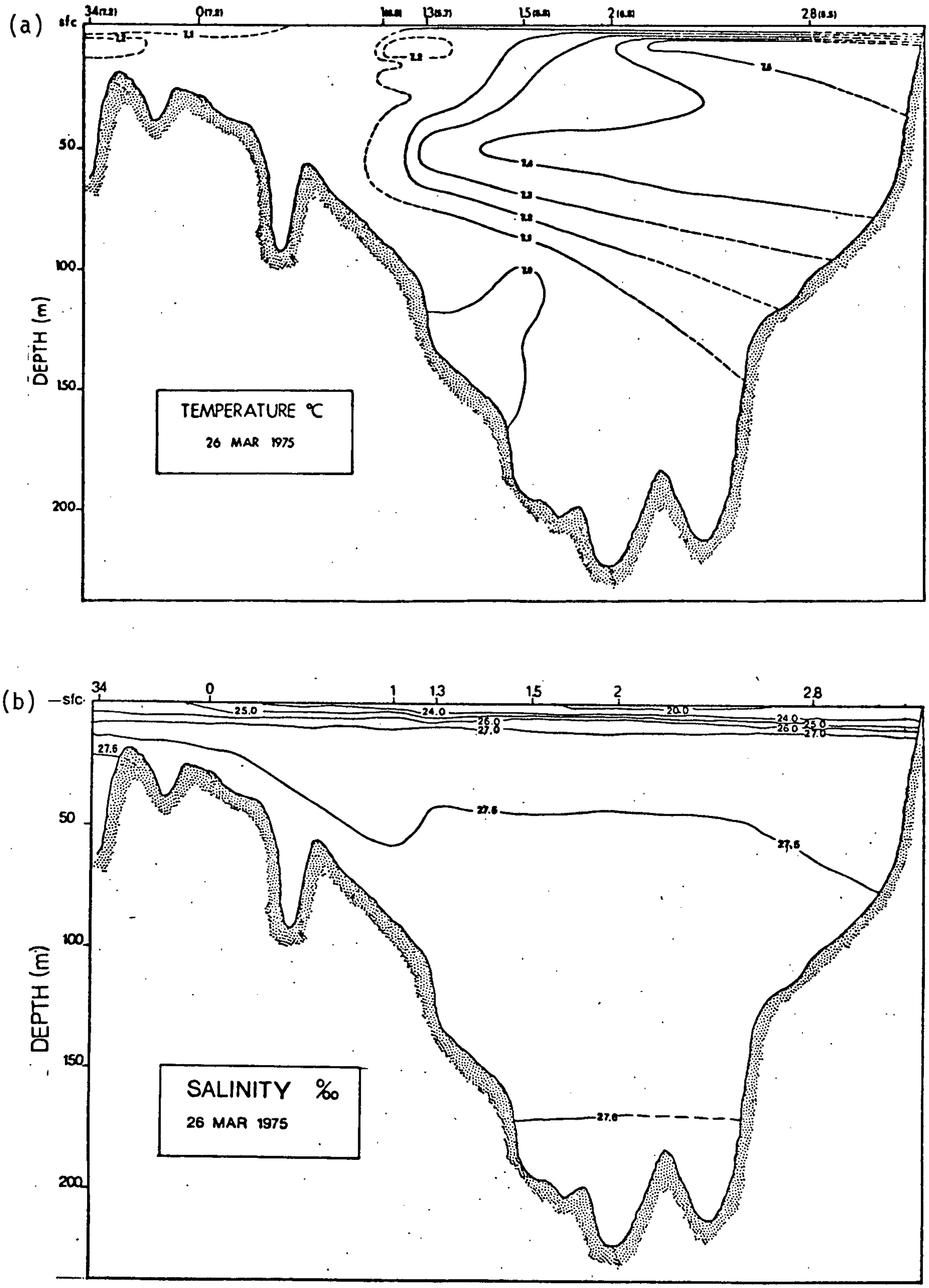
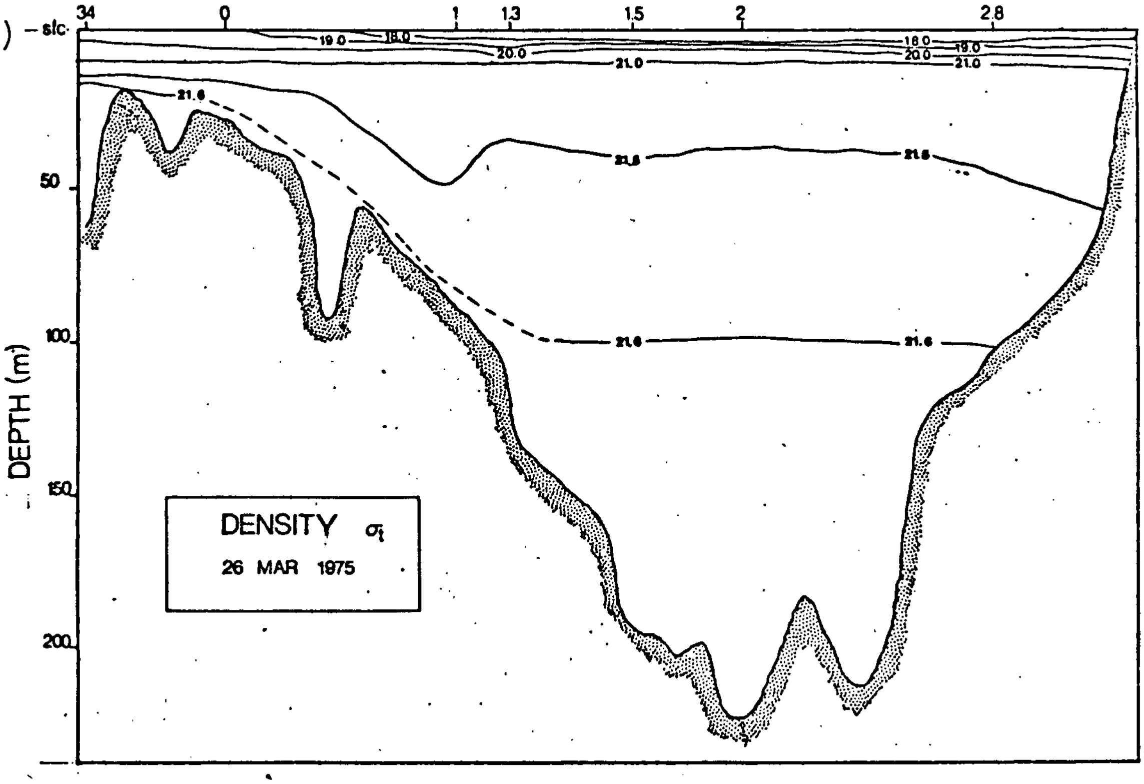
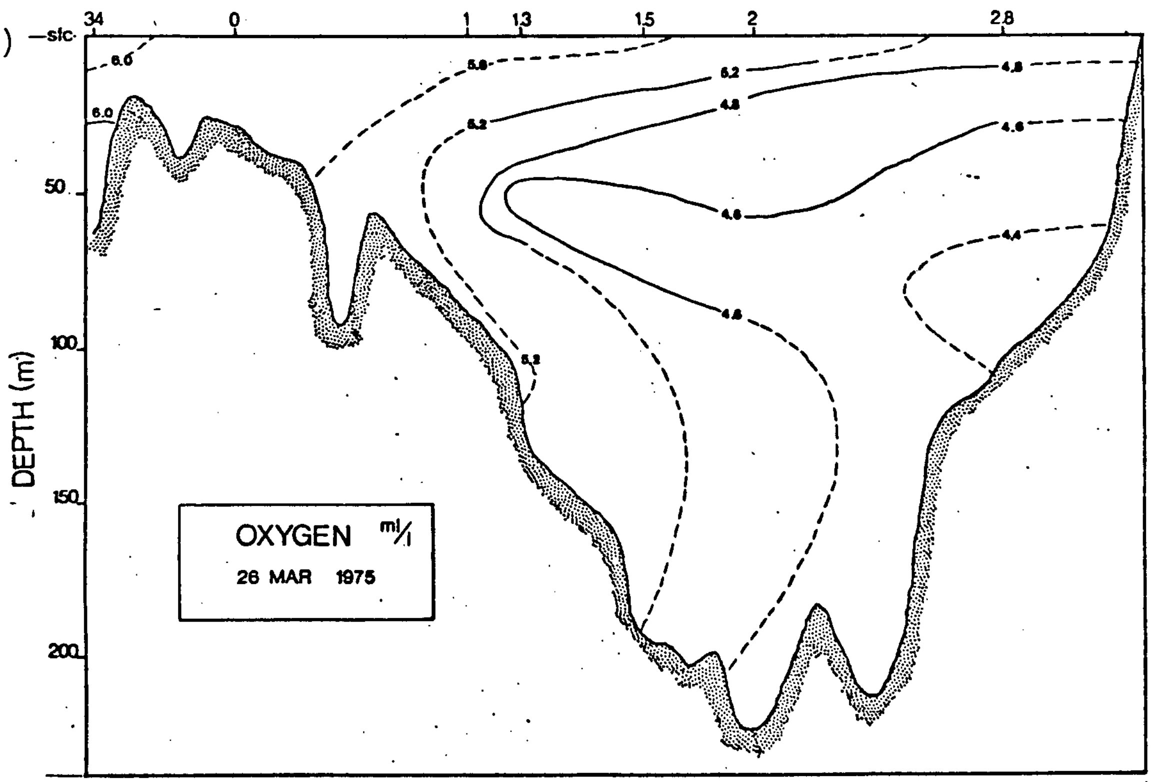


Figure 5.27 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Indian Arm, March 26, 1975

(c)


34
0
1
1.3
1.5
2
2.8
sfc
19.0
18.0
20.0
21.0
21.6
21.8
50
100
150
200
DEPTH (m)
DENSITY σ_t
26 MAR 1975

(d)


34
0
1
1.3
1.5
2
2.8
sfc
6.0
5.6
5.2
4.8
4.6
4.4
50
100
150
200
DEPTH (m)
OXYGEN ml/l
26 MAR 1975

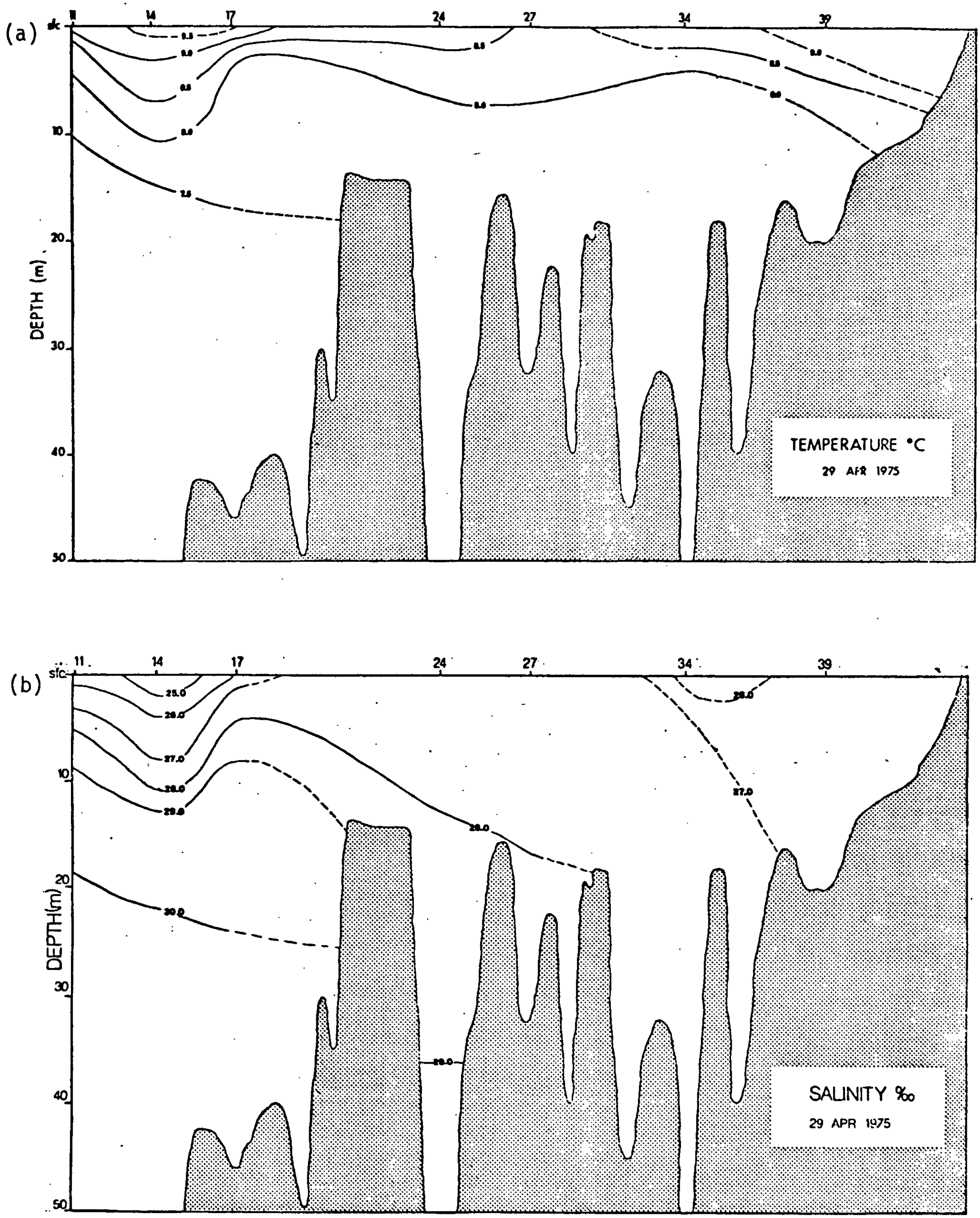
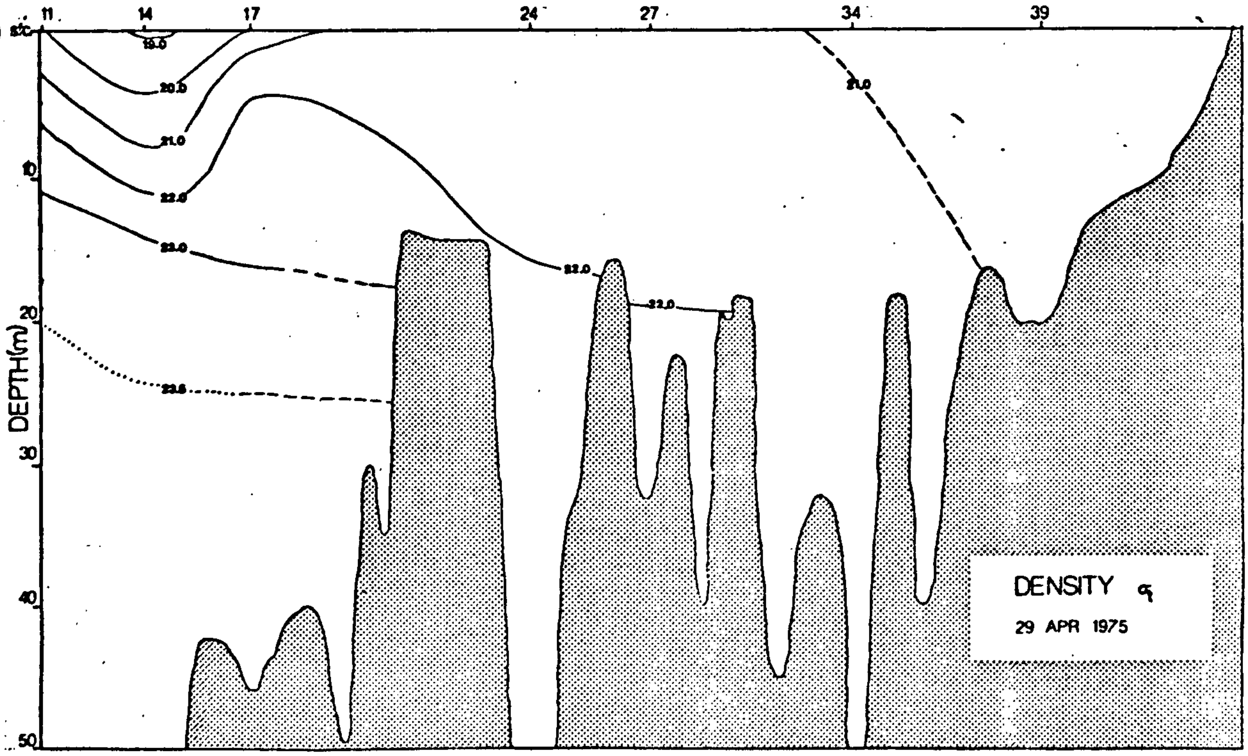
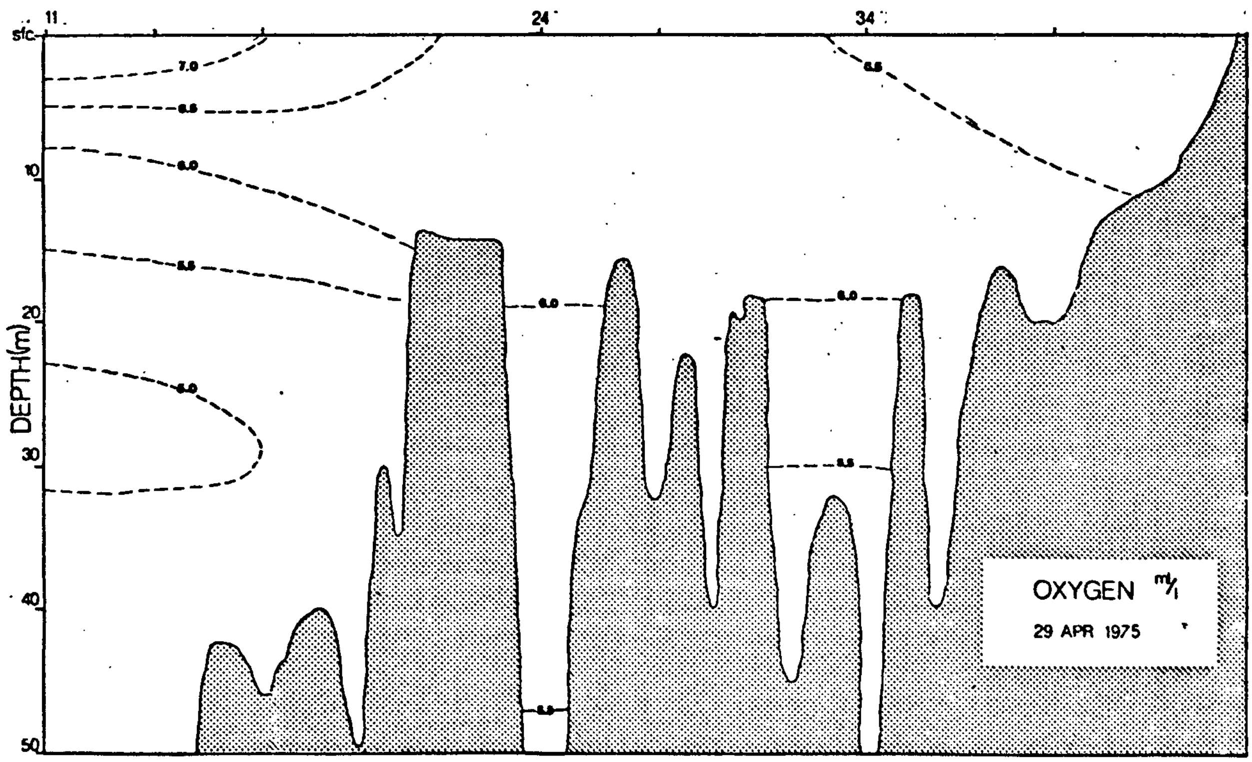


Figure 5.28 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Burrard Inlet, April 29, 1975

(c)


11
14
17
24
27
34
39
sfc
DEPTH(m)
10
20
30
40
50
20.0
21.0
22.0
23.0
22.0
22.0
21.0
DENSITY σ_t
29 APR 1975

(d)


11
24
34
sfc
DEPTH(m)
10
20
30
40
50
7.0
6.5
6.0
5.5
6.0
6.5
OXYGEN ml/l
29 APR 1975

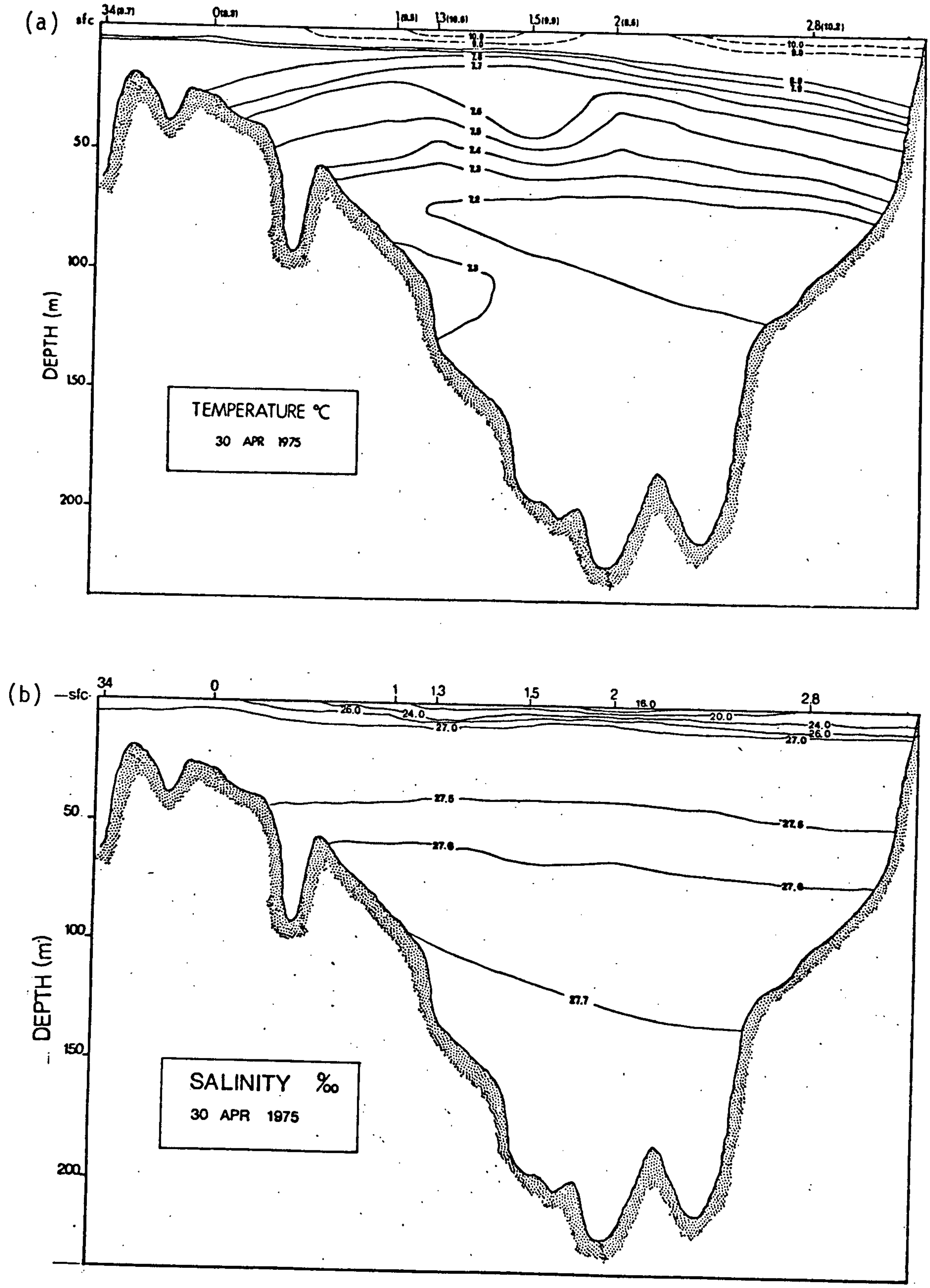
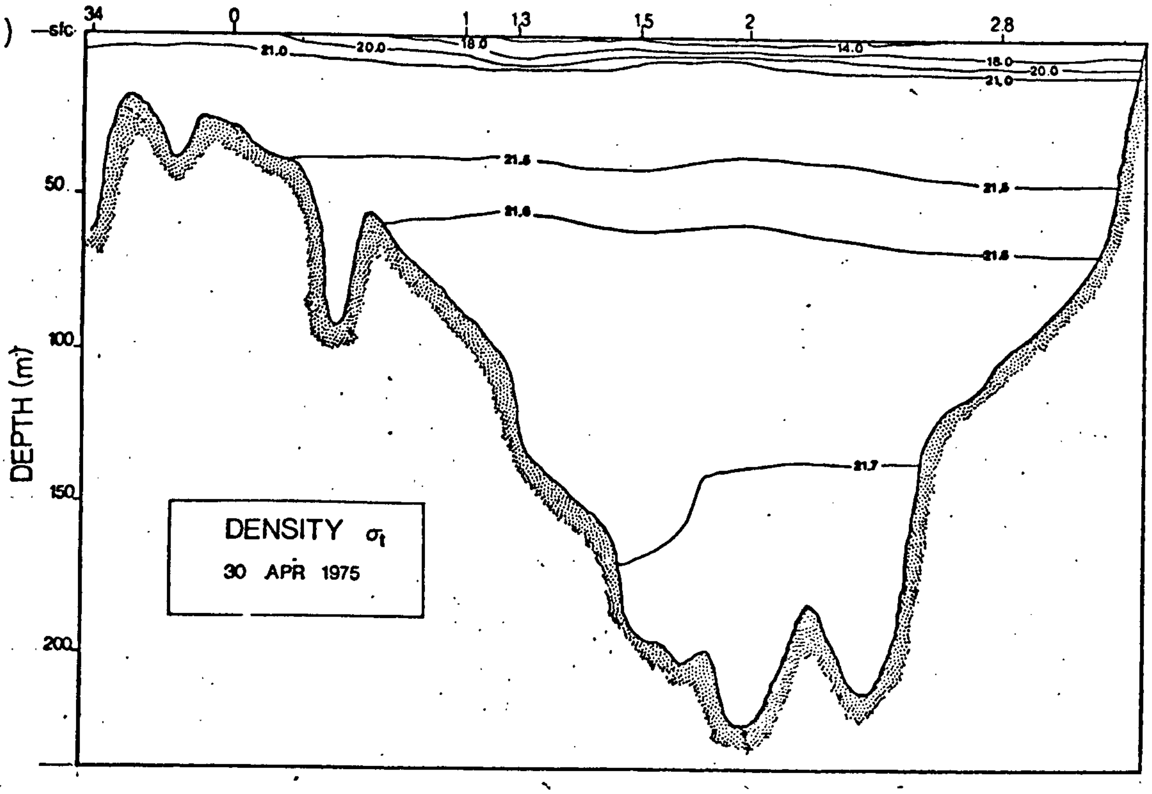


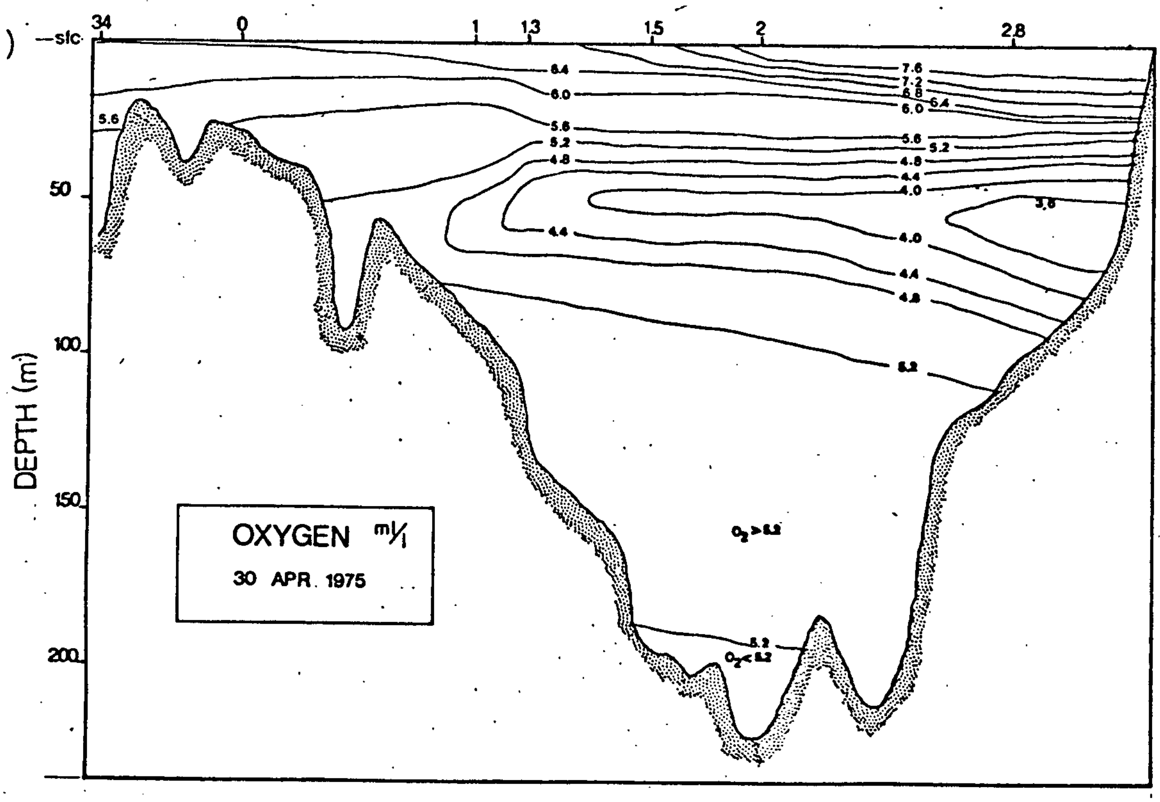
Figure 5.29 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Indian Arm, April 30, 1975

(c)



sfc
34
0
1
1.3
1.5
2
2.8
21.0
20.0
18.0
14.0
18.0
20.0
21.0
21.5
21.6
21.7
50
100
150
200
DEPTH (m)
DENSITY σ_t
30 APR 1975

(d)



sfc
34
0
1
1.3
1.5
2
2.8
6.4
6.0
5.6
5.2
4.8
4.4
4.0
3.6
7.6
7.2
6.8
50
100
150
200
DEPTH (m)
$O_2 > 5.2$
$O_2 < 5.2$
OXYGEN ml/l
30 APR. 1975

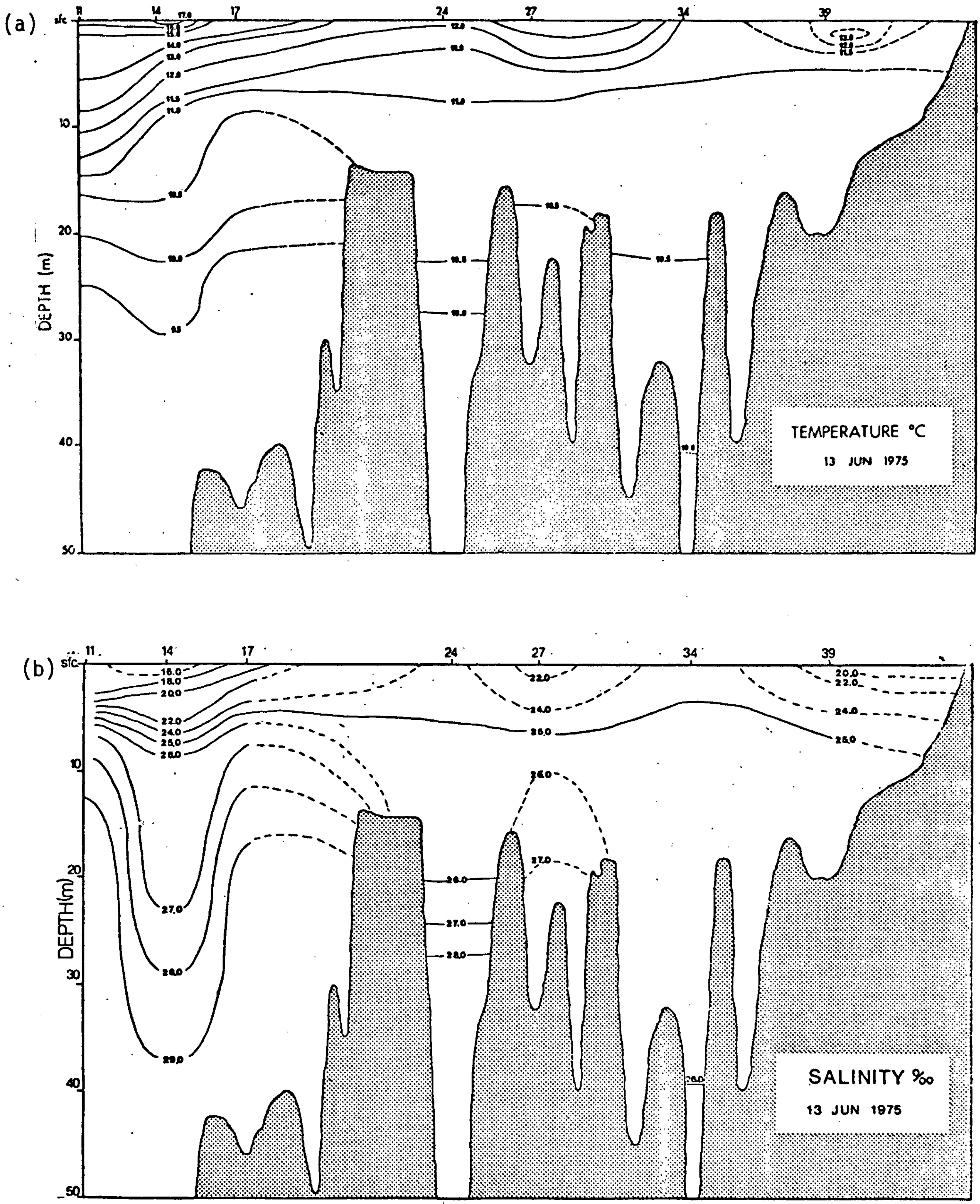
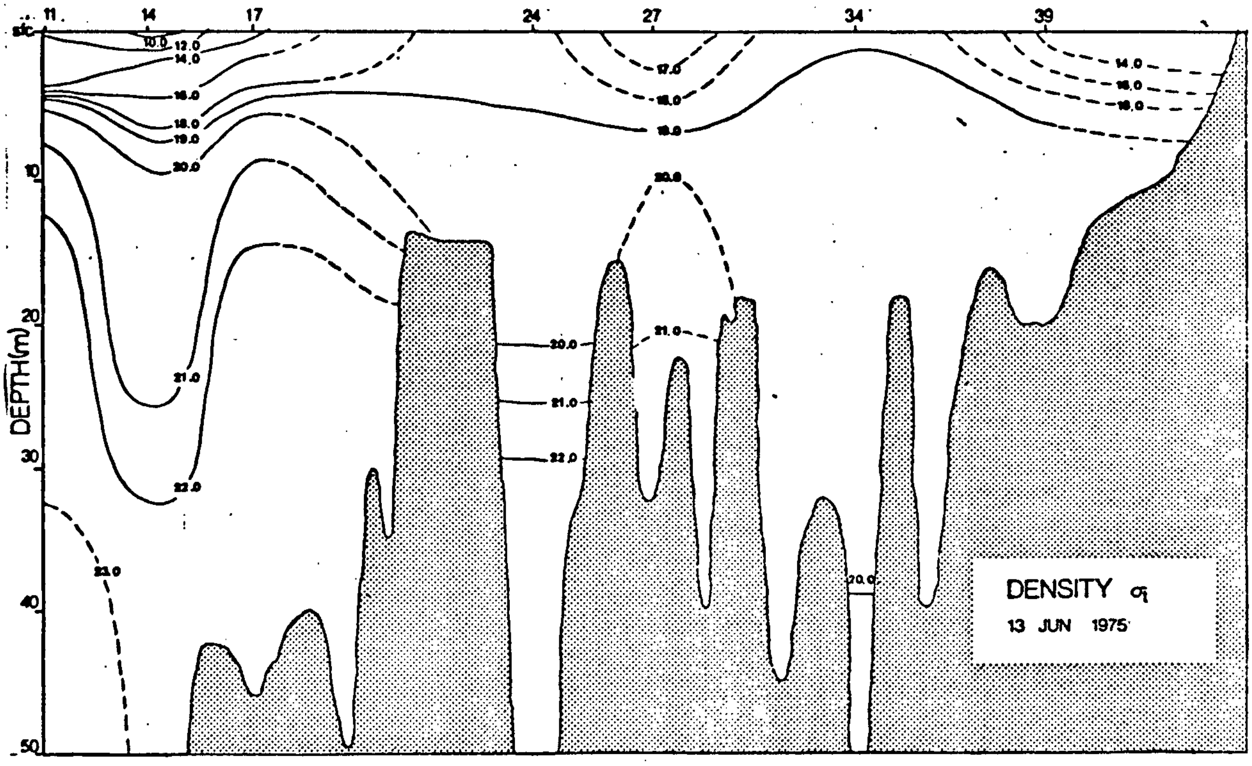
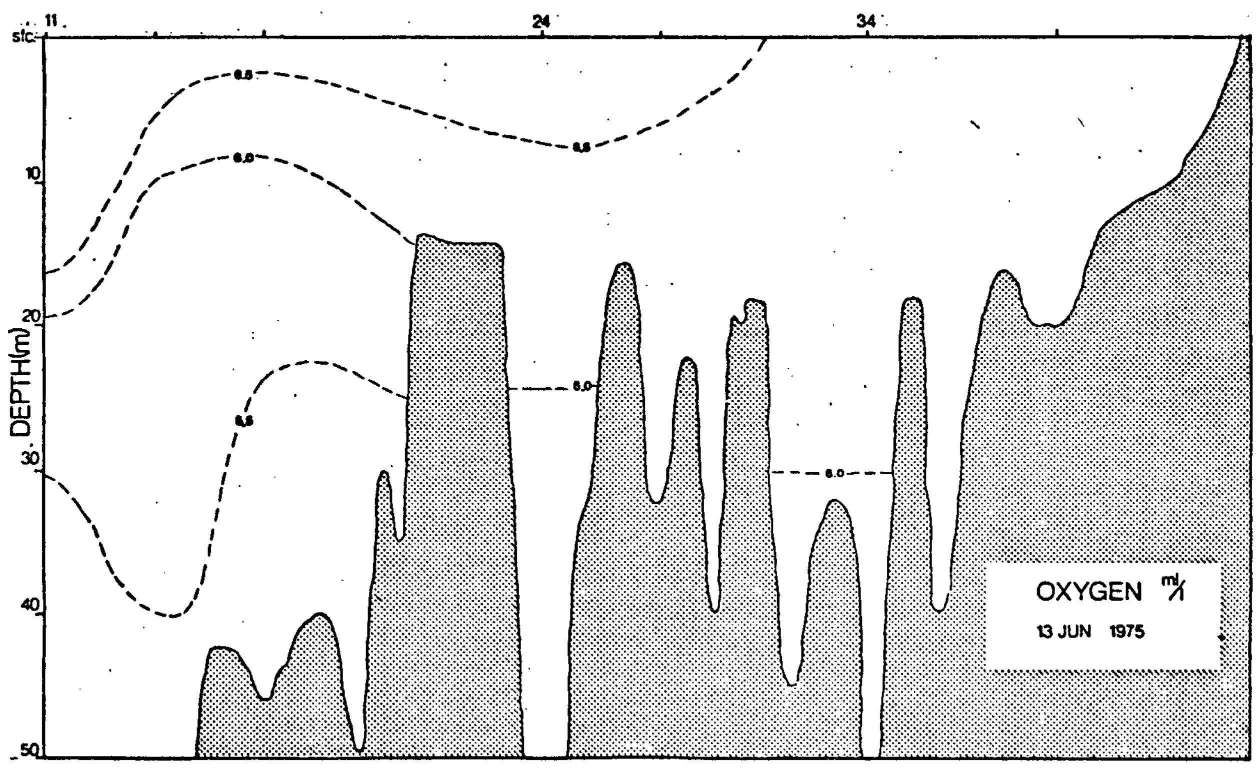


Figure 5.30 Longitudinal sections of (a) temperature (b) salinity
(c) sigma-t and (d) oxygen for Burrard Inlet, June 13, 1975

(c)


DENSITY σ_t
13 JUN 1975
DEPTH(m)

(d)


OXYGEN ml/l
13 JUN 1975
DEPTH(m)

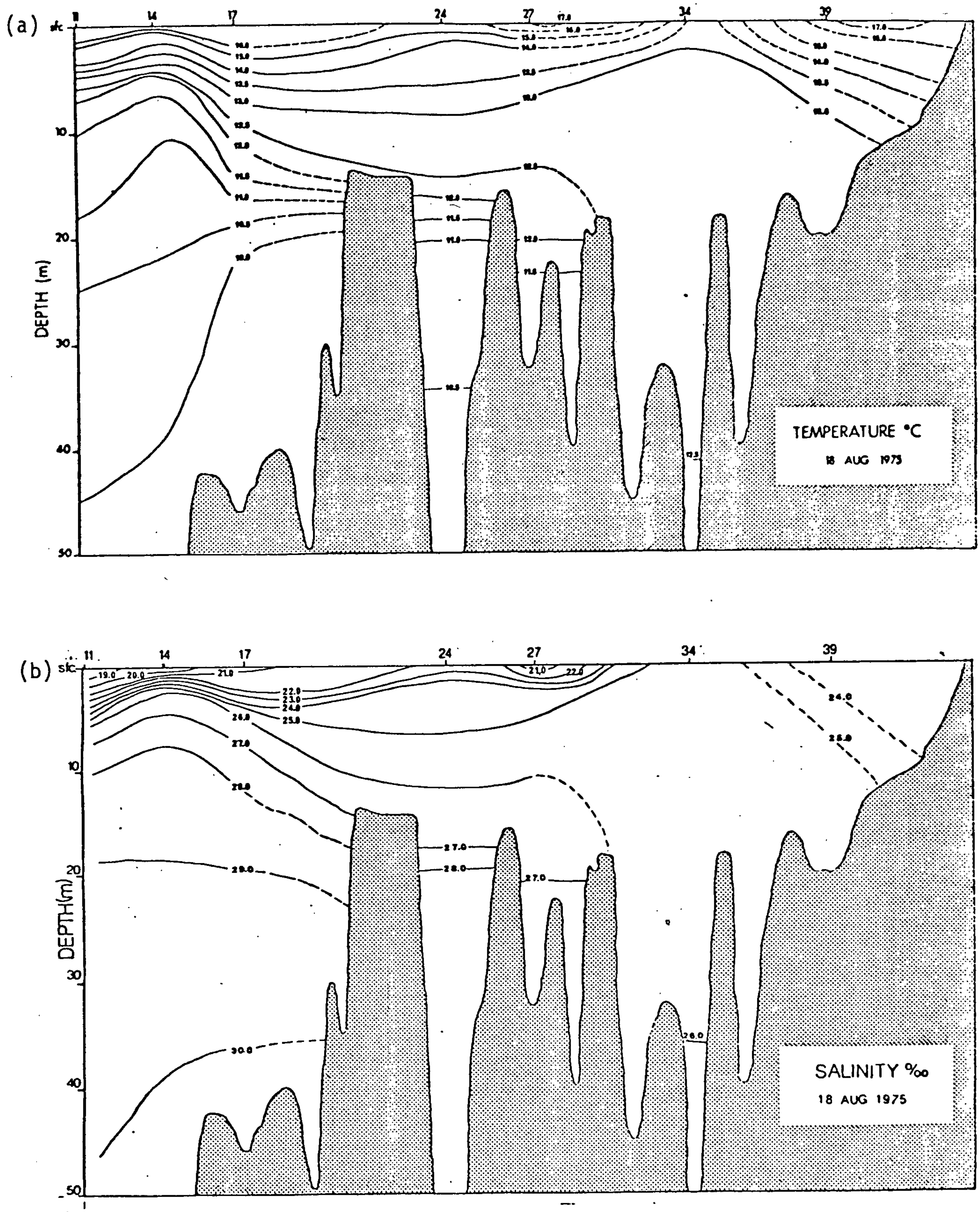
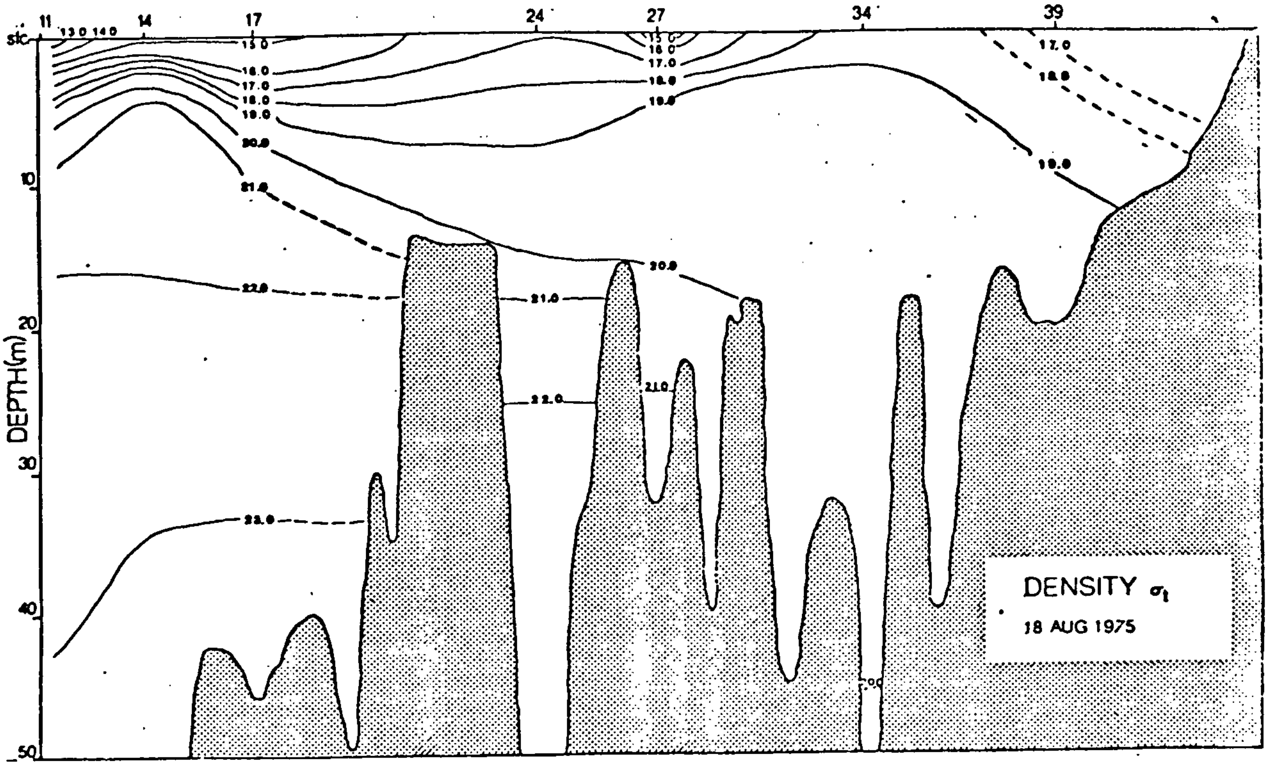
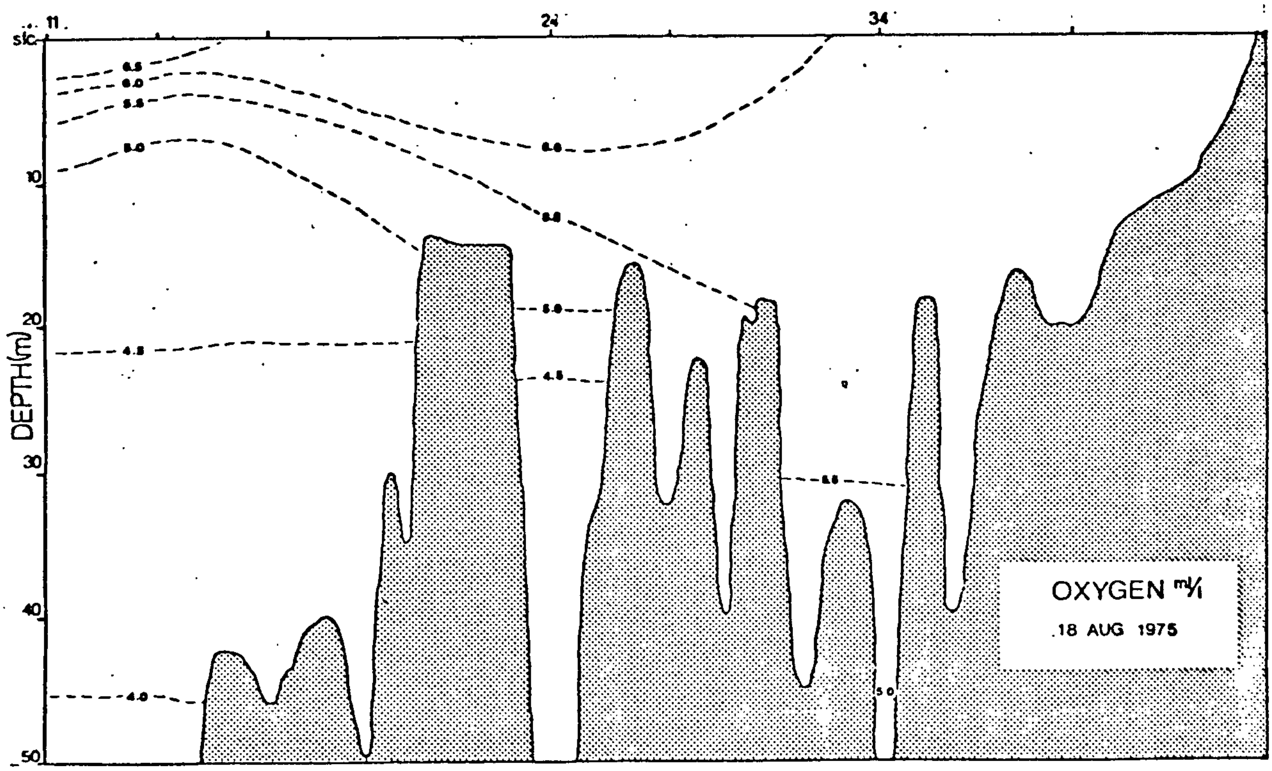


Figure 5.31 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Burrard Inlet, August 18, 1975

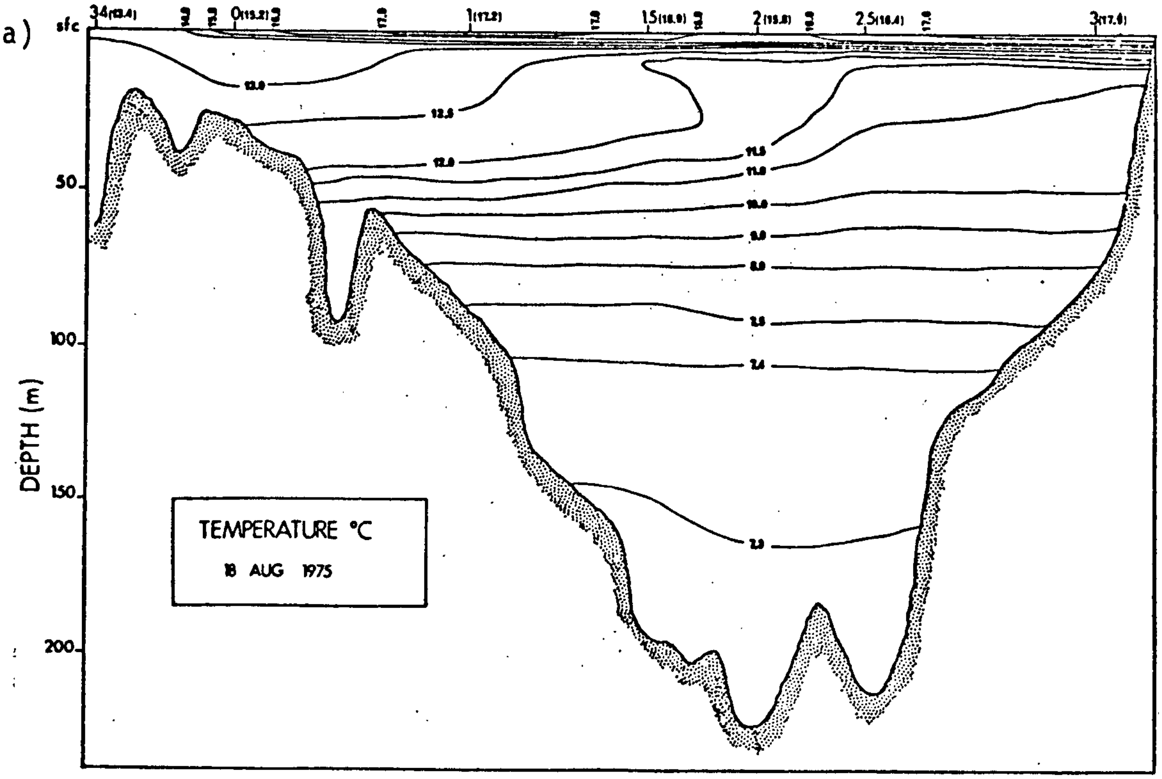
(c)


DENSITY σ_t
18 AUG 1975
DEPTH (m)

(d)


OXYGEN ml/l
18 AUG 1975
DEPTH (m)

(a)



(b)

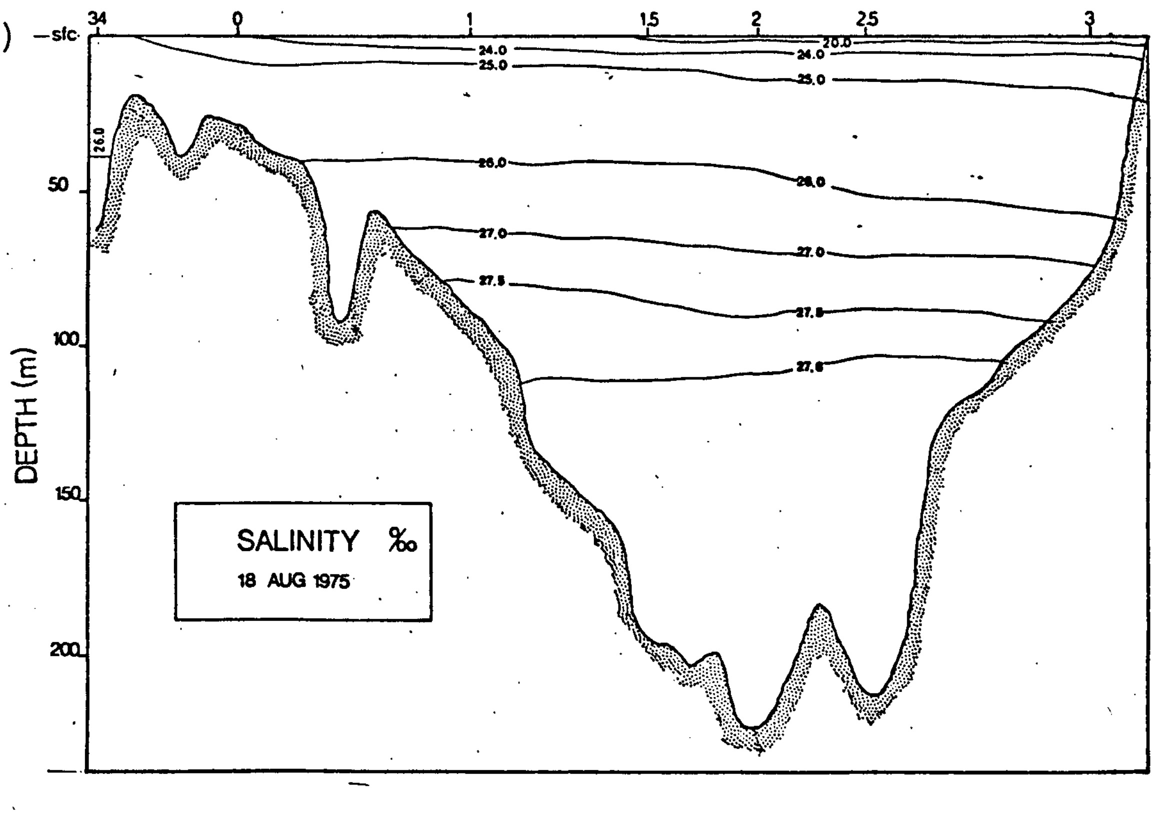
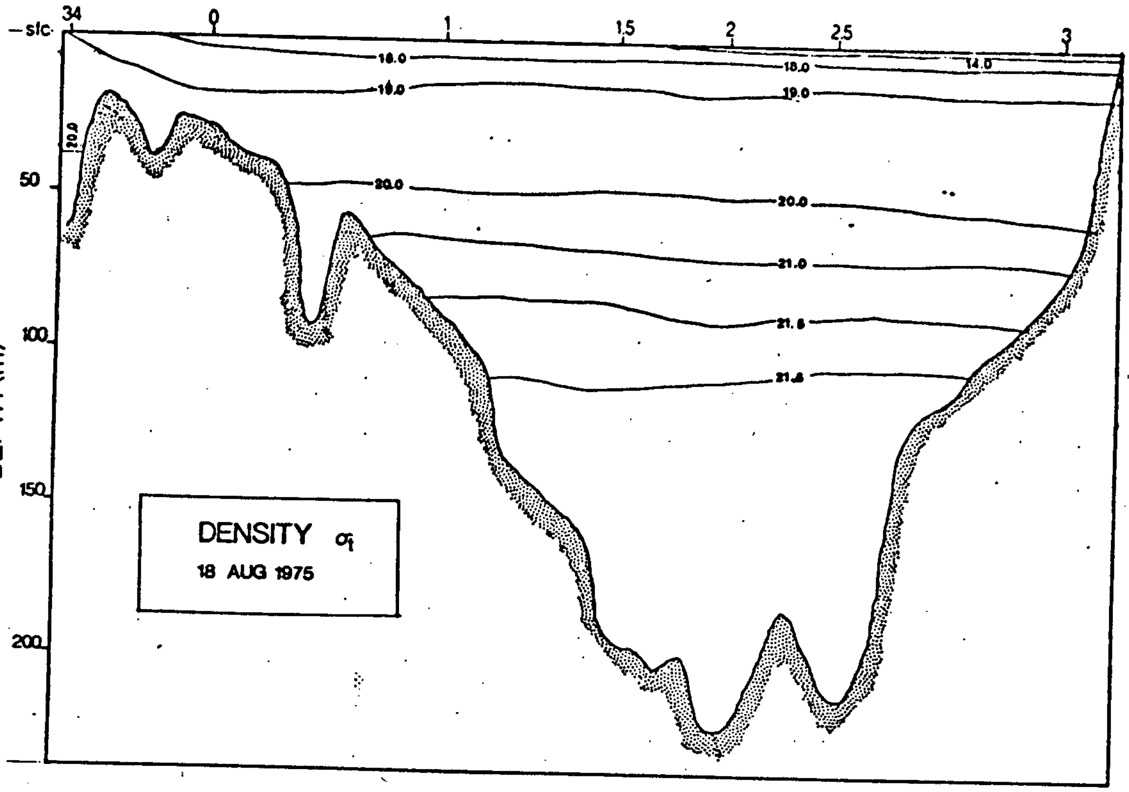
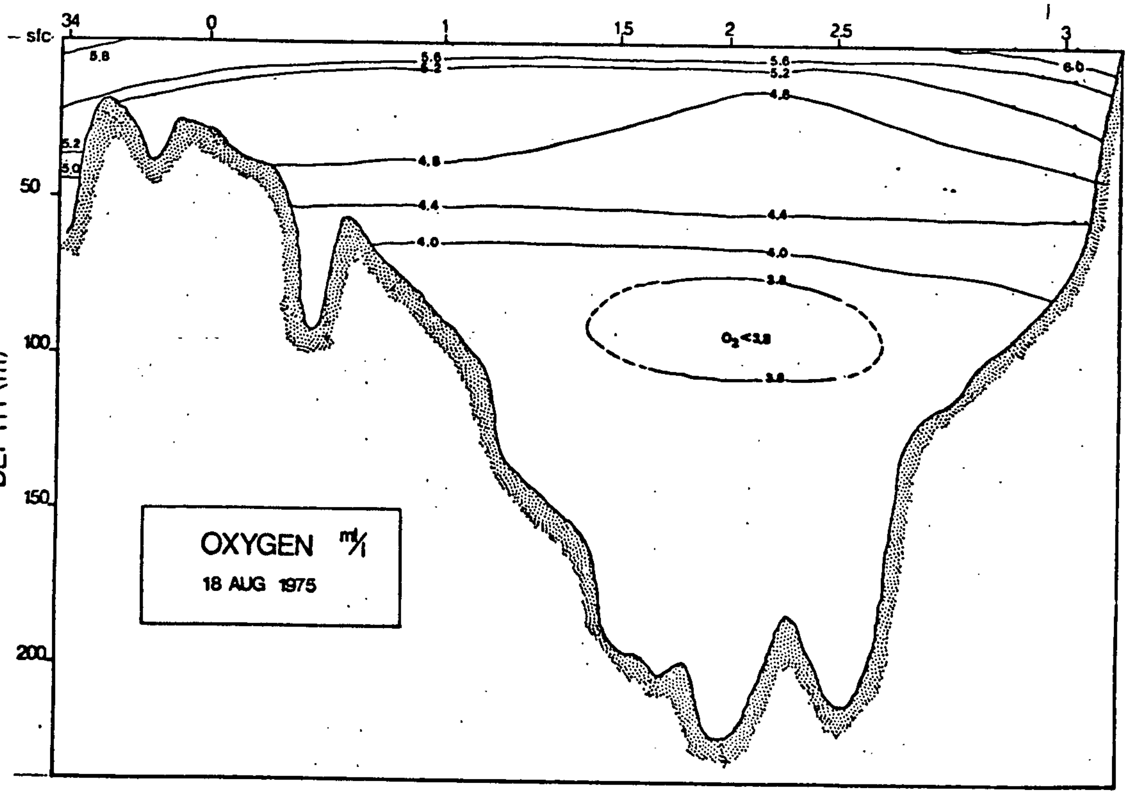


Figure 5.32 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Indian Arm, August 18, 1975

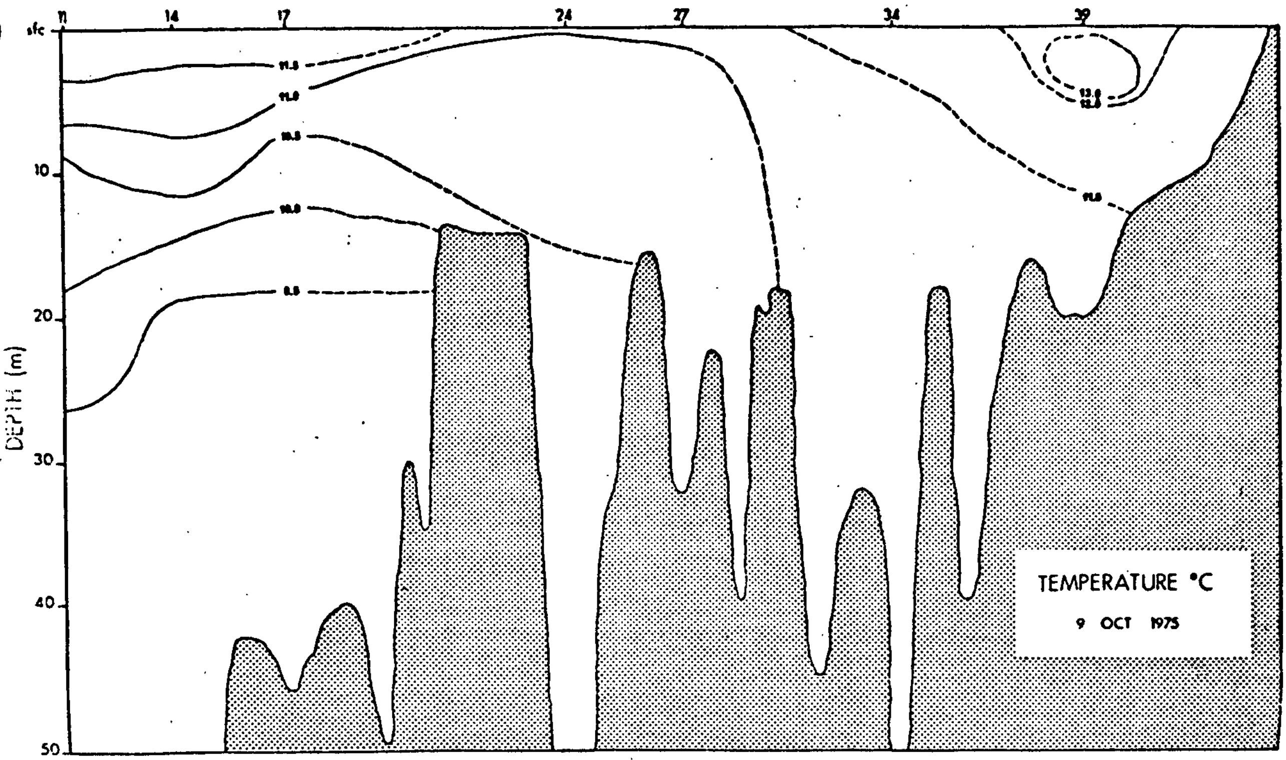
(c)


DENSITY σ_t
18 AUG 1975
DEPTH (m)
sfc
50
100
150
200
34
0
1
1.5
2
2.5
3
18.0
19.0
20.0
21.0
21.5
21.8
14.0

(d)


OXYGEN ml/l
18 AUG 1975
DEPTH (m)
sfc
50
100
150
200
34
0
1
1.5
2
2.5
3
5.6
5.2
4.8
4.4
4.0
3.8
O_2<3.8
6.0
5.8
5.0

(a)



(b)

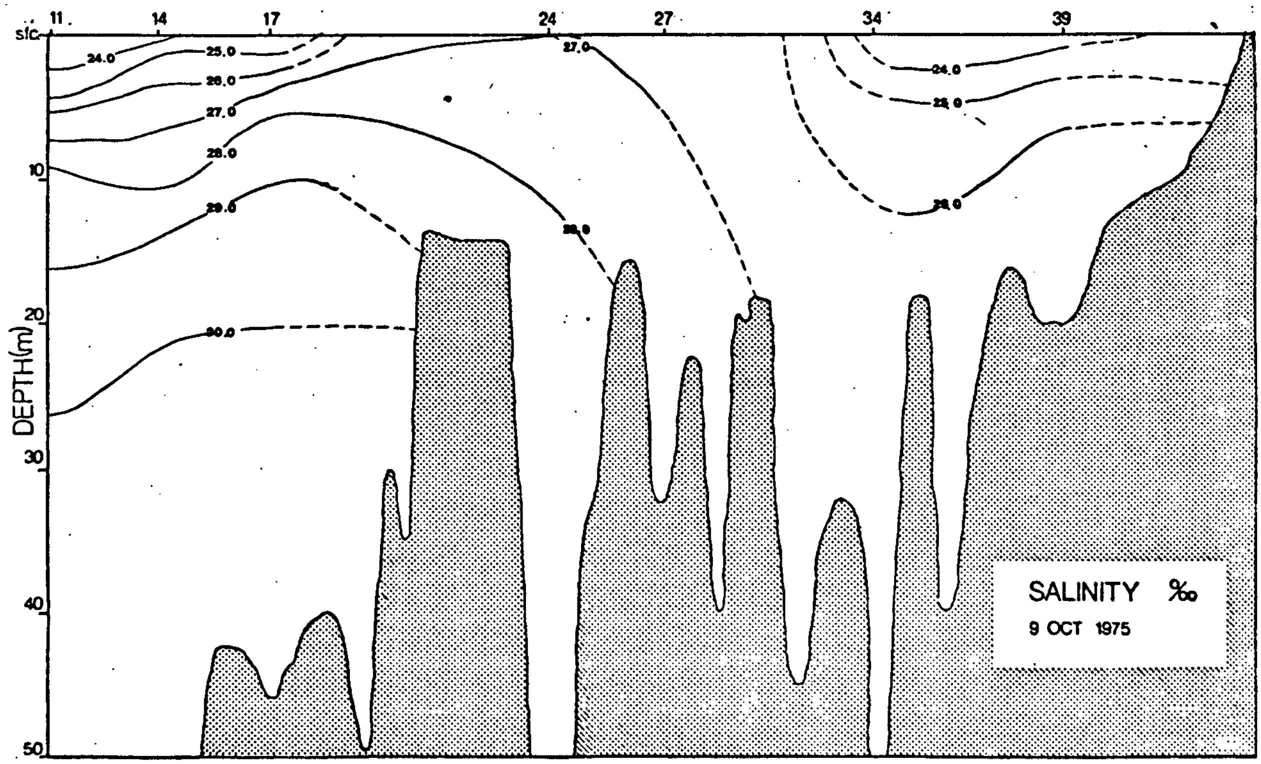
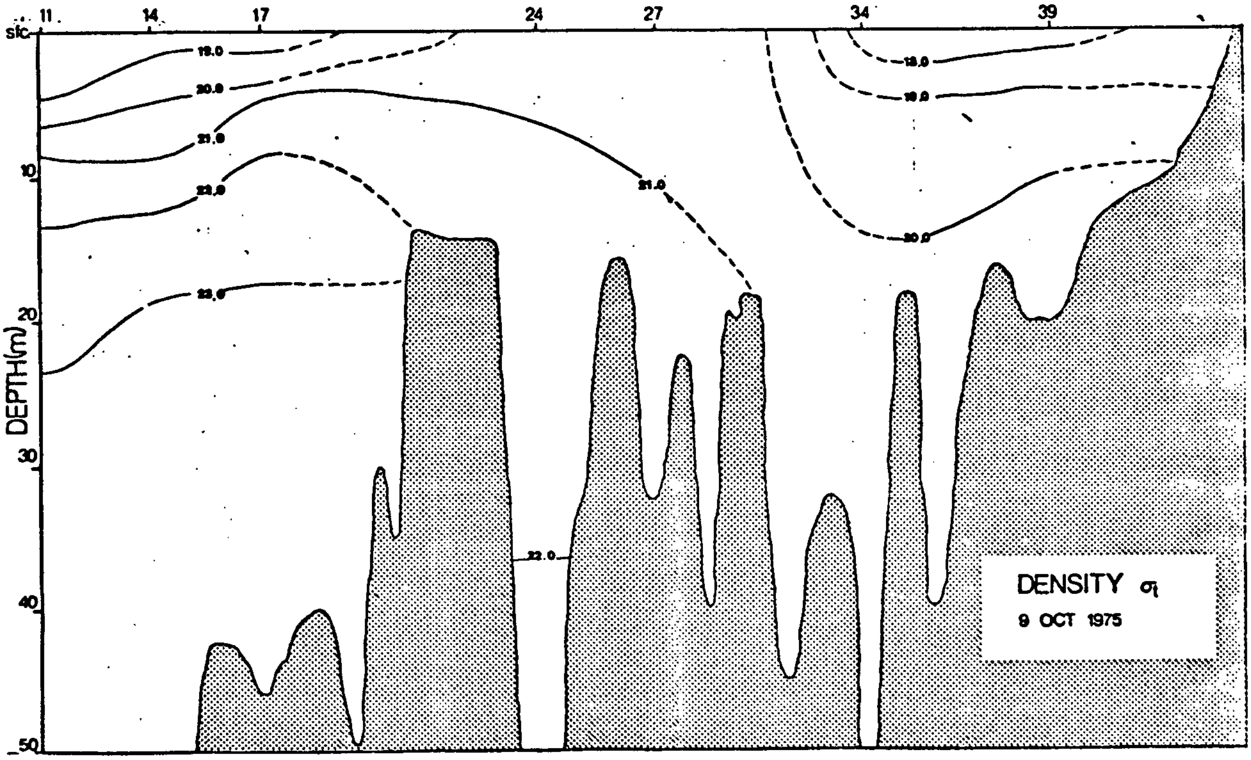
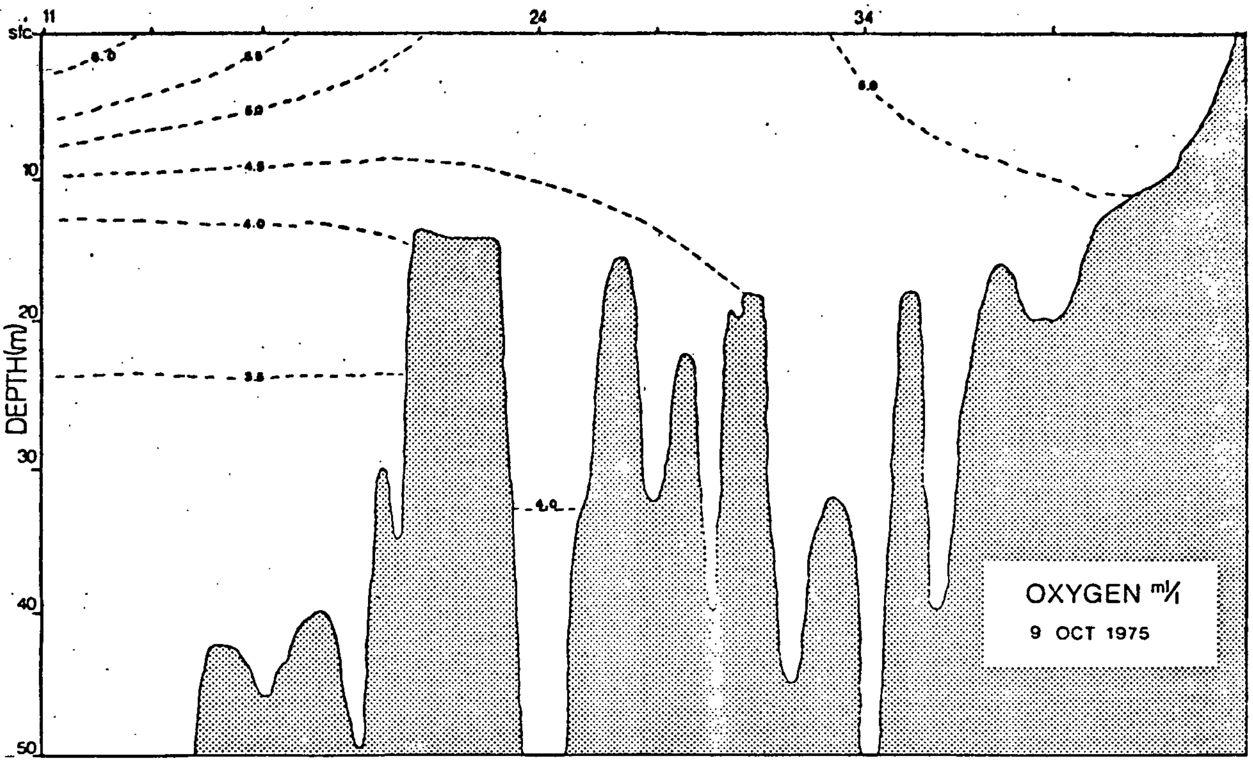


Figure 5.33 Longitudinal sections of (a) temperature (b) salinity (c) sigma-t and (d) oxygen for Burrard Inlet, October 9, 1975

(c)


sfc
11
14
17
24
27
34
39
10
20
30
40
50
DEPTH(m)
22.0
DENSITY σ_t
9 OCT 1975

(d)


sfc
11
24
34
10
20
30
40
50
DEPTH(m)
4.5
4.0
3.5
OXYGEN ml/l
9 OCT 1975

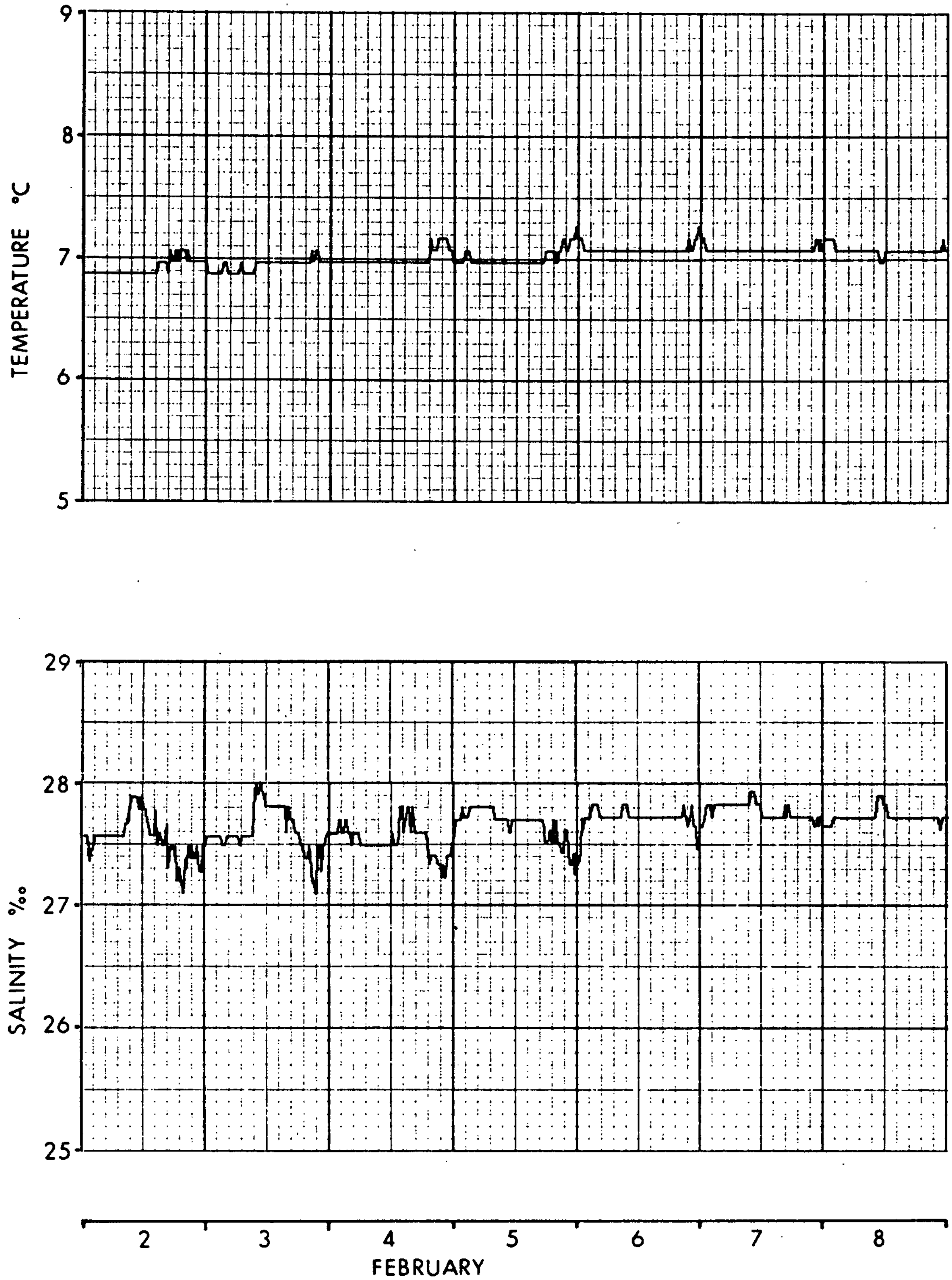


Figure 6.1 Detail of temperature and salinity records from near-bottom current meter on Indian Arm sill, showing intervals of possible instrument malfunction

Figure 6.2(a) Time-series of near-bottom currents on Indian Arm sill, December 5, 1974 to January 4, 1975

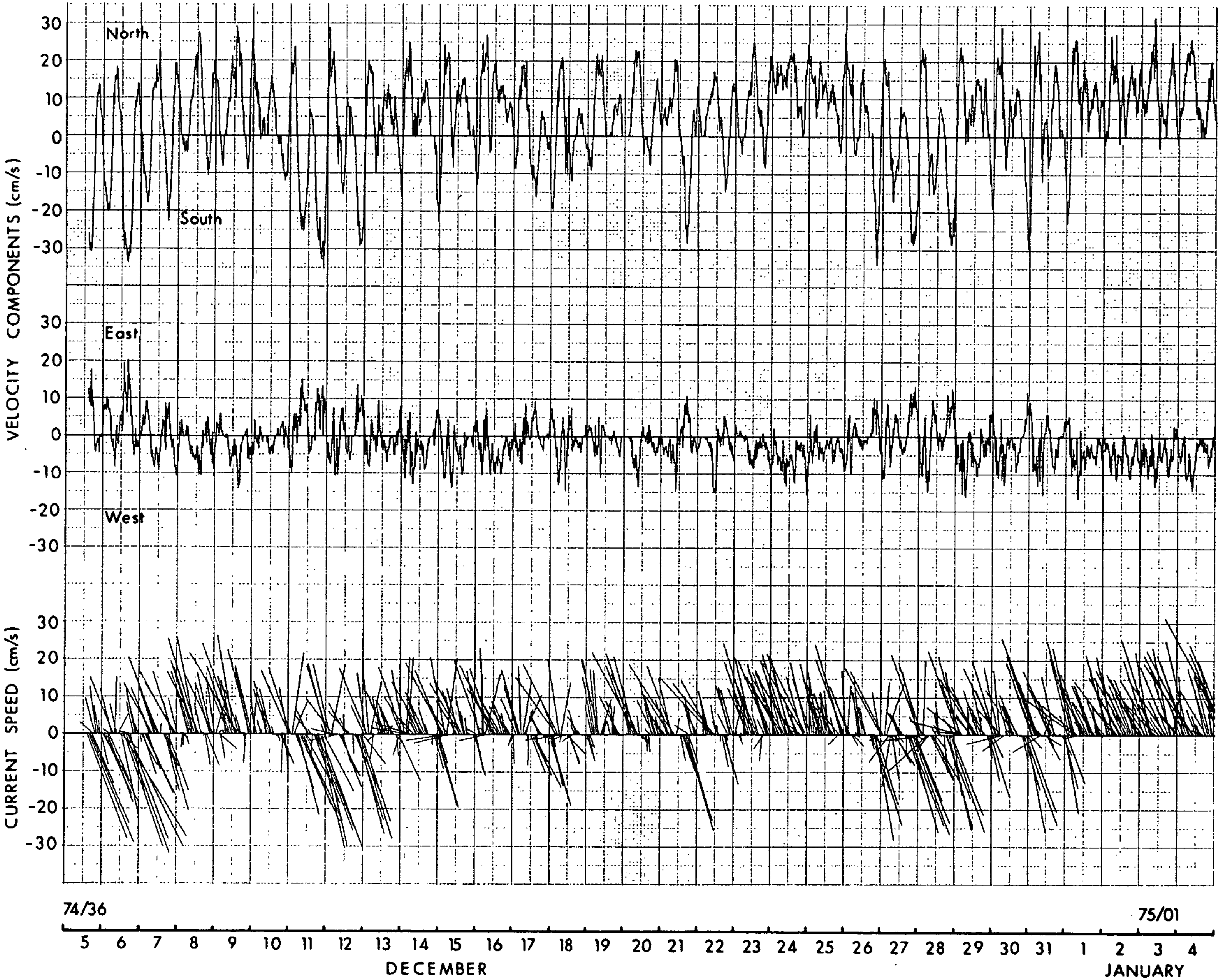


Figure 6.2(b) Time-series of near-bottom currents on Indian Arm sill, January 5, 1975 to February 4, 1975

Figure 6.2(c) Time-series of near-bottom currents on Indian Arm sill, February 5, 1975 to March 7, 1975

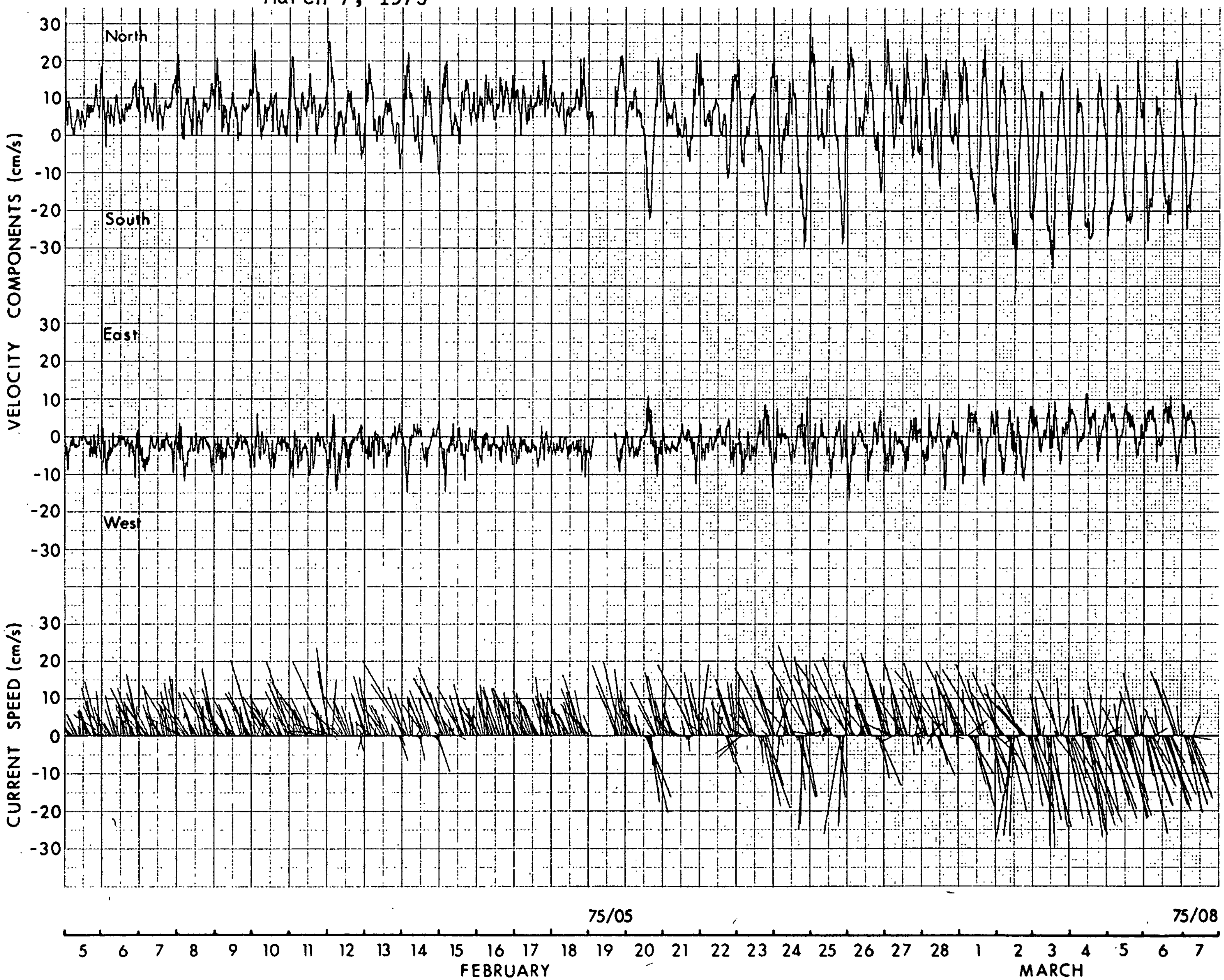
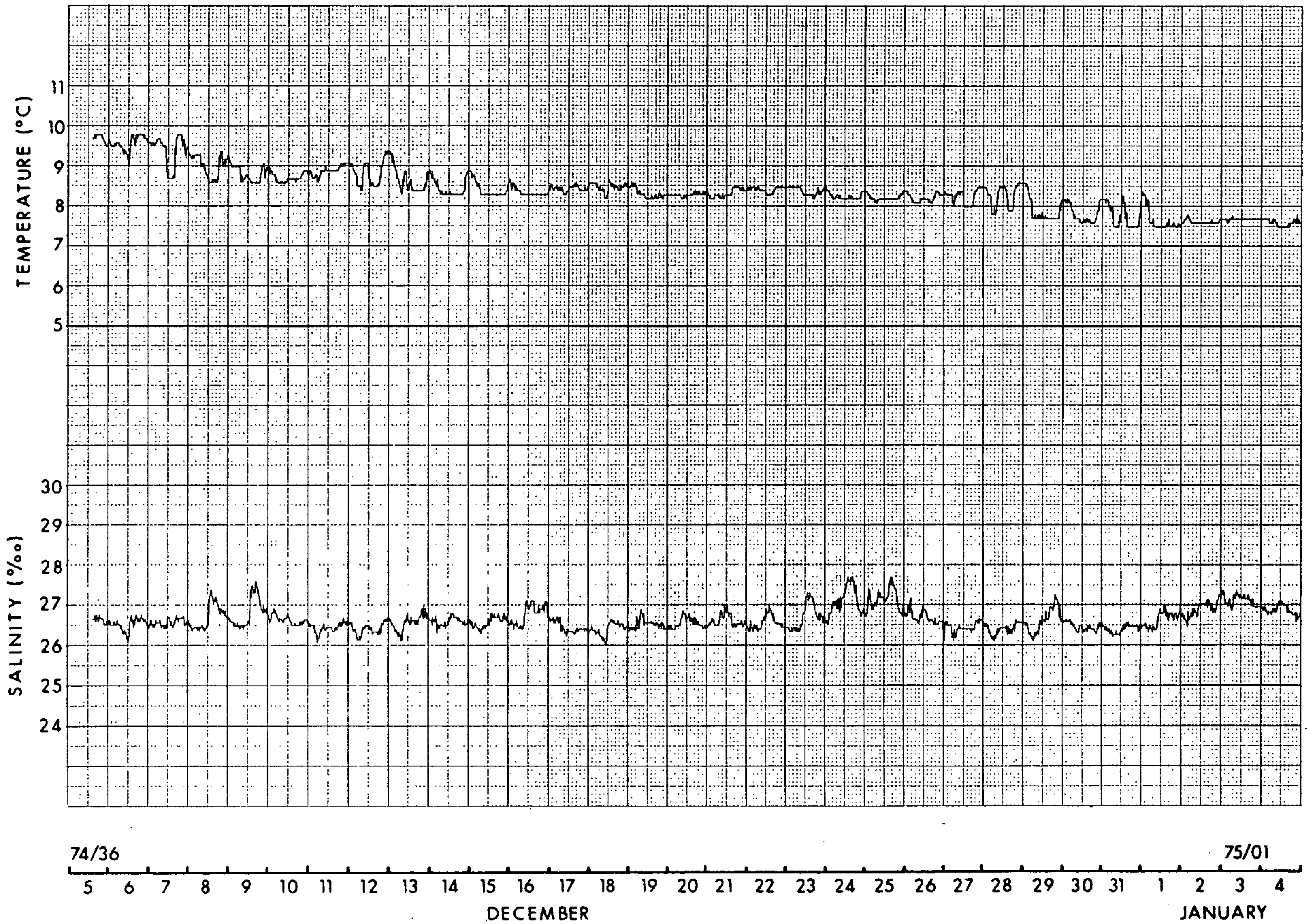


Figure 6.3 Time-series of temperature and salinity at current meter site on Indian Arm sill, December 5, 1974 to January 4, 1975



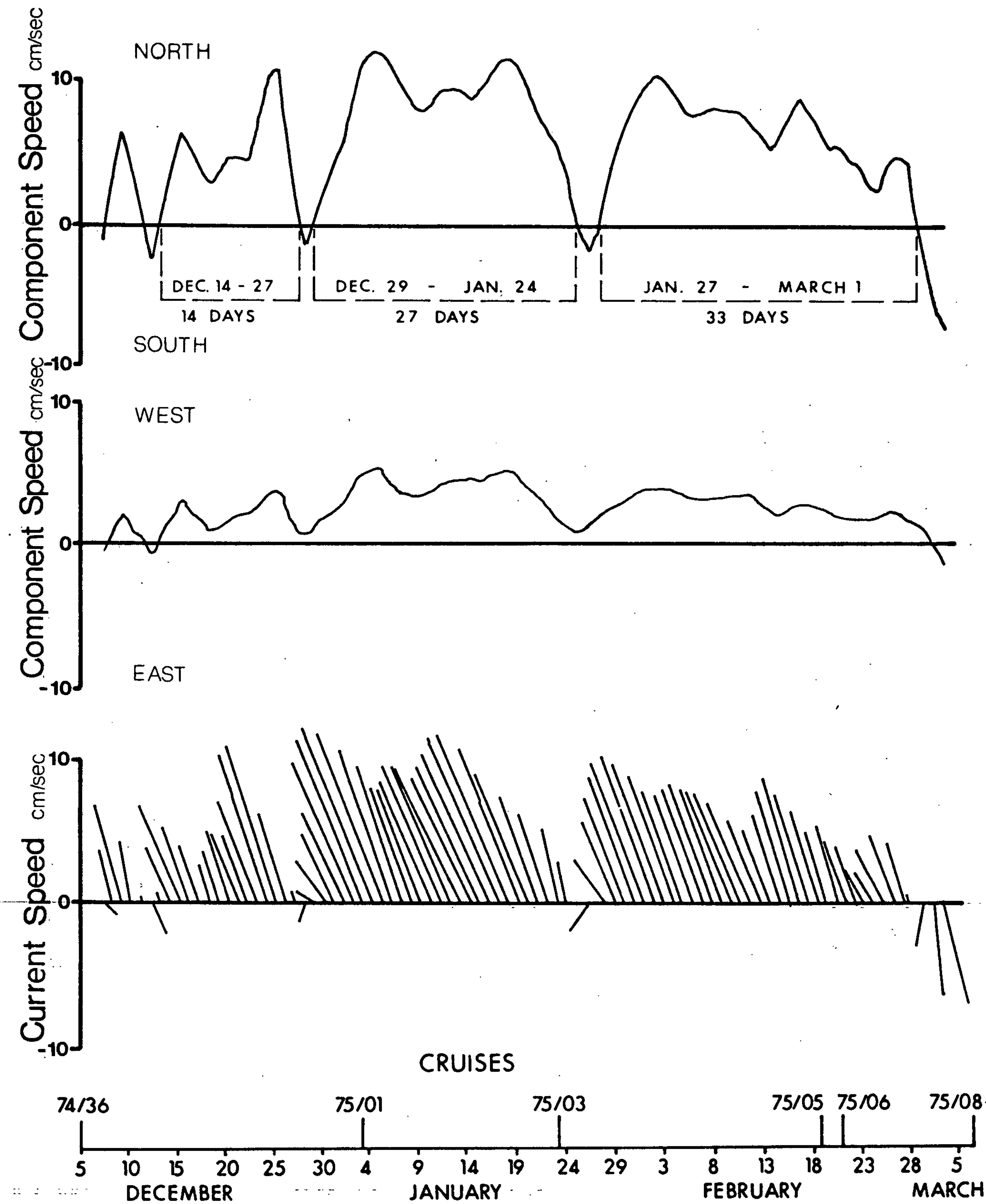


Figure 6.4 Time-series of averaged near-bottom currents on Indian Arm sill, December 5, 1974 to March 7, 1975

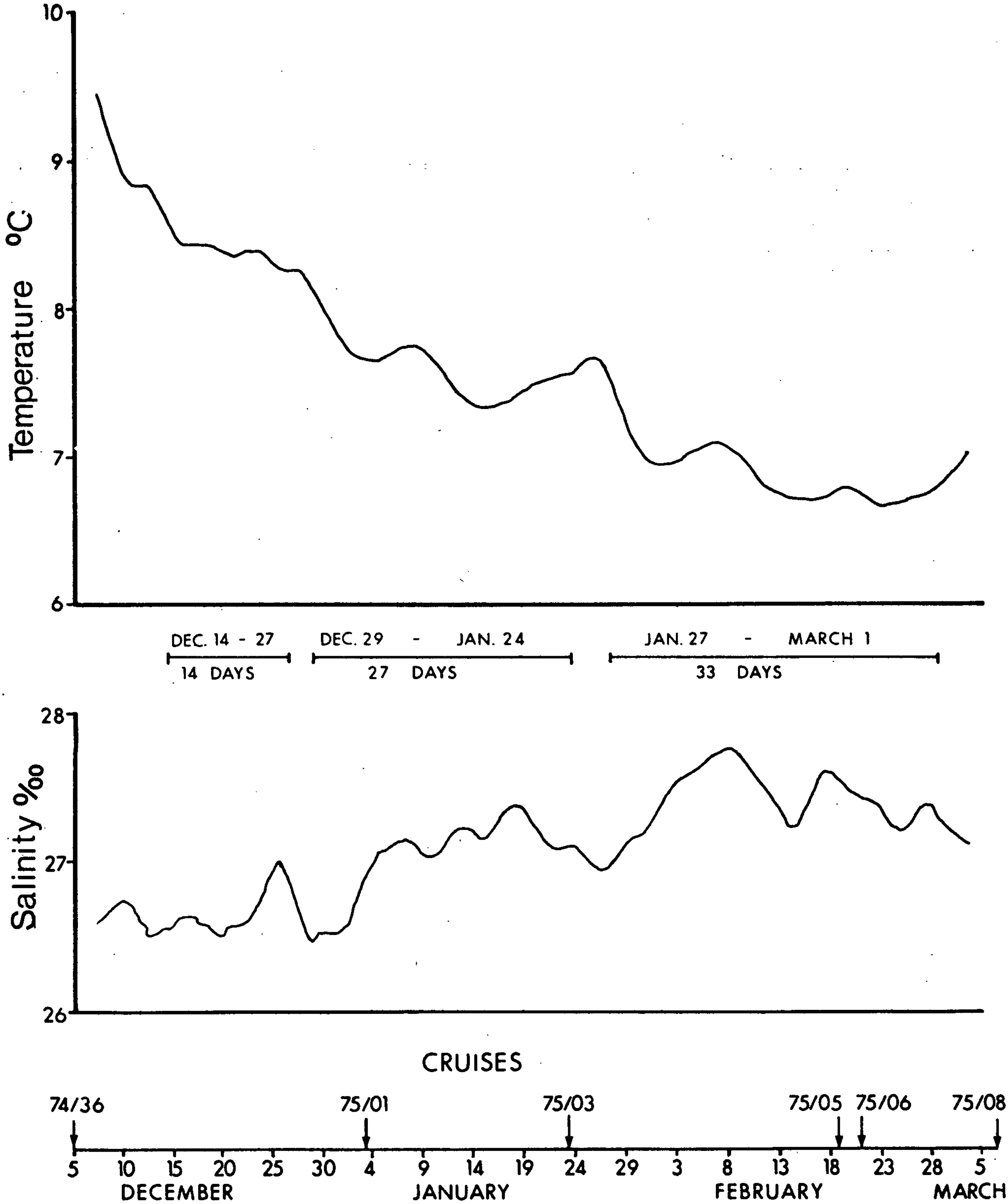
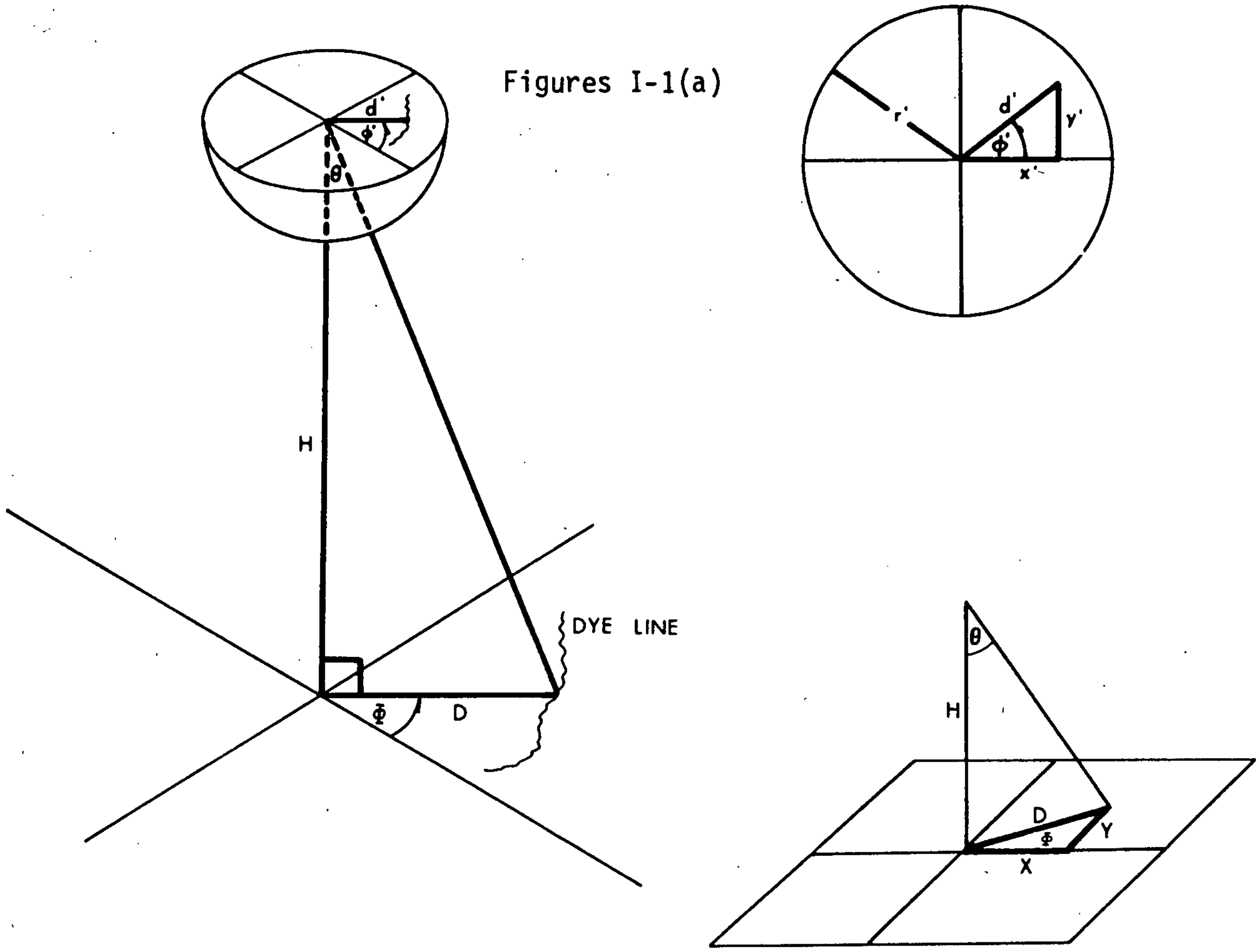


Figure 6.5 Time-series of averaged temperature and salinity at current meter site on Indian Arm sill, December 5, 1974 to March 7, 1975



Figures I-1(a)

Figure I-1(b)

Figure I-1 Geometry of coordinate transformation

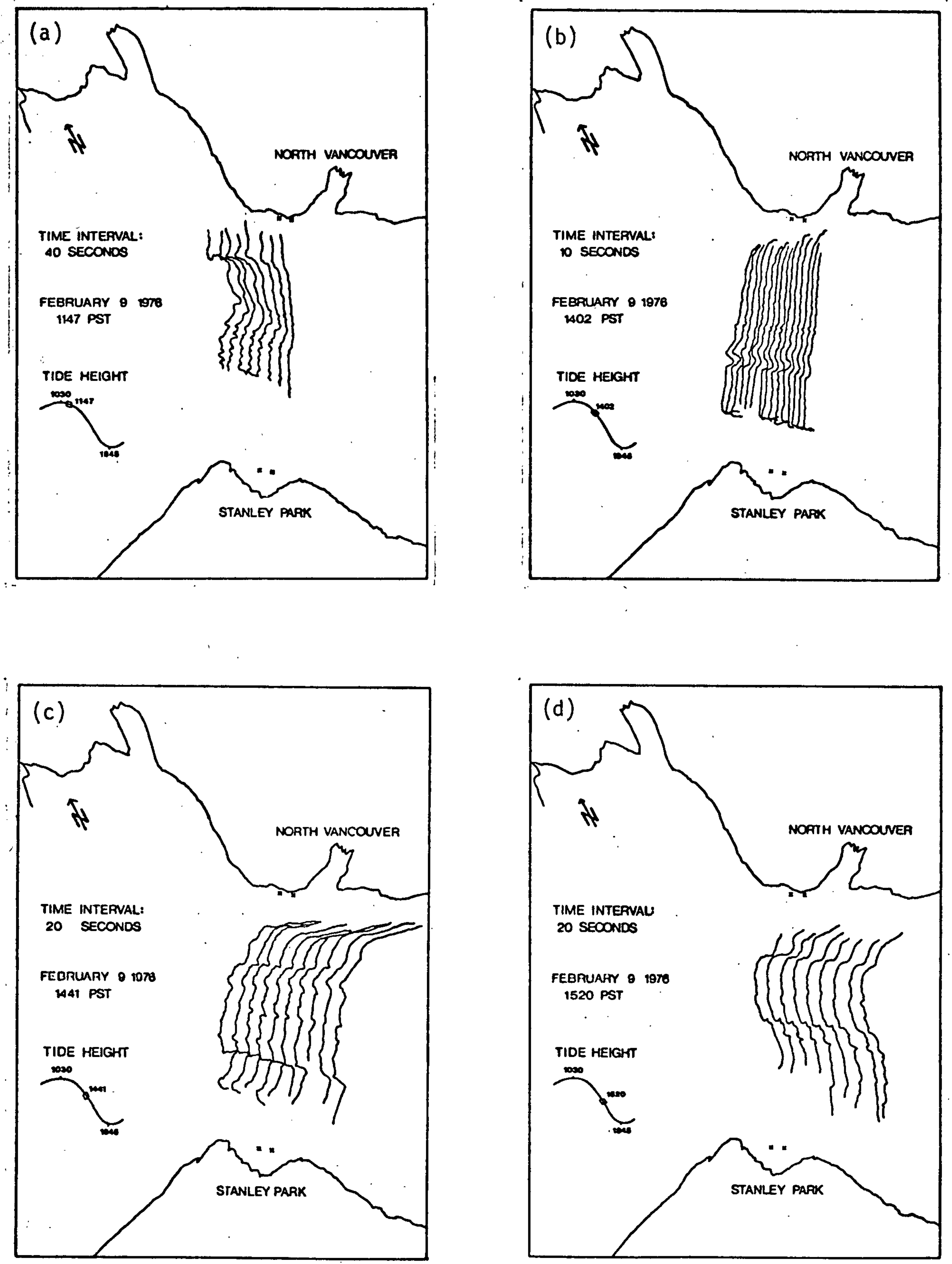


Figure I-2 Transformed positions of dye lines, February 9, 1976 at (a) 1147 PST, (b) 1402 PST, (c) 1441 PST and (d) 1520 PST

Figure I-3 Cross-channel velocity profiles, February 9, 1976