SOME ASPECTS OF THE OCEANOGRAPHIC STRUCTURE IN THE JERVIS INLET SYSTEM

by

John Robert Nicholas Lazier

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE

REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

in the department of

PHYSICS

We accept this thesis as conforming

to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

June, 1963

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the Head of my Department or by his representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Physics

The University of British Columbia,
Vancouver 8, Canada.

Date June 6/63

ABSTRACT

The variations in the distributions of temperature, salinity, and dissolved oxygen content in the water in the Jervis system of inlets, between July 1961 and March 1963, have been examined in order to ascertain net current patterns and interactions between the inlets. The depths of the entrance sills divide the inlets into two groups. Of the four inlets in the system three possess shallow sills which force the tide water to enter the inlets in a turbulent jet. The circulation pattern resulting from the influence of this jet on the inlet is proposed. In contrast, the sill of the largest inlet in the system (Jervis) is deep and the tidal flow does not destroy the vertical stratification in the inlet to any appreciable degree. The relatively small fresh water runoff into Jervis creates a weak estuarine circulation resulting in slow renewal of the intermediate and deep water. The low oxygen concentrations found at mid-depths near the head of Jervis are attributed to this abnormally slow renewal. A mid-depth oscillatory flow of unknown period was found during the winter of 1962-63 in Jervis Inlet. This flow is attributed to strong south-westerly winds which raise the water level in Jervis Inlet forcing a mid-depth outflow. The direction of this flow possesses a negative correlation with the depth of the surface layer.

ACKNOWLEDGMENTS

The author wishes to express his sincere gratitude to those who contributed to the completion of this study. In particular he wishes to thank Dr. G. L. Pickard under whose direction, encouragement, and helpful advice this work was carried out. The assistance and co-operation of Captain V. Dale-Johnson of the research ship C.S.S. "Ehkoli", and his crew are gratefully acknowledged. The author is also indebted to H. Heckl, H. Wilke, and M. Storm for technical assistance, and to Mrs. E. Storm for preparing the typescript. Finally, sincere appreciation is expressed to the Department of Mines and Technical Surveys for leave and financial assistance during the time of this study.

TABLE OF CONTENTS

LIST OF FIGURES

Figure

LIST OF FIGURES (Continued)

Figure

LIST OF FIGURES (Continued)

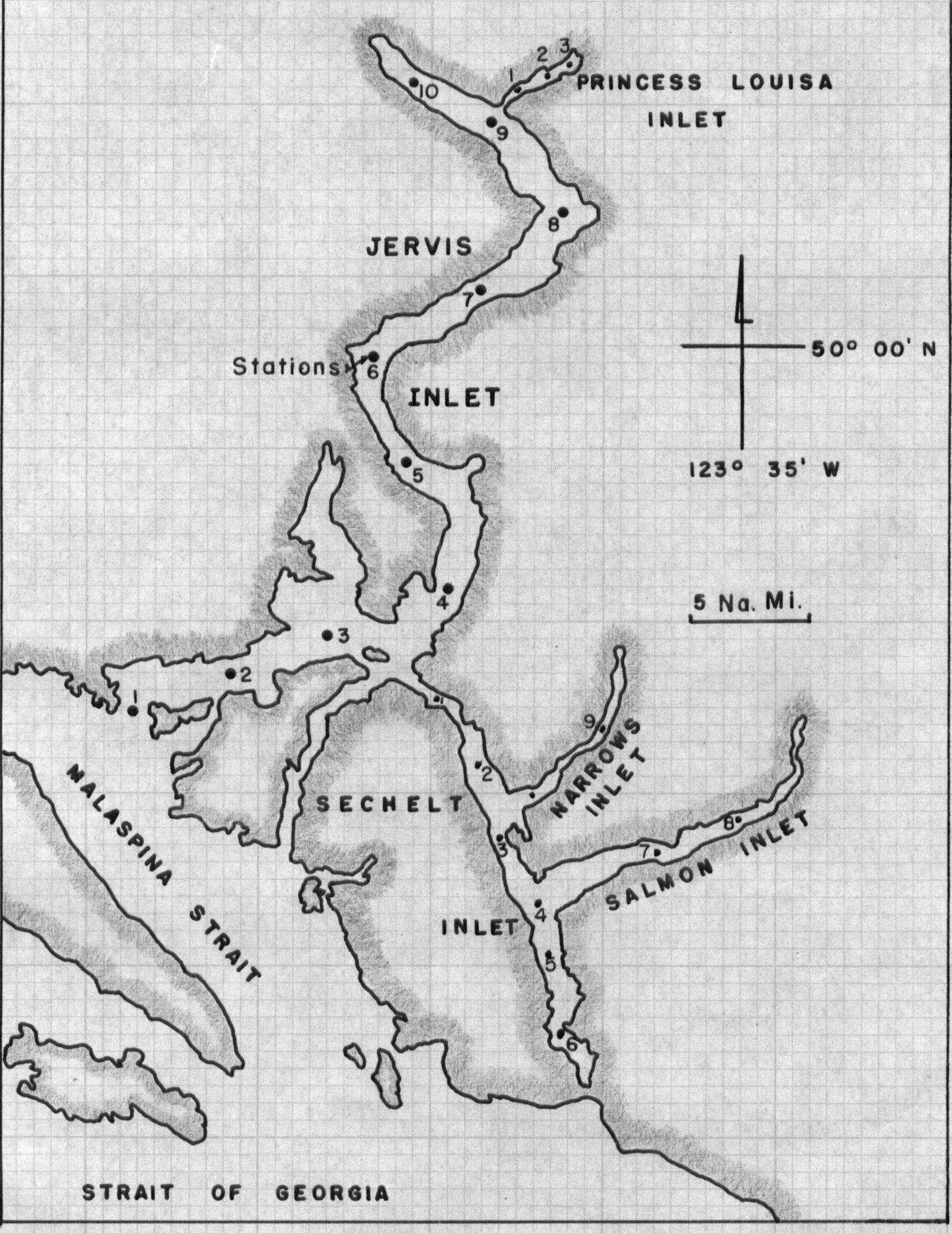
Figure

LIST OF FIGURES (Continued)

Figure

Figure 1

THE JERVIS INLET SYSTEM



I. INTRODUCTION

The "Jervis Inlet system" (figure 1) is comprised of Jervis, Princess Louisa, Sechelt, Salmon and Narrows Inlets. The seaward end or mouth of Jervis Inlet is located about 45 miles northwest of Vancouver, British Columbia. The physical characteristics of these inlets are similar to those of the other inlets of the British Columbia coast. They are elongated, narrow waterways with steep, roughly parallel, sides. The principal basins of each of the inlets in the system are partially separated from the adjoining basins, or channels by sills. The depths of these sills subdivide the inlets of the system into two groups. The largest group containing Princess Louisa, Sechelt and Narrows Inlets have "shallow" sills, while Jervis Inlet is separated from Georgia Strait by a "deep" sill.

The difference between a shallow and deep sill is somewhat arbitrary. In this account a shallow sill is one which confines the tidal flow to such a degree that the tide water enters, and leaves the inlet in a turbulent jet. The flow through the entrance channel of a shallow silled inlet is at any one time, predominantly unidirectional, either into the inlet or out. A deep sill allows the tide water to enter and leave the inlet without destroying, to any appreciable degree, the vertical stratification in the water column. The flow through the entrance channel of a deep silled inlet can be either into the inlet, out of the inlet or in both directions at the same time. Since there is no sill separating the basins of Sechelt and Salmon Inlets, the latter is treated as a branch of the former, and not as a separate inlet.

The purpose of this work was to investigate the circulation pattern in the Jervis system of inlets, stressing seasonal changes and the interaction between the interconnecting basins. Although considerable data had been collected before this programme was started it was limited to Jervis Inlet. Thus a new programme with the above purpose in mind was begun in 1961. The data collecting consisted of sampling the water at discrete depths at various stations (figure 1) throughout the inlet system. Atlas water sampling bottles were used in conjunction with Richter & Wiese, and Yoshino Keike reversing thermometers. The salinity of the water samples was determined by the Mohr silver nitrate titration method (Strickland and Parsons, 1960) and the dissolved oxygen content of the water was determined by the Winkler method (Strickland and Parsons, 1960).

Previous investigators notably Tully (1949), Pritchard (1952), Pickard and Trites (1956), Pickard (1961), and Gilmartin (1962) have discussed the general features of the coastal inlets. Because of land drainage and precipitation, all the inlets possess a thin surface layer of brackish water. This low-salinity surface layer "flows seaward, gaining in volume by entrainment of saline water from below as it does so and gaining in speed as it approaches the inlet mouth." (Pickard, 1961) To compensate for this loss of water from the inlet a subsurface inflow is generated. This "estuarine circulation" of surface outflow and subsurface inflow, however, is not possible in the shallow silled inlets. The circulation pattern in the shallow silled inlets is determined by the nature of the tidal jet and its interaction with the water in the inlet basin. A circulation pattern for these inlets is proposed later in this account.

The work of previous investigators also raised some unanswered questions. For example; Carter (1934) reported that the deep water in Princess Louisa Inlet was completely devoid of dissolved oxygen, but Pickard (1961) reported 1.7 ml/l of dissolved oxygen in May 1952 and 3.4 ml/l in June 1960, in the same body of water. Between each of these visits to the inlet, highly oxygenated water must have intruded to the deep zone, but the details of the process were not understood. Another problem which was studied in the present programme concerns the oxygen distribution in Sechelt and Jervis Inlets. In June 1957 an oxygen minimum was found at mid-depths in Sechelt and Salmon Inlets (Pickard, 1961), but in June 1961 no minimum could be found at mid-depths. However, the deep water in the inlets contained about 3 ml/l less dissolved oxygen than in 1957. Thus the circulation pattern in the inlet is able to support a mid-depth oxygen minimum at one time, but some time later the lowest oxygen concentration is found in the deep water. The data from all cruises to Jervis Inlet have revealed a region of water containing less than 2 ml/l of dissolved oxygen. Sometimes this water forms a mid-depth oxygen minimum, but at other times it forms a deep layer of "low-oxygen" water. The changes in dissolved oxygen distribution in these inlets are accompanied by changes in the temperature and salinity distribution, but the latter are not as spectacular.

Because the current structure in the shallow silled inlets is markedly different from that in the deep silled inlet (Jervis) these two categories are treated separately. It has also been deemed advisable to preface the discussion of the data with some of the conclusions of the study. It is hoped that this will give the reader an overall picture before the detailed data supporting the conclusions is given.

II. SHALLOW SILLED INLETS

Proposed Current Pattern

Princess Louisa, Sechelt, and Narrows Inlets have shallow entrance sills which restrict the movement of water in and out of these basins to the top few metres of the water column. The distributions of the oceanographic variables, temperature, salinity and oxygen, are similar in all three inlets. It is proposed that the circulations responsible for these distributions are also similar, because of the shallow sills. A circulation pattern common to all three shallow silled inlets is proposed below.

The important feature of these inlets is the exchange of tide water. The physical restrictions of the sill force the flood tide to enter the inlet as a violently turbulent jet. This jet, downstream of the sill, spreads out by entraining some of the surrounding water. This phenomenon is common to all "free" turbulent jets, (Rouse, 1959). The word "free" implies that there is no solid boundary in the fluid which affects the jet. A free jet may be visualized by injecting ink with a hypodermic needle into a large tank of water. Although this idealized state is not present in the inlet the jet will spread out until it comes in contact with the surrounding channel. Another property of a turbulent jet is that it will tend to "stick" to any solid boundary with which it comes into contact (Newman, 1961). Thus, the flood tide jet which is in contact with the bottom at the sill will tend to "hug" the bottom until buoyancy forces, inherent in the density stratification in the inlet, force it up.

The jet will produce a homogeneous mass of water near the mouth of the inlet. The depth of this mass will be much greater than the sill depth due to the jet "hugging" the bottom, and the volume will be greater than the actual volume of flood water because of entrainment. Near the sill the force of the tidal jet will be great enough to erode the surface layer, but as the turbulence dies out the flood water will sink under the surface layer. This phenomenon gives rise to a visible tide-line or "junk-line" where floating debris collects.

The water of the flood tide originates in the surface water outside the inlet, and therefore the density of this water will vary during the year reflecting the changes in air temperature and surface runoff. Because of the physical difficulties no water samples have been taken from the tidal jet as it crosses the sill, but data from the surface layer just outside the sill indicate that the average density of the flood tide water varies as shown in figure 2. This curve shows a maximum density in late winter, and a minimum in early summer. There will undoubtedly be many small fluctuations in this curve, but they will not alter the general decrease in spring and rise in the autumn. The value of the maximum in late winter will vary from year to year as will the minimum, depending on seasonal temperatures and rainfall.

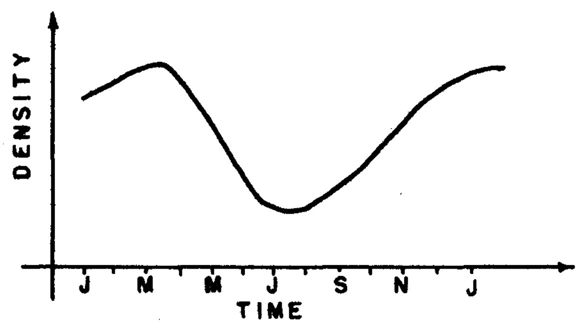


Figure 2. Average annual variation of the flood tide water.density.

For simplicity in describing the effect of the tidal flow on the inlet, suppose that the temperature, salinity and dissolved oxygen of the water in the inlet below the runoff layer are completely uniform. Assume further that the density of the flood tide water is at a maximum for the year, and is just about to start decreasing due to spring runoff and temperature conditions. Figure 3 depicts the conditions in the inlet when the water of the flood tide is less dense than the homogeneous indigenous water below the surface layer.

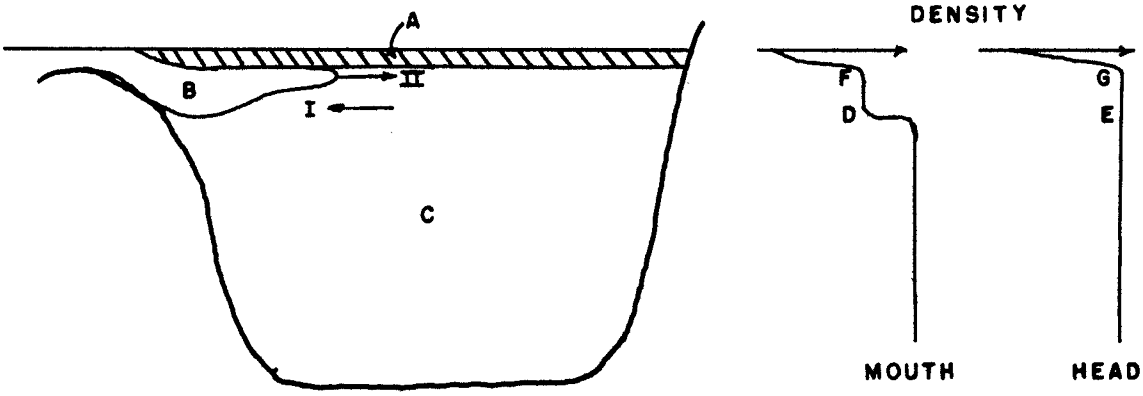


Figure 3. Hypothetical schema of a shallow sill inlet following a flood tide in spring. The letters are explained in the text.

Layer A is the low density surface layer in the inlet formed by runoff and precipitation. Water mass B is the homogeneous mass of flood tide water, and C represents water in the inlet below the surface layer. Water mass C is homogeneous but denser than water mass B. Because the density of the flood water (B) is greater than the density of water in the surface layer (A), water mass B lies under the surface layer A. The mixing due to the tidal jet destroys the surface layer near the sill. Vertical density profiles for positions near the mouth and head are shown on the right in figure 3. It is clearly seen in these profiles that the density of the water at D and F is less than at G and E. Thus a horizontal density and pressure gradient is created which results in horizontal flow. The water at G and E will flow toward the mouth under the tide water (arrow I figure 3) while the tide water will flow up-inlet, (arrow II), between the surface layer and flow I. These two currents create a shear between two water masses of different characteristics, and the tendency will be for these water masses to exchange their characteristics and become homogeneous. This process is depicted in figure 4.

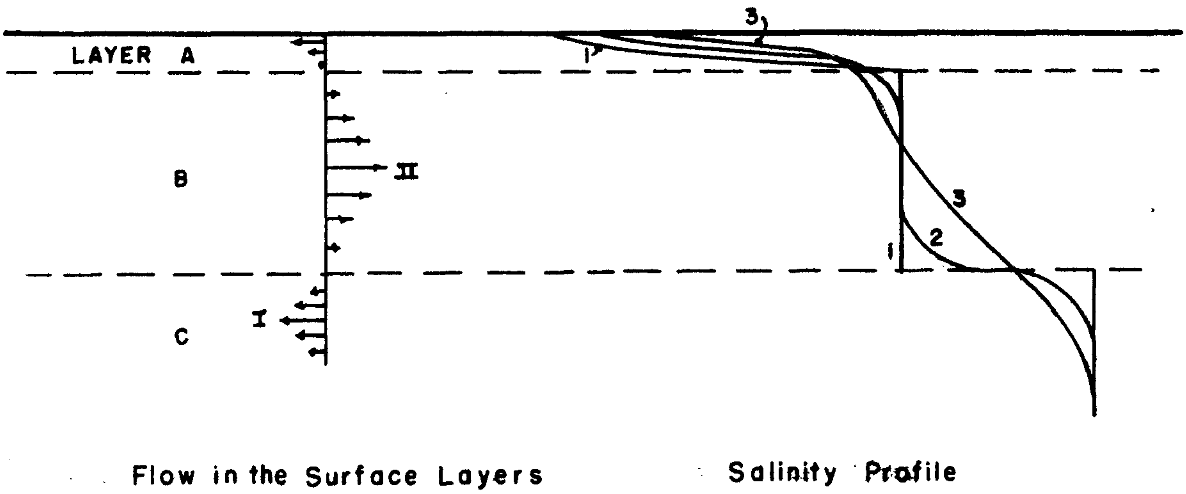


Figure 4. Changes in the vertical salinity gradient when subjected to the indicated shear.

The profile labelled 1 represents the idealized salinity distribution before any shear takes place between the three layers, (i.e. layers A, B and C of figure 3). Profiles 2 and 3 represent the salinity distribution after the shear has been acting for some time, (Trites, 1955). Arrows I and II represent the same flows as in figure 3.

As long as the density of the flood tide becomes progressively less the mechanism just described will prevail. Also, as the density difference between the flood water and the deep water becomes greater, the density stratification in the upper layers of the inlet becomes more pronounced. The layer of water in the inlet which is affected by the flood tide water will become thicker, because of the continual exchange effected by the shear between flow I and II (figure 3 and 4). However, as the density gradient in the inlet becomes greater, this shear will tend to be confined, which puts a lower bound on the depth of the affected region. Another factor which may tend to dictate the depth of this layer is the behaviour of the tidal jet. If the density of the tide water was exactly the same as all the water in the inlet, the tidal jet would flow into the inlet unaffected by buoyancy forces. The limits of such a jet will be called the "natural" limits. These "natural" limits determined by the physical properties of the jet and the surrounding channel are changed by a density stratification in the inlet. But the jet will tend to destroy this stratification and regain its "natural" limits. Thus the lower bound on the region affected by the jet will depend on the density stratification in the inlet and the "natural" limits of the tidal jet.

The flow depicted in figure 3, as mentioned, will continue as long as the density of the flood tide water is less than that of all the water in the inlet below the surface runoff layer. In the late summer, autumn, and early winter the density of the flood water is increasing (figure 2) and the conditions in the inlet are changed to those shown in figure 5. In the vertical density profiles at the right of the figure it is seen that the density of the water at F and D is greater than that at G and E. The horizontal pressure gradient resulting will tend to push the tide water (B) up-inlet (arrow II) at an intermediate depth. This mass of water flowing in at mid-depth will lift up the water above the intrusion (arrow I). This water will tend to join the outflow of the surface layer. Now

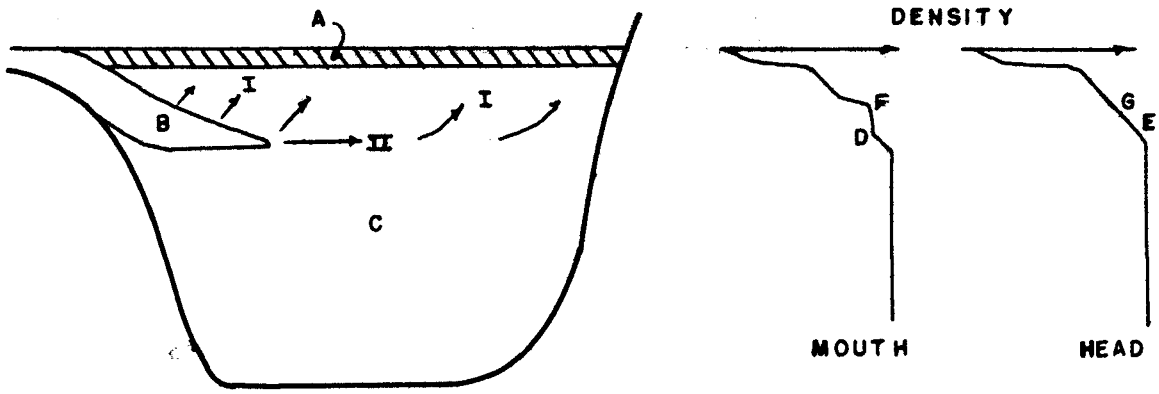


Figure 5. Hypothetical schema of a shallow sill inlet following a flood tide in autumn. The letters are explained in the text.

the region of greatest shear is moved downwards, which will force an exchange of heat and salt with deeper layers than before. This effects a deepening of the intermediate layer. As the season progresses and the density of the tide water increases, the thickness of the region affected by the flood tide water increases, but the density difference between the intermediate and deep layers becomes less. The stages of this process are shown in figure 6.

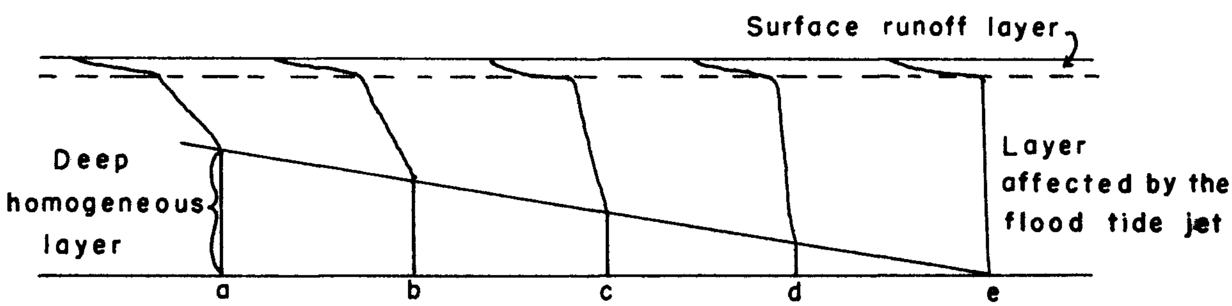


Figure 6. Changes in the salinity profile in a shallow sill inlet as the density of the flood tide increases in the autumn.

The sinking of the flood tide water produces flushing by replacing the indigenous inlet water at the depth of sinking. The indigenous water is pushed up and towards the head of the inlet.

The depth to which flushing proceeds will become greater as the density of the flood water increases. During most years the flood tide density does not increase enough to replace the bottom water. In this case the density structure proceeds to the state shown in figure 6c or 6d. Occasionally flushing of the bottom water does occur leaving a density profile similar to that shown in figure 6e. The greatest depth of the flushing occurs at the time of greatest density of the flood tide water, usually in late winter. Modifications to the vertical density structure produced by spring conditions are confined to the upper layers of the inlet, and any density structure left by incomplete flushing in the deep regions (figure 6c or 6d) will remain throughout the next year.

The distribution of dissolved oxygen in the shallow silled inlets presents some regular features complementary to the mechanisms just discussed. The flood tide water originates in the oxygen rich surface layers outside the inlet, and is violently mixed in the presence of air as it enters the inlet. These factors combine to produce a water mass generally rich in oxygen. The region in the inlet most strongly influenced by the flood tide water will exhibit high oxygen values. Between flushings, the region below this influence is cut off from sources of oxygen other than the small amount that diffuses down from the upper layers. This deep, relatively "stagnant" zone displays a low or declining oxygen concentration. This is attributed to oxygen demand in the water resulting from oxidation of detrital material falling from the surface layers. This essentially two layer distribution is modified by flushing, and by biological production and consumption of oxygen in the upper layers. These modifications will be discussed as they appear in the data, which are given in the following sections.

Princess Louisa Inlet

Princess Louisa Inlet opens into Jervis Inlet at $50^{\circ}9.7'$ N $133^{\circ}51'$ W on the north-east shore of Queen's Reach. It is roughly four miles long and one-half mile wide, with an average depth of about 120 metres. The plan and longitudinal profile of the inlet are shown in figure 7.

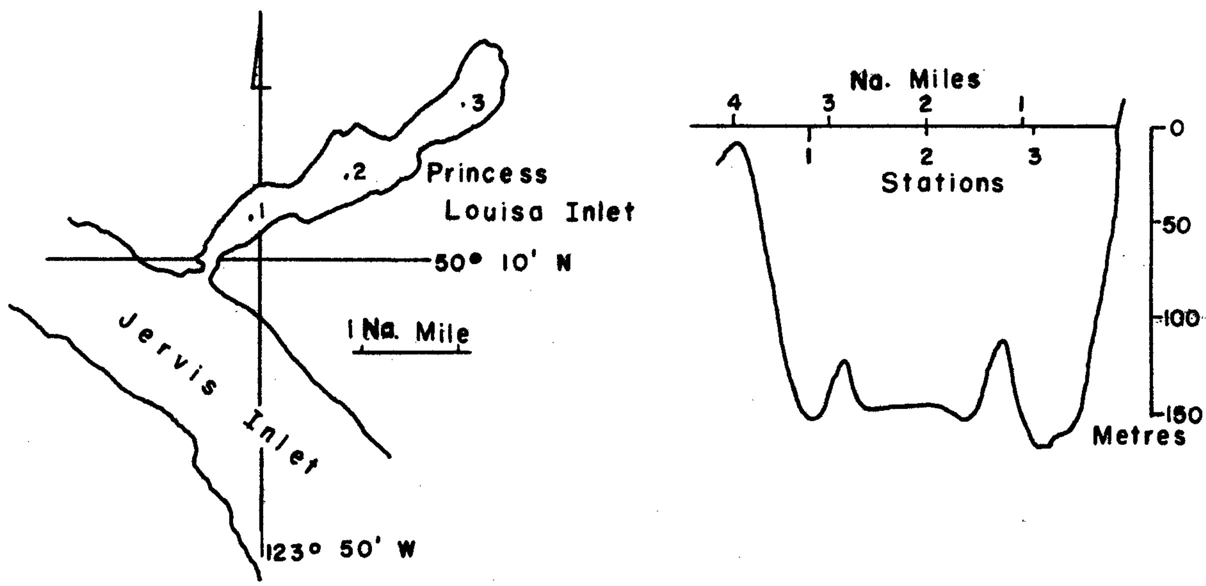


Figure 7. Princess Louisa Inlet.

As mentioned previously, a shallow sill at the mouth restricts communication with Jervis Inlet. The threshold depth of the sill varies from about 6 to 11 metres depending on the state of the tide. The width of the channel at its shallowest point is 60 metres. The mountainous terrain surrounding the inlet produces very steep sides, both above and below the water line. These walls tend to isolate the inlet from high winds, resulting in a calm water surface and the absence of appreciable wind mixing. The data obtained from this inlet during 1962 and early 1963 are discussed below in relation to the mechanisms proposed previously.

March 1962

The first cruise of the series, in March 1962, revealed a water mass with only small variations in temperature, salinity, and dissolved oxygen. Although the greatest range of observed values was $\Delta T=0.47\ C^{o}$ $\Delta S=0.46$ ‰ and $\Delta O_2=1.29$ ml/l some horizontal gradients were observed, as shown in figure 8.

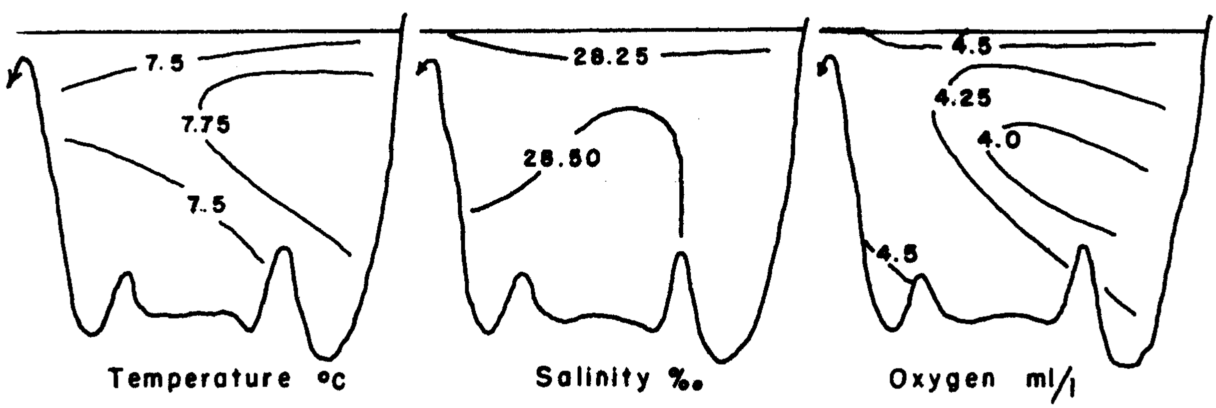


Figure 8. Longitudinal profiles of temperature, salinity and dissolved oxygen in Princess Louisa Inlet, for March, 1962.

The deep water at stations 1 and 2 characterized by high dissolved oxygen, low temperature and high salinity is noticeably different from the intermediate water at all three stations characterized by relatively high temperature, low salinity, and low oxygen. There seems little doubt from this and the shape of the isopleths that the former water mass is new to the inlet. Thus the inlet is in the process of being flushed right to the bottom by the sinking of the high density flood tide water.

May 1962

The variations in May, of temperature, salinity and dissolved oxygen in the vertical direction are much greater than the horizontal variations. For this reason the horizontal variation is neglected and the inlet is treated as a single column of water. The curves in figure 9 represent the average variation with depth of temperature, salinity and oxygen for March and May 1962. The profiles for March show an almost uniform body of water, as mentioned previously, but the profiles for May reveal the effects of a decrease in tide water density due to spring runoff and temperature conditions.

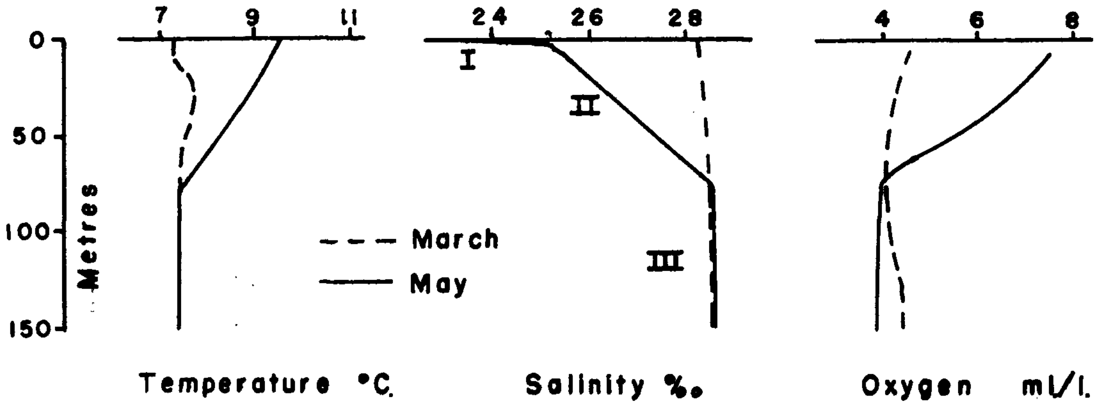


Figure 9. Average vertical temperature, salinity and oxygen profiles for March and May 1962.

The salinity profile shows three distinct layers; the top relatively fresh 5 metres (layer I figure 9), the intermediate layer to 75 metres (layer II), and the deep homogeneous layer (layer III). The steep linear gradients in layer II are attributed to the shear between the up inlet flow of tide water and the down inlet flow, at mid-depth, as proposed on page6 and in figure 3. These gradients are very similar to the proposed profile number 3 in figure 4.

It is interesting to note that the surface layer (layer I) of relatively fresh water exhibits no large temperature gradient corresponding to the large salinity gradient in the layer. This appears to be quite an uncommon occurrence and is discussed more fully on page 17.

The salinity, and hence density, of the deep homogeneous zone (layer III) is greater in May than in March. This could only happen if the flood tide continued to increase in density after the March cruise, thus prolonging the flushing. The lower dissolved oxygen content in this layer is attributed to oxygen demand in the water, but it may be an effect of continued turnover after the March cruise.

July 1962

Figure 10 shows the average vertical distributions of temperature, salinity, and oxygen for July 1962 compared with those for May 1962. The surface, intermediate, and deep layers are present as in May, but between the latter two there is a new layer (layer IIa) of very steep gradients in temperature and salinity. The depth at which the deep homogeneous zone begins has not changed since May. This depth of about 75 metres appears to represent a lower boundary for layer II and IIa when the density of the flood water is decreasing. A reason for this lower boundary was proposed on page 8. The large gradients in layer IIa are a result of a large density drop in the water of the flood tide. There is not a linear gradient through layers II and IIa because the tidal jet has enough energy to erode large gradients only to a certain depth; about 40 to 50 metres in this case.

The high dissolved oxygen content above 75 metres in May and July is attributed to production of oxygen by phytoplankton in the upper layers. The phytoplankton blooms occur in both Princess Louisa and Jervis Inlets. The high oxygen concentration in the upper layers of Jervis Inlet appear in layer II in Princess

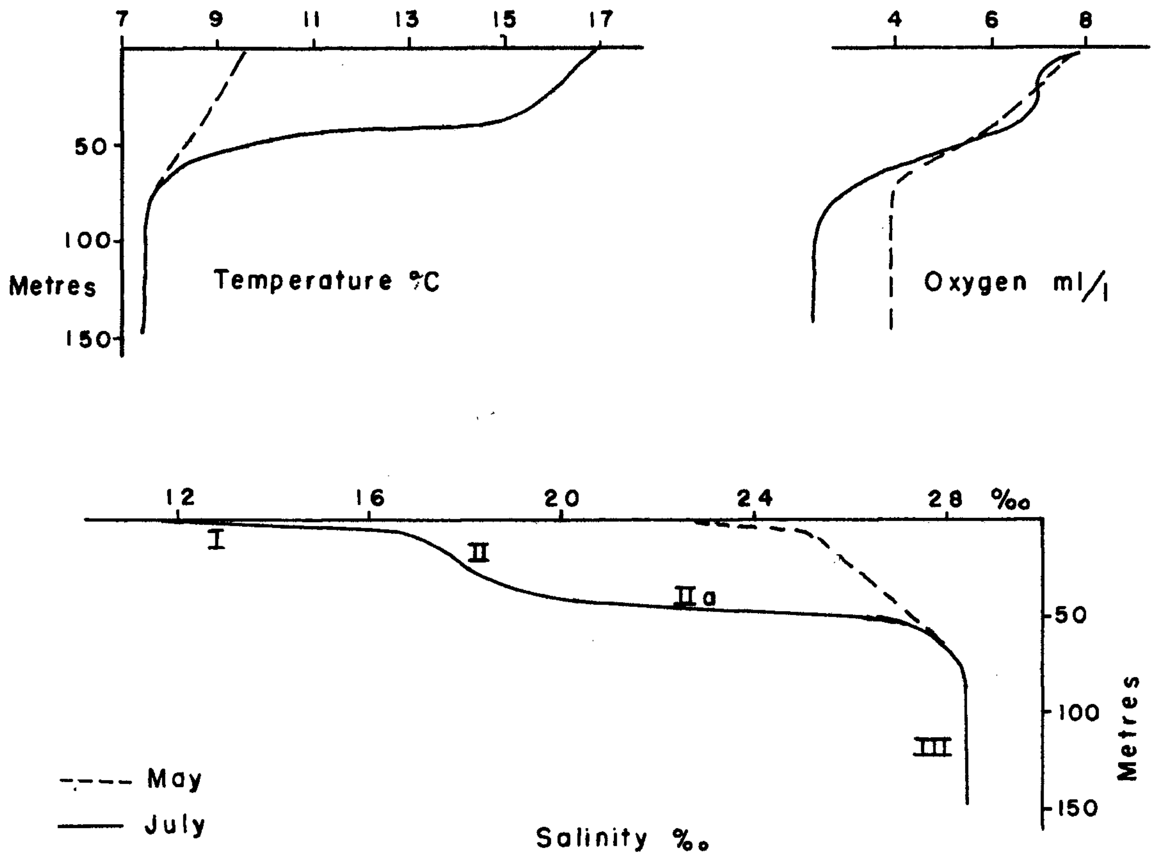


Figure 10. Average vertical temperature, salinity and oxygen profiles for Princess Louisa Inlet during May and July 1962.

Louisa Inlet by virtue of the flood tide. The oxygen curve for July shows a sharp change in gradient at 40 metres. This level coincides with the bottom of layer II which is the limit of influence of the tidal jet. Below this depth the oxygen content is not being increased by phytoplankton production or by renewal from the tide, but is being depleted continually because of the oxygen demand in the water. The oxygen concentration in the deep zone (layer III) is 2.3 ml/l in July which is a decrease of 1.6 ml/l since May.

October 1962

The average vertical profiles for July and October are compared in figure 11. The four distinct layers are still present, but the water in layer I has lost a considerable amount of heat while gaining salt. This layer is also thicker. The increase in density of the water in layer II indicates that the density of the flood tide water is increasing. Because the density of the tide water is increasing the current pattern in the inlet changes to that depicted in figure 5, and discussed on page 9 .

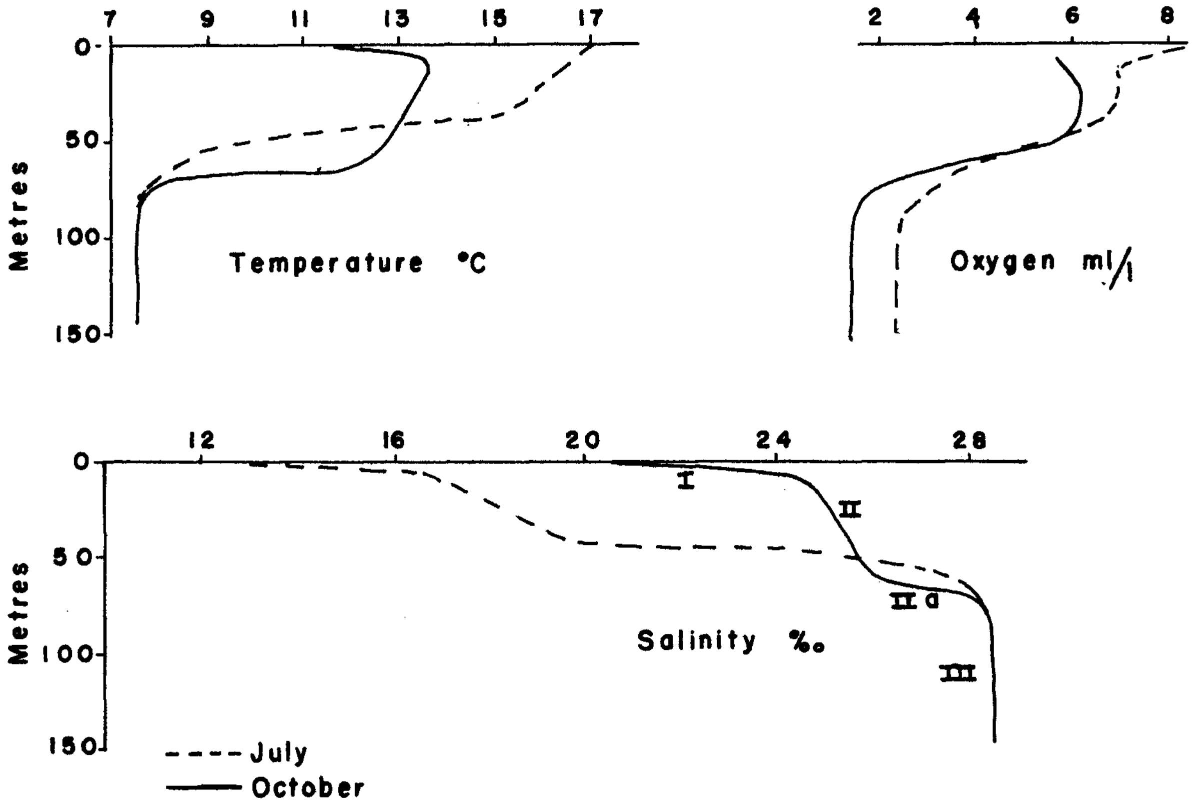


Figure 11. Average vertical temperature, salinity and oxygen profiles for July and October 1962.

The flood tide water now flows up inlet at an intermediate depth instead of just under the surface layer as it did when the tide water was decreasing in density. The increased exchange with the deep region resulting from the sinking tide water increases the depths of layers II and IIa.

In October, the surface layer of relatively fresh water (layer I) exhibits a distinct temperature gradient (figure 11). It was noticed (page 14) that there was no such temperature gradient in the surface layer in May 1962. This was also true in July 1962 (figure 10). The main source of heat in the surface layer is solar radiation. This heat which is absorbed by the water is either radiated back or is carried out of the inlet with the surface run-off. The downward transport of heat is limited by the stability of the surface layer. Thus if there is more heat per unit volume of water in the surface layer than in the underlying layers, it must mean that the surface layer is gaining more heat by radiation than it is losing by back radiation or advection. Also, if there is less heat in the surface layer, it must be losing heat faster by back radiation and advection than it is gaining by direct radiation. If, as in May and July, there is no difference in heat content between the surface layer and the water below there must be a balance between heat gain and loss. In this case the transport of heat through the large density gradient of the surface layer becomes important.

November 1962

The average vertical profiles for October and November are shown in figure 12. The vertical distribution reveals a continued erosion of layer IIa, and a further loss of heat accompanied by a gain of salt in layer II. These changes are brought about by the continuation of the processes produced by an increasing flood tide density.

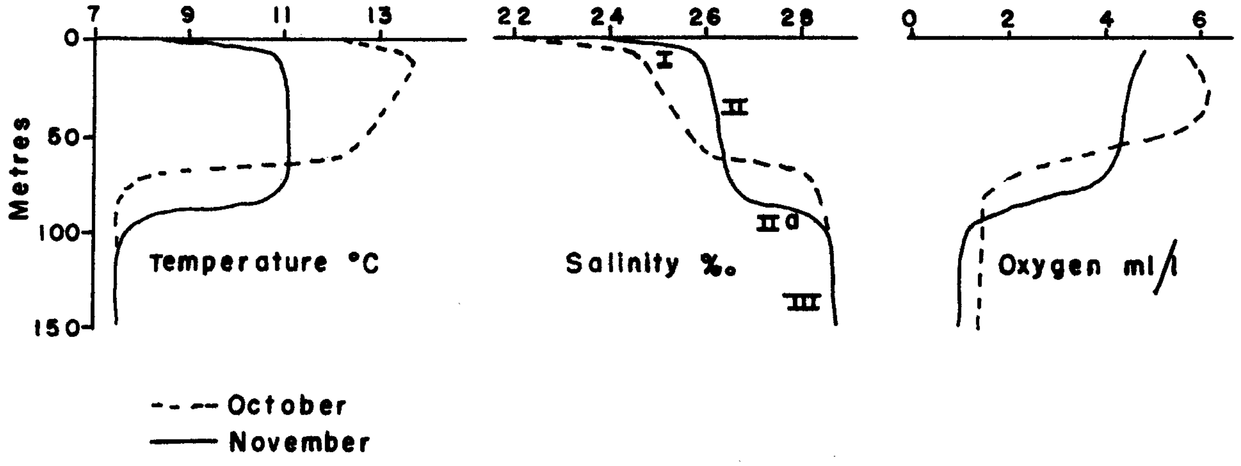


Figure 12. Average vertical profiles for Princess Louisa Inlet during October and November 1962.

January 1963

A comparison of the November 1962 and January 1963 profiles (figure 13) indicates a continued increase in the density of the flood tide water. Layer II which reflects the changes in flood tide characteristics shows a large heat loss, but a relatively minor gain

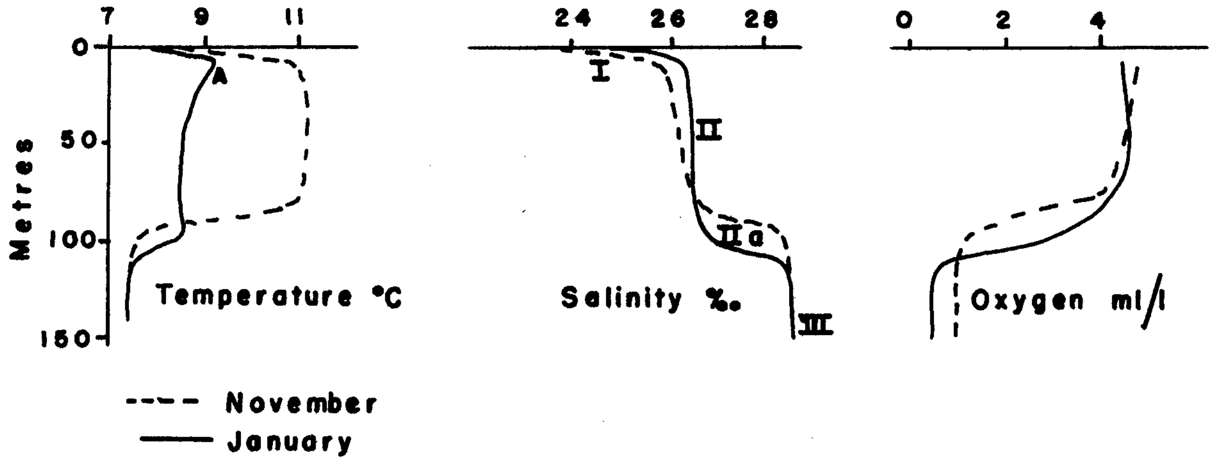


Figure 13. Average vertical profiles for Princess Louisa Inlet during November 1962 and January 1963.

in salinity. An interesting feature of the temperature profile for January is the maximum just below the surface runoff layer (A). The flood tide water which evidently has a lower temperature has sunk below this region leaving it with the higher temperature it had earlier in the year.

February 1963

The February profiles (figure 14) show two distinct, nearly uniform, regions in layer II with a slight oxygen minimum between them. These two regions are labelled IIb and IIc in figure 14. After the cruise in January the flood tide water continued to sink to the bottom of layer II and flow up inlet. The shear created by this flow forced an exchange in the properties between layer II and layer III. This continuous exchange increased the depth of the region affected by the flood tide water (layer II). The profiles slowly changed until they appeared as shown by the dotted lines. Then suddenly the density of the flood tide water decreased and floated near the surface. This sudden change in density created the steep gradients at 50 metres (figure 14). The change in flood water density was accompanied by a drop in both temperature and salinity.

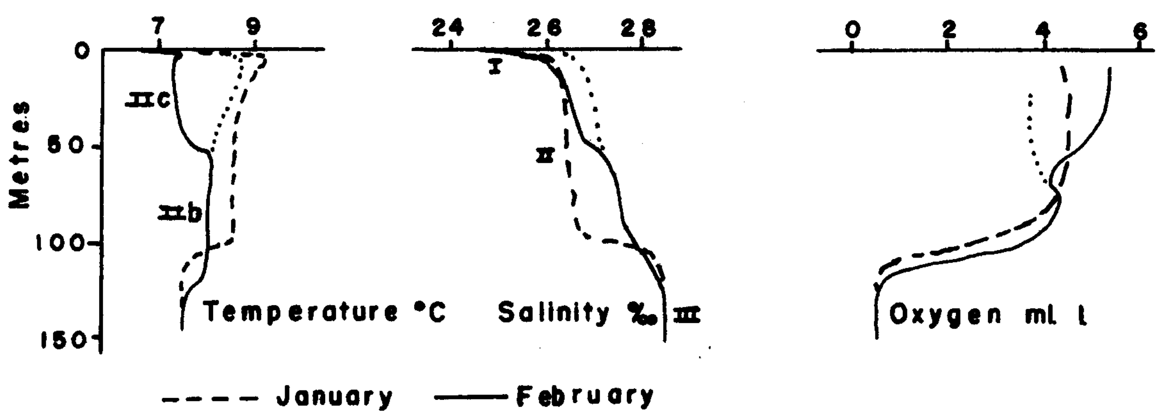


Figure 14. Average vertical profiles for Princess Louisa Inlet during January and February 1963.

A drop in temperature increases the density but a drop in salinity decreases the density. It is assumed that the effect of the salinity change is greater than the effect of the temperature change. The oxygen minimum lies just below the steep gradients at 50 metres, and therefore between the layers influenced by the tide water.

March 1963

The profiles (figure 15) indicate that the density of the flood tide water has decreased since February. The tidal jet has eroded the sharp gradients at 50 metres and extended its influence to 85 metres. Changes below this level are very slight, but greater than previously. Deep water changes are discussed in the next section.

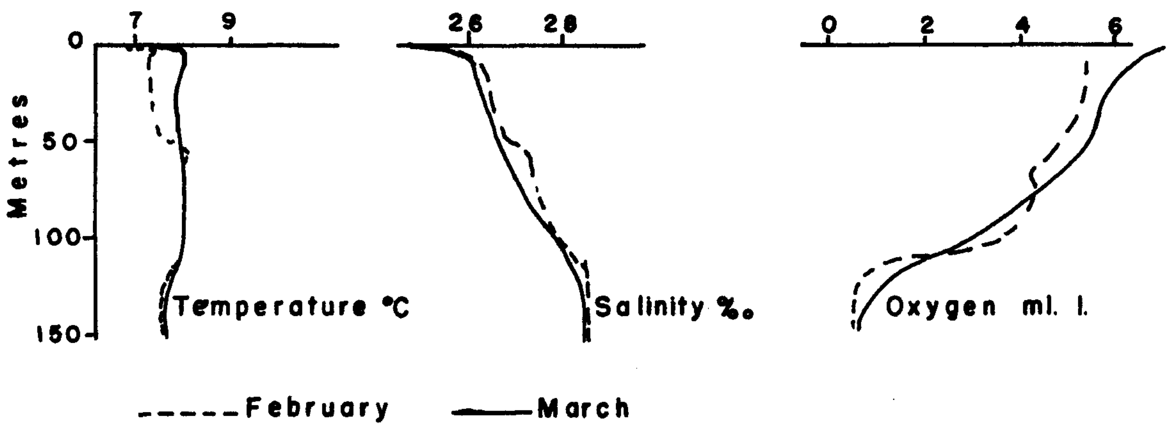


Figure 15. Average vertical profiles for Princess Louisa Inlet during February and March 1963.

The Deep Layer

In the preceding discussion very little was said about the changes of temperature and salinity occurring in the deep homogeneous water. Figure 16 shows the changes in temperature, salinity, and oxygen in this layer throughout the year. All observations taken in the deep layer were plotted on the same graph and the best curves drawn. Because the ordinate scales are greatly expanded the assumed error range for each variable is shown also. These error ranges apply to each observation individually, and to a single competent observer. The errors of measurement when observing the same water mass at different times and by different observers is not estimated. Thus the accuracy is assumed to be within the limits shown in figure 16, but the precision is not known. However, it is possible to draw quite smooth definite curves through the plotted points, and it is assumed that the error between cruises and observers is not appreciably different from the errors of an individual measurement. Thus the precision of the observations is assumed to be within the same limits of error as the accuracy of the observations.

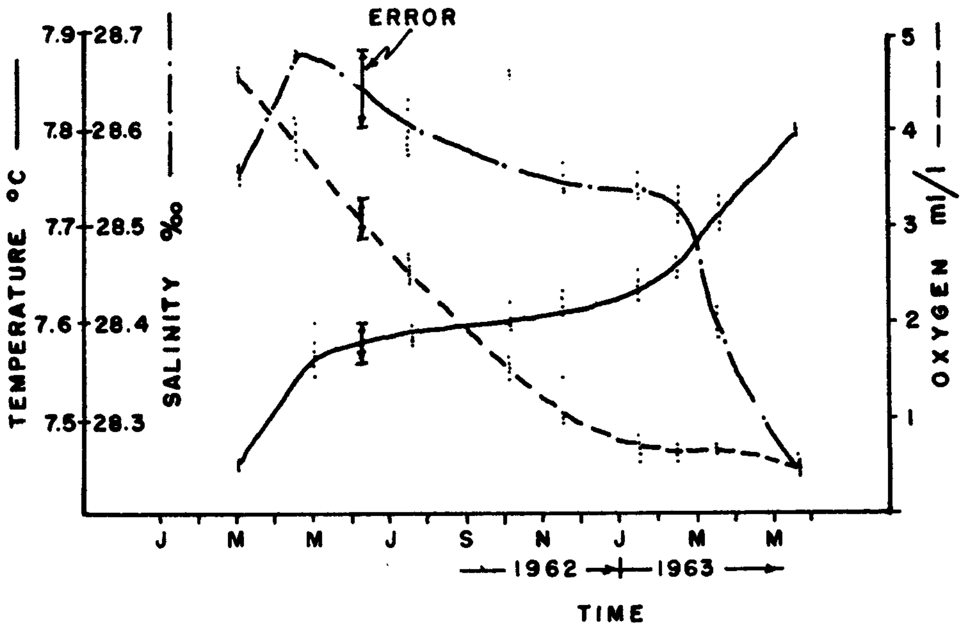


Figure 16. Temperature, salinity, and oxygen concentration in the deep layer of Princess Louisa Inlet plotted against time.

The salinity curve shows a sharp rise between March and May 1962 indicating the continued renewal of the deep water after the March cruise. From May to the following February the salinity decreased at a fairly uniform rate from a high of 28.67 to 28.51‰ in February 1963. From February to March 1963 the salinity dropped sharply to 28.38‰ . This is a drop of 0.13‰ in a month as compared to a drop of 0.16‰ in the previous nine months.

The temperature curve also shows a sharp rise between March and May 1962. This temperature rise which is accompanied by a salinity rise is attributed to continued turnover between March and May. From May 1962 to February 1963 the temperature rises uniformly from 7.56 °C in May to 7.66 °C in February. From February to March 1963 there is a rise of 0.07 C°.

After the density of the flood tide water started to decrease in the spring of 1962 the deep homogeneous layer was effectively cut off from the upper layers in the inlet. The gradients of temperature and salinity were such, throughout the year, that diffusion would slowly decrease the salinity and increase the temperature of the deep water, as observed between May 1962 and February 1963. The rapid rise of temperature and drop in salinity between February and March 1963 is thought to be due to increased diffusion during this time. This increased diffusion is attributed to the sinking of the flood tide water which would "stir up" the deep water to a greater degree than when the flood tide floats near the surface.

The oxygen curve in figure 16 shows a rapid decling from 3.9 ml/l in May 1962 to 0.5 ml/l in January 1963. This rapid decline is attributed to the oxygen demand of detrital material.

After January 1963 the oxygen content remained almost constant. This is thought to be a result of the increased exchange between the deep and intermediate waters caused by the sinking flood tide water.

The changes of all three variables between May 1962 and January 1963 appear to be a result of the relative isolation of the deep layer during these months. When the density of the tide water increases in the fall and winter the layer influenced by the tidal jet becomes thicker and exchange with the deep layer increases. This increased exchange between the deep and intermediate layers increases the rate of salinity decline and temperature gain, and decreases the rate of oxygen loss.

Figure 17 is the same as figure 2 with the addition of a line representing the change of density in the deep layer. Because salinity is the most important factor in determining density this line should be similar to the change of salinity with time as shown in figure 16. However, the ordinate scale in figure 16 is greatly expanded and the salinity curve appears as a straight line in figure 17. Because of diffusion the density of the deep water will

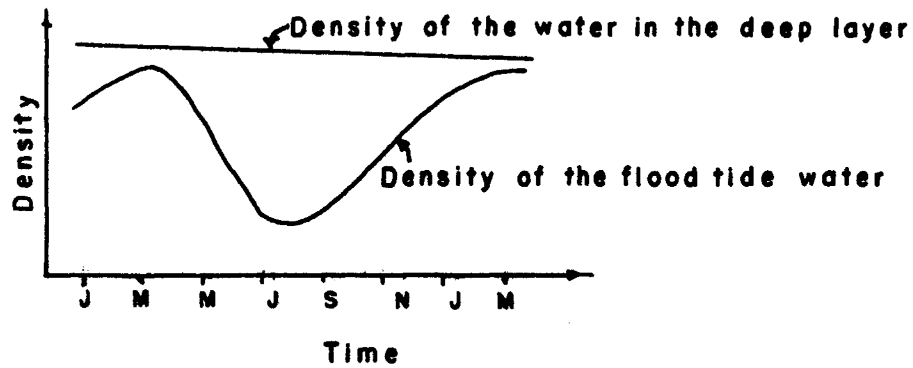


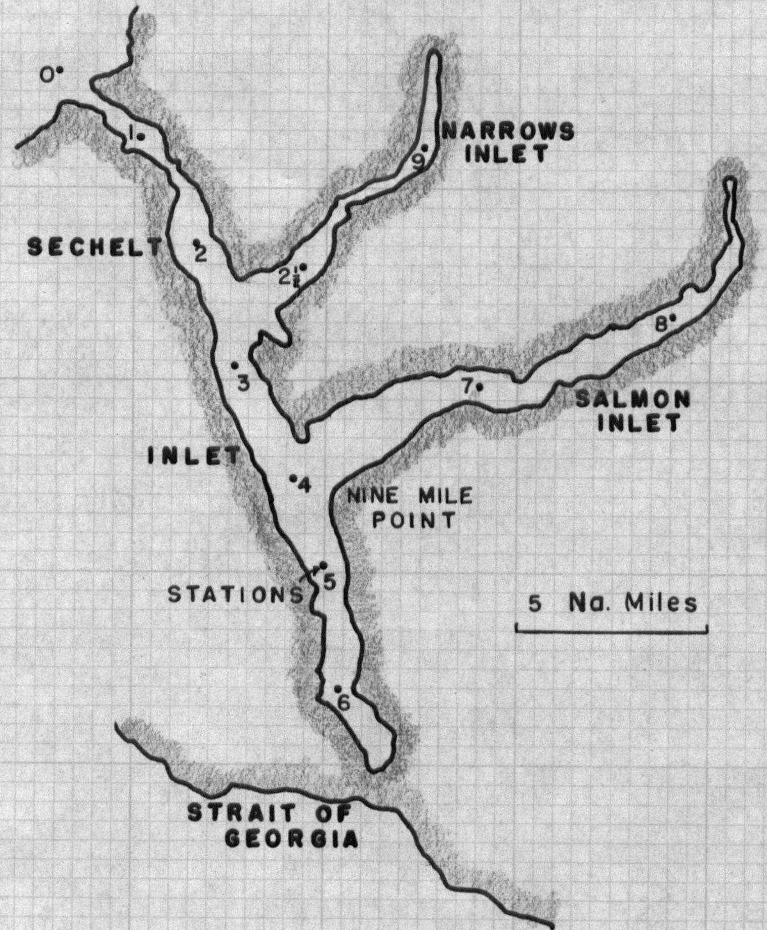
Figure 17. Comparison between the variation of flood tide density and deep water density with time.

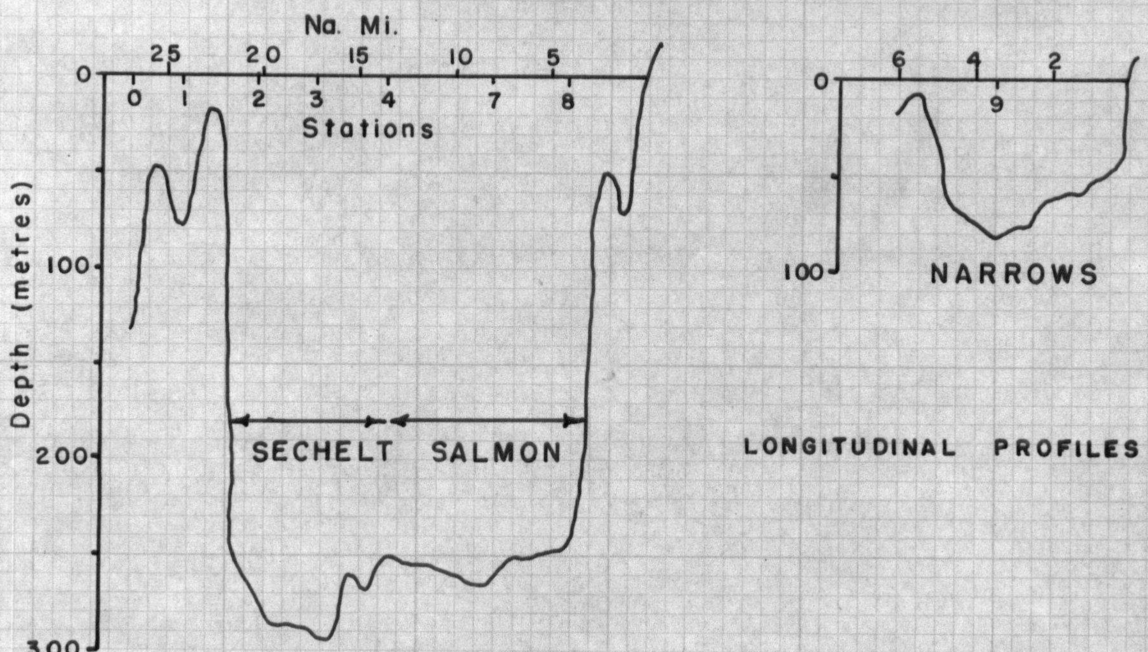
slowly decrease as observed. The density of the flood tide water will vary in the general manner shown. It is inevitable that the density of the tide water will someday become greater than the density of the deep water. When this occurs flushing will take place, as it did in the spring of 1962. However, the maximum density of the flood tide water is not the same each year, and the interval between each flushing is unpredictable. An abnormally high tide water density will cause flushing sooner than if normal conditions prevailed.

In order to predict the time of deep water flushing it is necessary to know when the density of the flood tide water will be greater than the density of all the water in the inlet. The annual variation of tide water density proposed in figure 2 is not accurate enough for this purpose. Short term variations in runoff, and current patterns in Jervis Inlet both affect the tide water density. These factors are unpredictable on a long term basis. However, if the density of the flood tide water could be compared with the density structure in the inlet it would be possible to predict to what depth the flood water would sink when it entered the inlet. Possibly the caretaker at the camp situated at the mouth of Princess Louisa Inlet could be persuaded to take samples of the flood tide water. The density of these samples could be correlated with meteorological data, specifically air temperature and rainfall. Changes in the current pattern and vertical density structure in Jervis Inlet may be predictable from wind vector data. It is proposed later in this thesis that an up inlet wind in Jervis increases the thickness of the surface layer. This may decrease the density of the tide water entering Princess Louisa. A prolonged

FIGURE 18

THE SECHELT INLET SYSTEM





LONGITUDINAL PROFILES

down inlet wind may bring denser water nearer the surface of Jervis, which would in turn increase the density of the flood tide water of Princess Louisa. Thus there may be a correlation between the wind vector in Jervis and the flood tide water density entering Princess Louisa Inlet. The variation of deep water salinity ($\propto$ density) in Princess Louisa Inlet for 1962 is shown in figure 16. Because the deep water was not flushed in the winter of 1962-63 this curve only represents part of the salinity variation between flushings. It will be necessary to monitor the density of the deep water until the next flushing to understand the complete cycle. The decrease in salinity of the deep water will depend on the vertical salinity gradient in the basin. During 1962 the salinity of the deep layer was nearly uniform and the decrease throughout the year was as shown in figure 16. In 1963 there will be, judging from the March 1963 profiles, a steeper salinity gradient during the year. The density of the deep water may decrease more rapidly in 1963 than in 1962.

Sechelt Inlet System

The plan of the Sechelt Inlet system and the longitudinal profiles of the basins are shown in figure 18. The system is comprised of Sechelt, Salmon, and Narrows Inlets. The water in the system communicates with that of Jervis over a shallow sill at Skookumchuck Narrows. In the discussion below Sechelt and Salmon Inlets are treated as one inlet. The tip of Sechelt extending from Nine Mile Point to Porpoise Bay is neglected, because it receives only a small proportion of the runoff which enters the system. Narrows Inlet is treated separately since its basin is separated from Sechelt Inlet by a shallow sill.

The circulation pattern proposed earlier for the shallow silled inlets results in the distributions of temperature, salinity and oxygen being very similar in Princess Louisa and Sechelt Inlets. The greater size of the Sechelt - Salmon system allows larger horizontal gradients to exist, and the inlet can not be treated as a single column of water at all times.

The following cruise by cruise discussion of the data is given with the proposed mechanisms in mind.

July 1961

The average vertical temperature and salinity profiles for July 1961 are given in figure 19 with the longitudinal profile of dissolved oxygen. The longitudinal profiles of temperature and salinity are not shown because the horizontal gradients of these variables are so small in comparison to the vertical gradients. The temperature, and salinity distribution clearly divides the water column into three layers. The top layer (layer I) extending to 5 metres is formed from runoff water and is characterized by relatively low salinity and high temperature. The high temperature of this layer is due to the greater influx of heat, from direct solar radiation, than loss of heat by back radiation and advection out of the inlet of sensible heat. The intermediate layer (layer II) lying between 5 and 65 metres is the region most strongly influenced by the character of the flood tide water. The linear gradients of temperature and salinity in layer II are attributed to the shear created

Figure 19. Temperature, salinity, and dissolved oxygen distributions in Sechelt Inlet during July 1961.

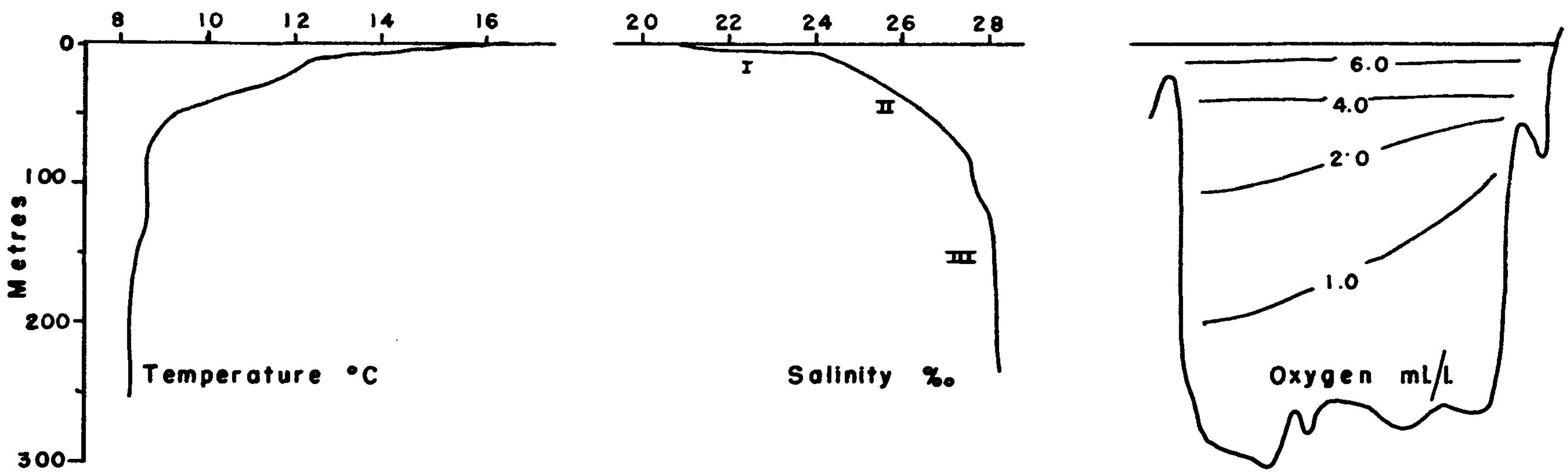
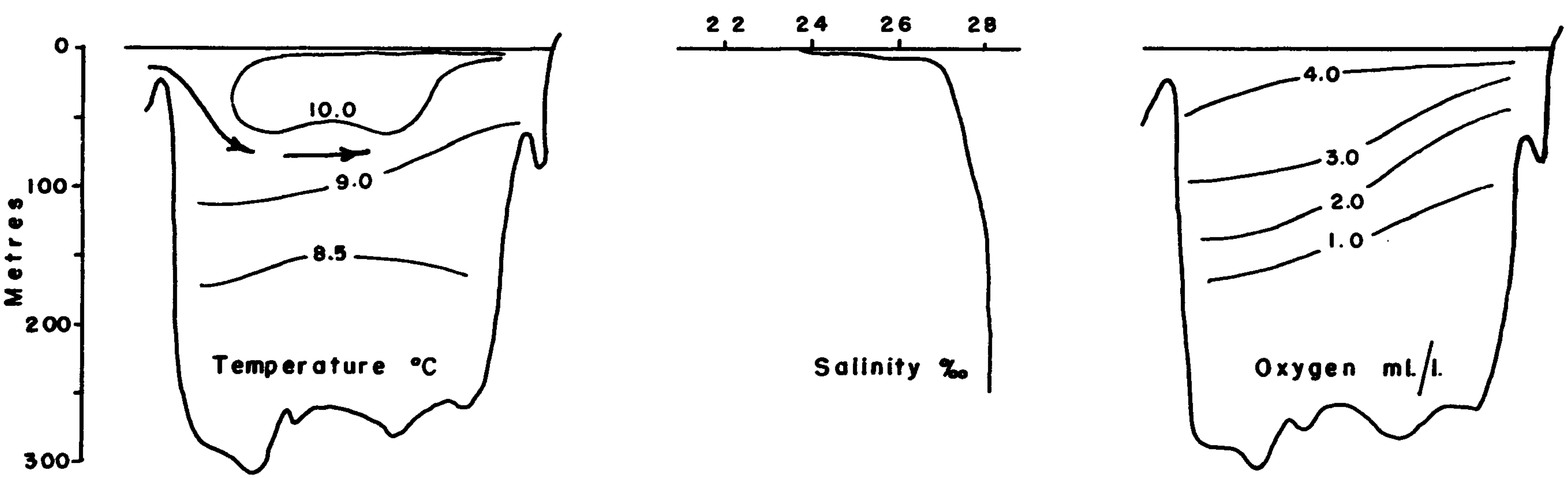


Figure 20. Temperature, salinity and dissolved oxygen distribution in Sechelt Inlet during November 1961.



between the up inlet flow of tide water and the compensating mid-depth down inlet flow. This process was discussed more fully on page 7 . The oxygen content of the water in the deep layer (layer III) is less than 1.0 ml/l. This is considered low and attributed to stagnant conditions. The water in this layer is below the layer of tidal influence and is effectively cut off from advection of highly oxygenated water. Oxidation of organic matter in this isolated zone will continue to reduce the oxygen concentration until the water is replaced by flushing. The temperature and salinity of the water in layer III is not uniform, but displays slight changes in gradient between 65 and 125 metres. This "structure" is thought to be a remnant left by incomplete flushing in the previous winters. See pages 8 and 9 .

November 1961

It has been assumed (page 5) that the density of the flood tide water increases with time in the autumn. As a result, the tide water sinks to intermediate levels and produces the current pattern proposed on page 9 . The profiles for November 1961 (figure 20) indicate some of the symptoms of this motion. The flood tide water, characterized by low temperature and high oxygen concentration, has sunk to an intermediate level upon entering the inlet. This water has subsequently moved up inlet, pushing before it the indigenous low-temperature, low-oxygen water, which rises near the head of Salmon Inlet. The arrows drawn on the longitudinal temperature profile (figure 20) represent this flow. The effect of this movement is to produce a water mass of high oxygen concentration and low temperature near the mouth, and a mass of low-temperature, low-oxygen

Figure 21. Temperature, salinity and dissolved oxygen distribution in Sechelt Inlet during March 1962.

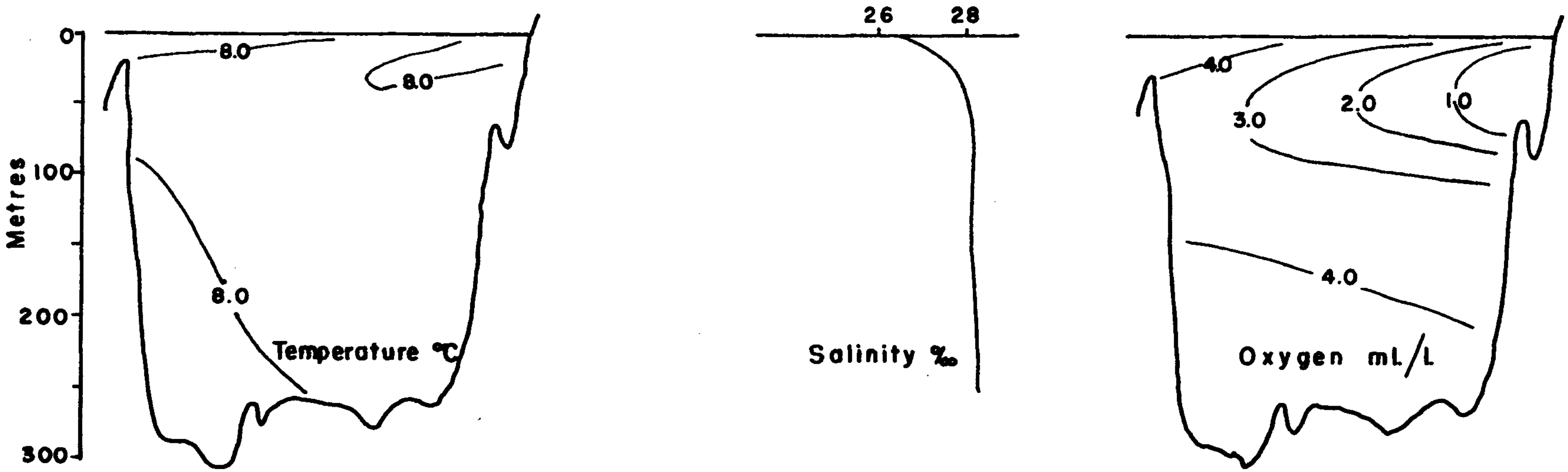
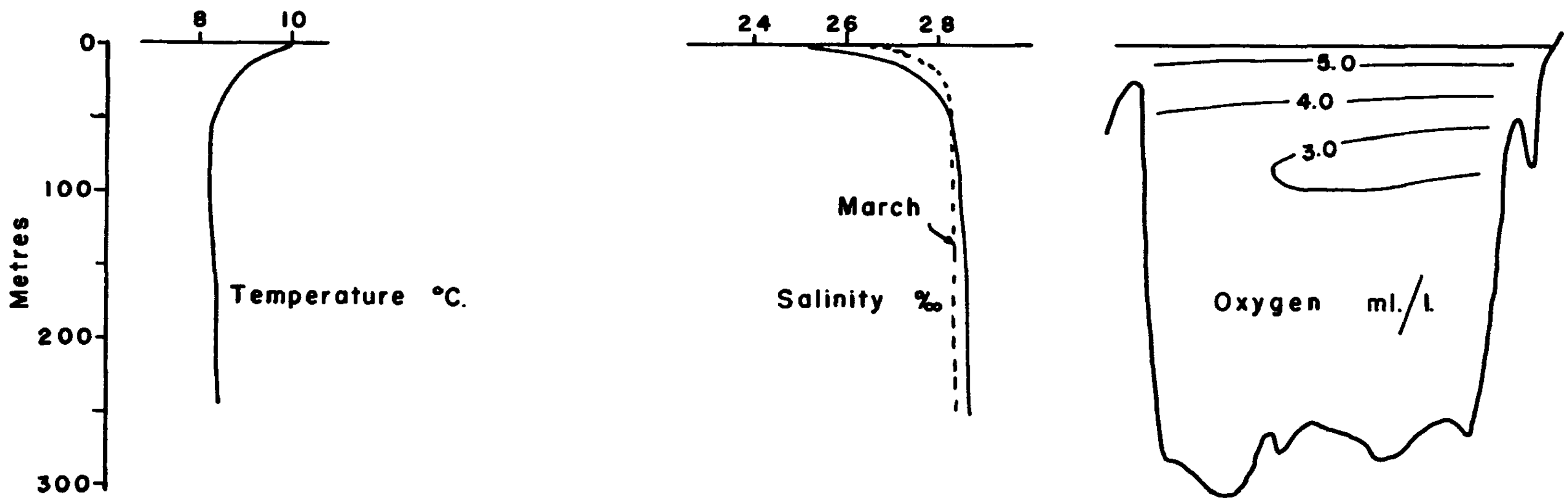


Figure 22. Temperature, salinity and dissolved oxygen distribution in Sechelt Inlet during May 1962.



water near the head. The 10 °C isotherm defines, in the body of the inlet, the water least affected by this movement.

March 1962

The longitudinal oxygen profile shown in figure 21 indicates that flushing of the deep water is in progress. The oxygen concentration in the deep layer has increased by 3.5 ml/l since November 1961. This increase could only be produced by advection into the region of highly oxygenated flood tide water. The water replaced by this inflow has been pushed up and towards the head of the inlet to form an oxygen minimum layer centred at 50 metres.

May 1962

The average vertical profiles for March and May are compared in figure 22. The 0.3‰ increase of salinity in the deep water is due to continued flushing after the March cruise. This prolonged flushing has caused most of the water which formed the oxygen minimum in March to leave the inlet. However, there still exists a slight minimum at 50 metres. The oxygen content in the deep layer has decreased by about 0.3 ml/l since March, indicating that the flushing of this region has ceased. When the deep flushing stops, the influence of the flood tide is limited to the surface layers again, and the oxygen concentration in the deep layer decreases due to the oxygen demand of detrital material.

July 1962

The profiles for July 1962 (figure 23) are similar to profiles for July 1961 (figure 19) except that the oxygen concentration in the deep zone is about 3 ml/l higher in July 1962. The data for March and May 1962 indicated flushing of the deep water

Figure 23. Temperature, salinity and dissolved oxygen distribution in Sechelt Inlet during July 1962.

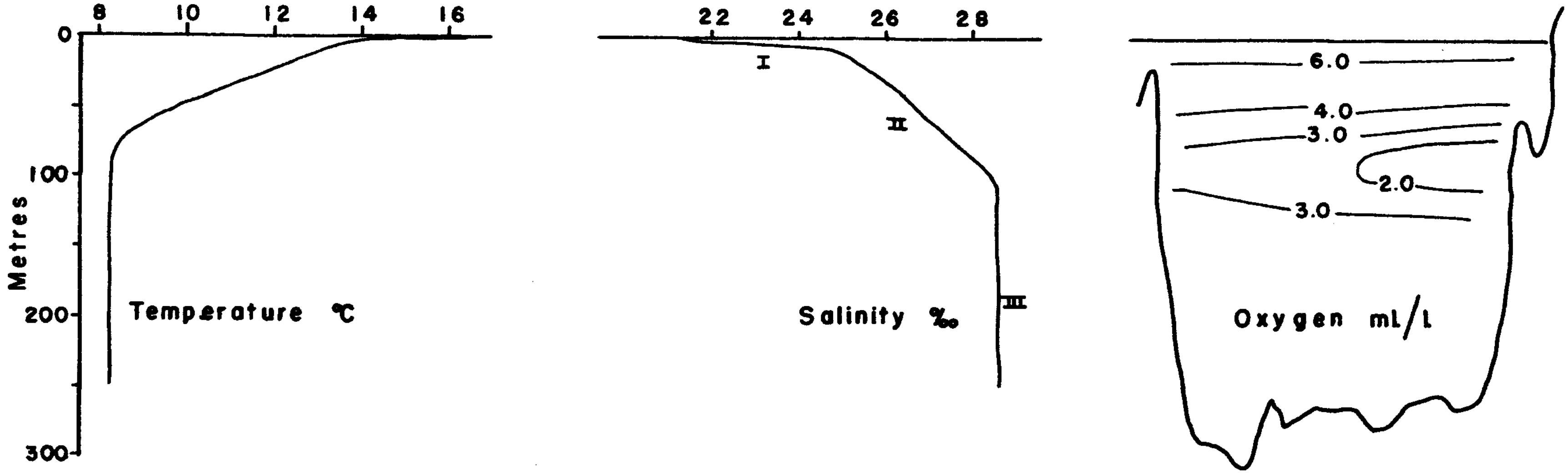
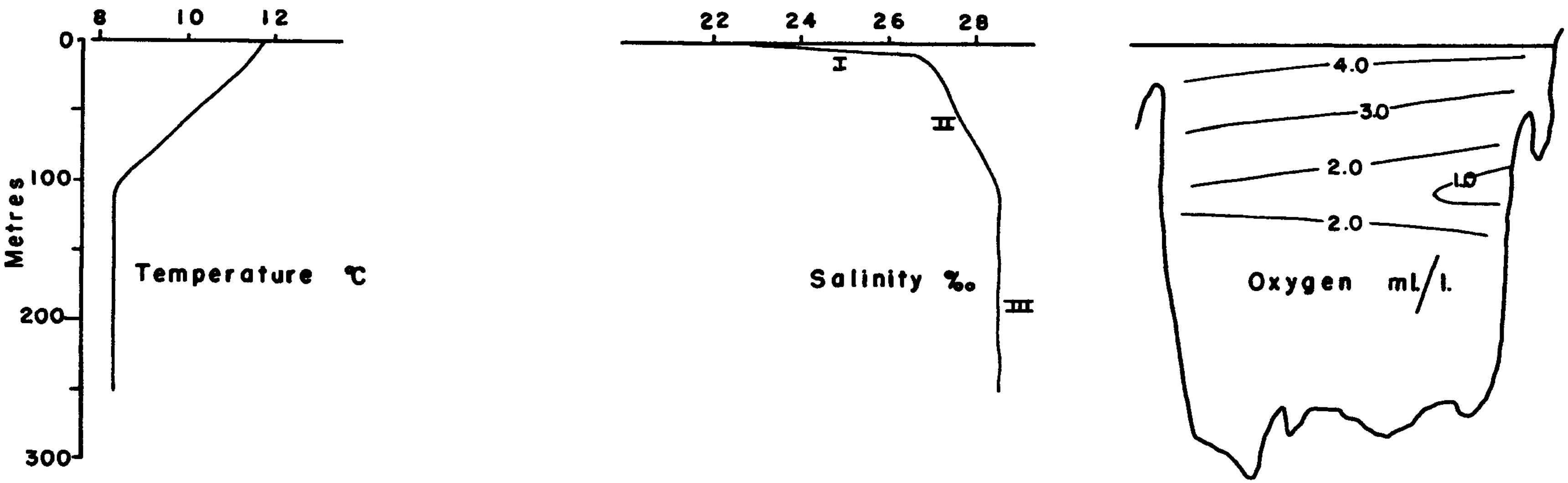


Figure 24. Temperature, salinity and dissolved oxygen distribution in Sechelt Inlet during October 1962.



during the winter of 1961-62. The high oxygen values in the deep layer in July 1962 are indicative of this recent flushing. The low oxygen values in the deep layer in July 1961 indicate that flushing has not occurred for a considerable time prior to this cruise.

October 1962

As observed previously the increasing density of the flood tide water in the autumn months is accompanied by a loss of heat, and gain of salt in layer II. At this time the layer influenced by the tidal jet (layer II) becomes thicker due to increased exchange with the deep zone. These changes are observed in the October profiles (figure 24) when compared to the July profiles (figure 23). Notice also the oxygen minimum, just under layer II, which was formed during the flushing in the winter of 1961-62.

November 1962

The November 1962 data presents "the exception to the rule". Comparison of the average vertical profiles for October and November (figure 25) shows a decrease in salinity in layer II instead of an increase which would be expected if the flood tide density was increasing. The vertical temperature profiles for stations near the head, middle, and mouth of the inlet are given in figure 27. These profiles emphasize the temperature decrease accompanying the salinity decrease. The profiles for the middle and head show a temperature maximum at 40 metres. The layer above this maximum has cooled considerably due to the relatively cool tide water moving up inlet near the surface and mixing with the underlying water. The cooling of the upper 40 metres is most likely not due to wind mixing. The temperature and salinity in a wind mixed layer is

Figure 25. Temperature, salinity and dissolved oxygen distribution in Sechelt Inlet during November 1962.

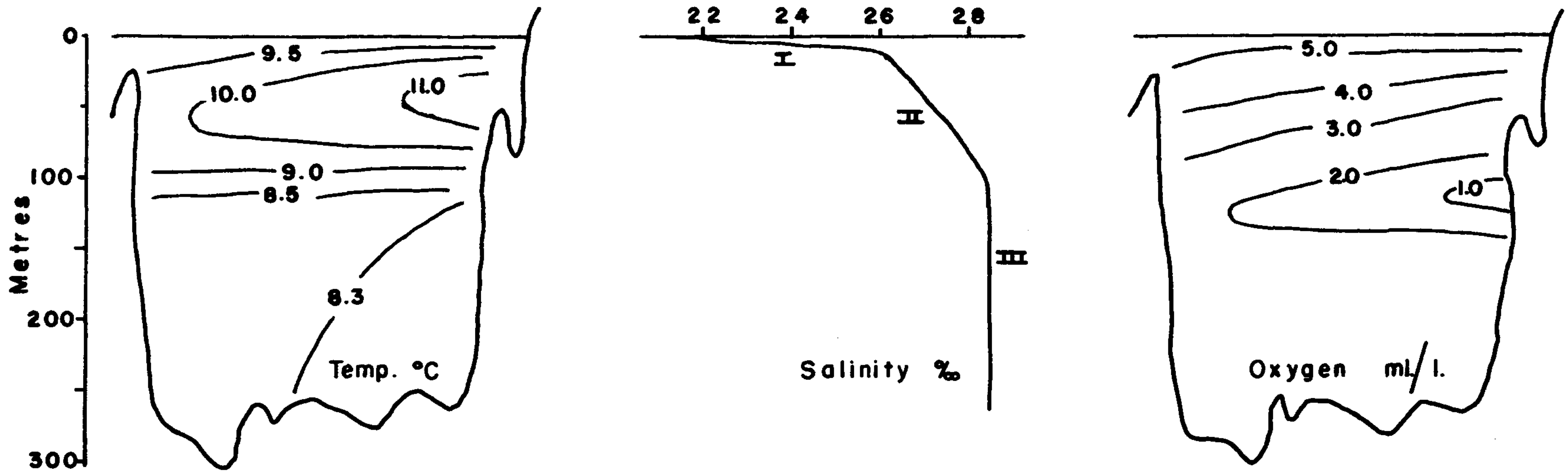
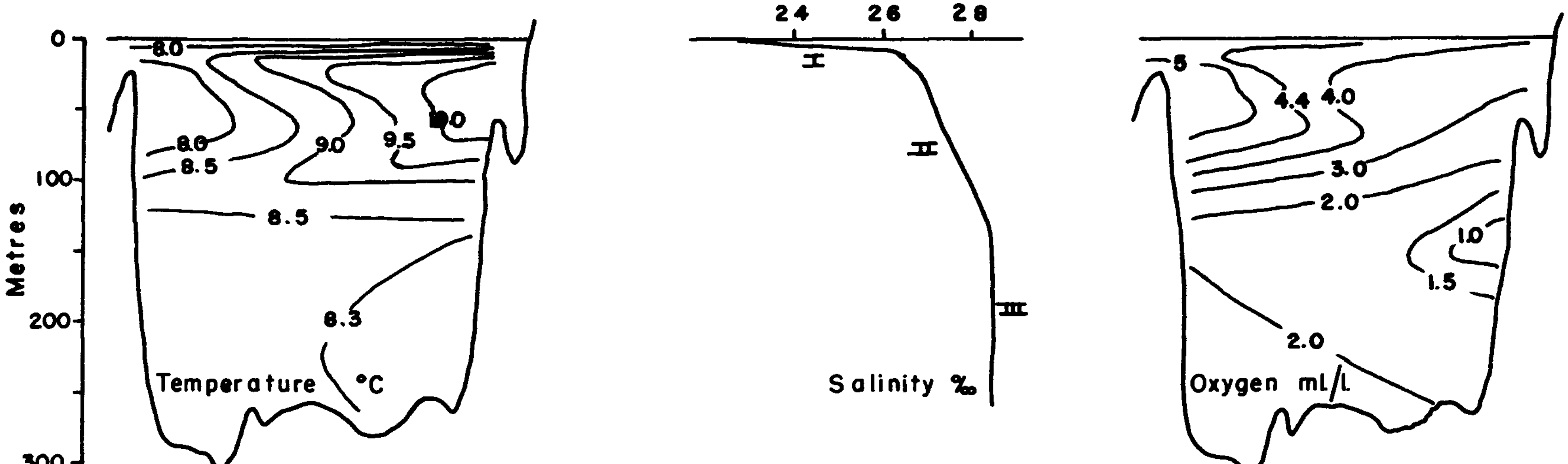


Figure 26. Temperature, salinity and dissolved oxygen distribution in Sechelt Inlet during January 1963.



more uniform than observed here. The body of water near the mouth, which is nearly homogeneous with respect to temperature is a product of the tidal jet.

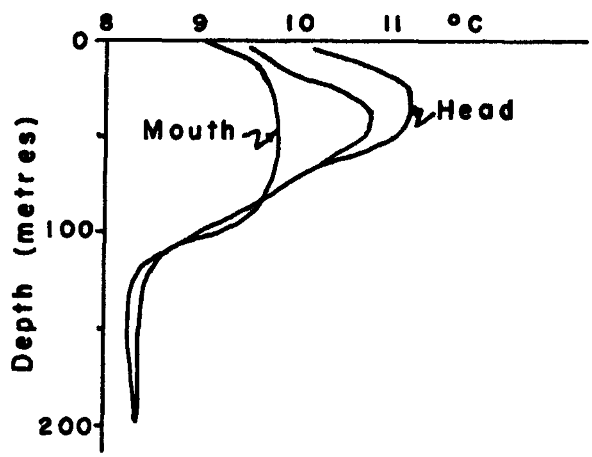


Figure 27. Vertical temperature profiles near the head, middle and mouth of the Sechelt-Salmon Inlet system during November 18th 1962.

January 1963

The January profiles shown in figure 26 exhibit the most convincing data in favour of a mid-depth intrusion of flood tide water which subsequently moves up inlet. The longitudinal profiles of temperature, and oxygen show a very pronounced tongue of homogeneous low-temperature high-oxygen water near the mouth. This homogeneous water, which is the end result of the tidal jet, is flowing up inlet. Because of its density, most of this layer lies below the threshold depth of the sill, and the ebb tide will be composed of the water above. Vertical profiles at the head and mouth, of temperature and oxygen, are shown (figure 28) to emphasize the homogeneity of the tidal water and the up inlet flow. The two low-temperature "bumps" A and B in the temperature profile correspond

Figure 29. Temperature, salinity and dissolved oxygen distribution in Sechelt Inlet during February 1963.

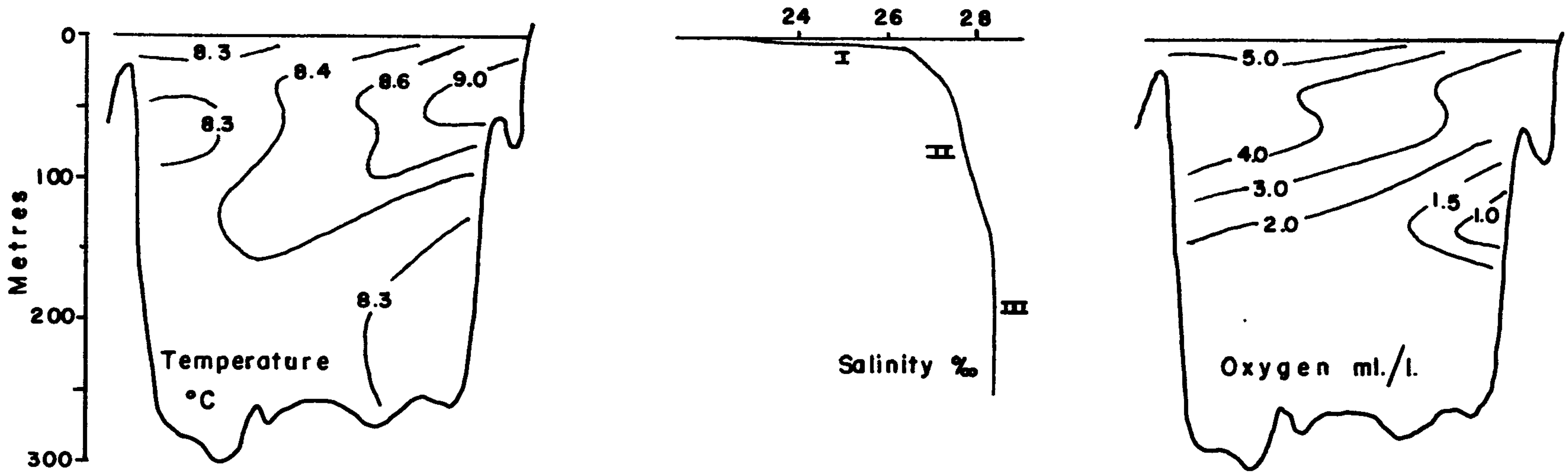
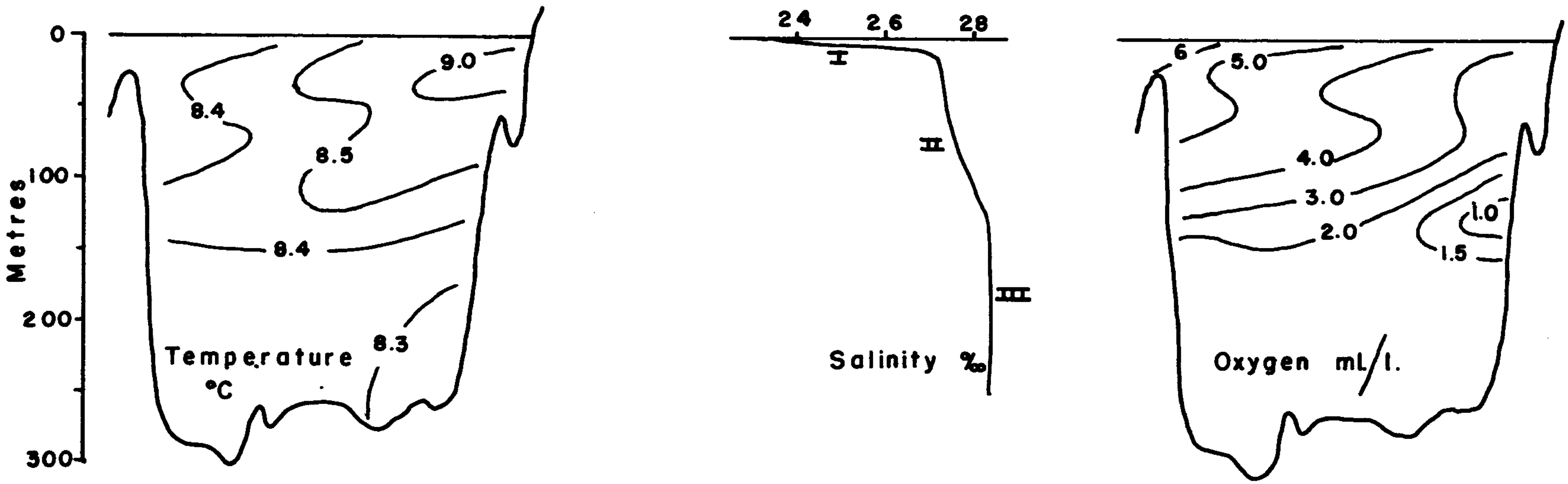


Figure 30. Temperature, salinity and dissolved oxygen distribution in Sechelt Inlet during March 1963.



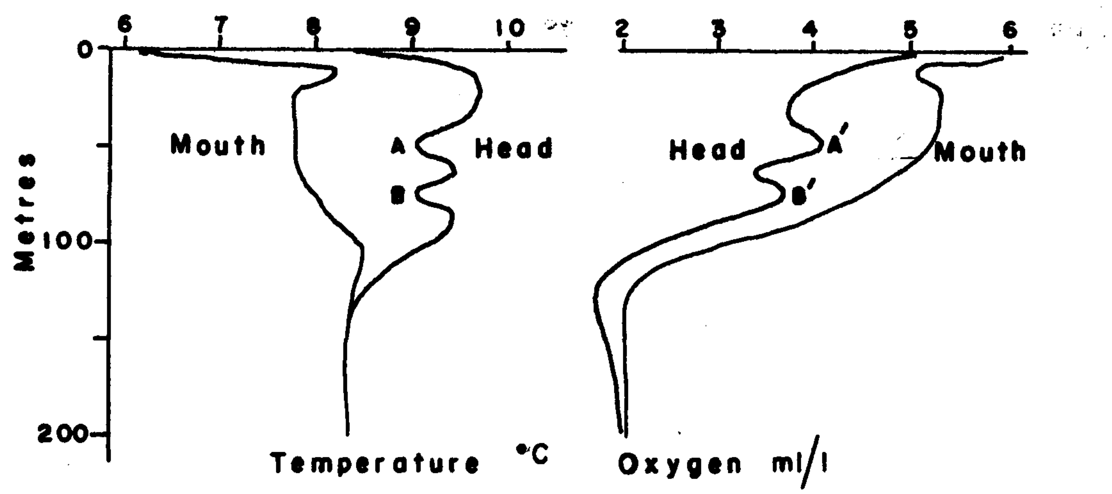


Figure 28. Temperature and oxygen profiles near the head and mouth of the Sechelt-Salmon Inlet system during January 20th, 1963.

exactly with the high oxygen "bumps" A' and B' in the oxygen profile. The water in the layer defined by these "bumps" has moved up inlet in thin "sheets". Each sheet is probably produced by a different tide, and exhibits slightly different density.

February 1963

The February profiles (figure 29) show the same processes that were dominant in January, but not so spectacularly. The longitudinal plots of temperature and oxygen show tongues of low-temperature high-oxygen water intruding up inlet at about 50 to 75 metres.

March 1963

The March profiles (figure 30) display very little that was not evident in the January and February distributions. Mid-depth intrusions are evident in the temperature and oxygen profiles. The

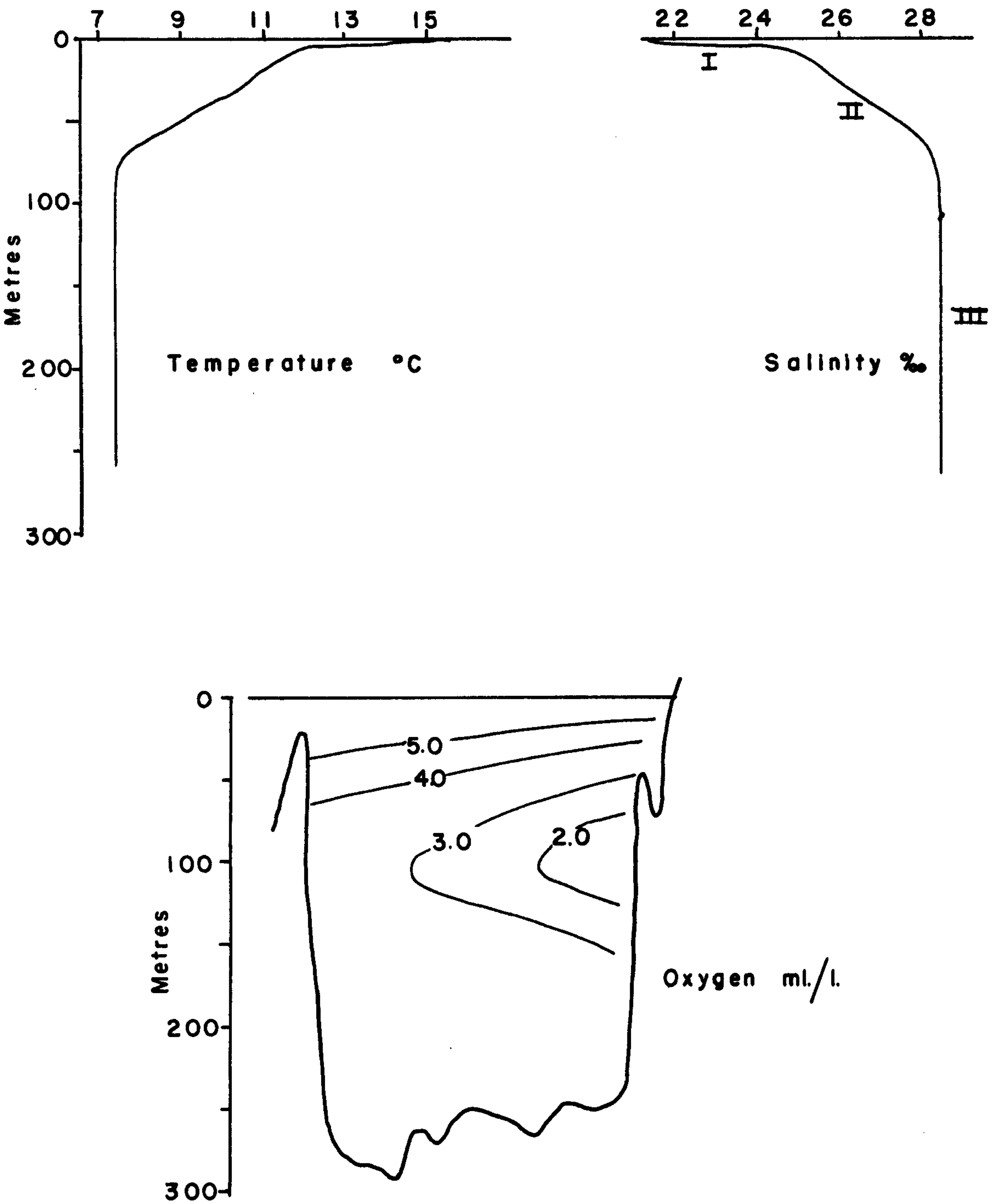


Figure 31. Temperature, salinity and dissolved oxygen distribution in Sechelt Inlet during July 1957.

salinity and thus density of the water in layer II is greater in March as shown in the comparison between the two months.

July 1957

The first cruise to the Sechelt - Salmon Inlet system was in July 1957. The data (figure 31) are given out of chronological order because they were taken four years before the continuous series. Notice how similar the profiles for July 1957 (figure 31) are to the profiles for July 1962 (figure 23). Because of this similarity it is assumed that the previous history of each distribution is the same. Layer I is due to runoff and layer II is the region influenced by the tidal jet. The water in layer III is nearly uniform with respect to temperature and salinity, while the oxygen content of this deep zone is relatively high. This high oxygen is attributed to recent flushing, most likely in the winter of 1956-57. The oxygen minimum at 100 metres was reported by Pickard (1961). It is believed to be a remnant of the old low-oxygen deep water that was lifted up by a recent intrusion of water that flushed the deep zone.

Narrows Inlet

Narrows Inlet (figure 18) is partially separated from Sechelt Inlet by a shallow sill at Tzoomie Narrows. The Inlet is about 5¼ miles long and ½ mile wide. The greatest depth in the inlet is only about 85 metres, and therefore it is the shallowest inlet in the Jervis Inlet system. The annual variations in the temperature, salinity, and oxygen distributions are very similar to those in Princess Louisa and Sechelt Inlets. It is thought that the current patterns proposed previously are valid in Narrows Inlet.

The vertical temperature, salinity, and oxygen profiles divide the water column into three distinct layers. The runoff layer of relatively low salinity water occupies the top 5 to 10 metres. Below the surface layer is the region affected by the tidal jet. The thickness of this intermediate layer is usually about 50 metres. The water in the inlet below the influence of the tidal jet occupies the third layer. This is the deep layer, usually characterized by a uniform temperature and salinity. Because the inlet is so shallow the deep layer is thin and sometimes is hard to detect. The vertical temperature salinity, and dissolved oxygen profiles for the only station in the inlet are shown in figure 32 for ten cruises between July 1961 and March 1963. These profiles are discussed below.

July 1961

The surface (layer I), intermediate (layer II), and deep (layer III) layers are evident in the temperature and salinity distributions for July 1961. The almost linear salinity and temperature gradients in layer II are attributed to the shear

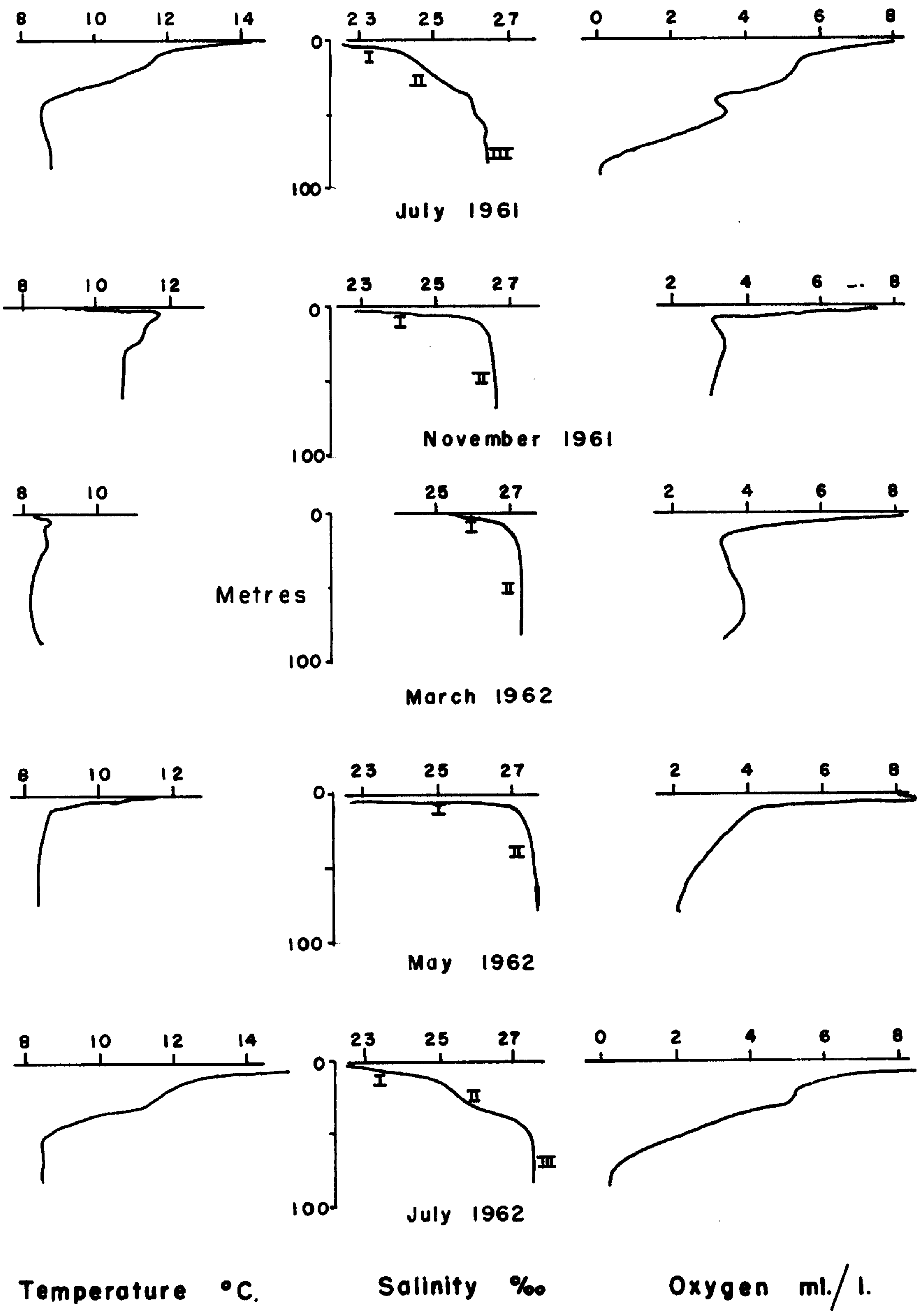


Figure 32. Vertical profiles of temperature, salinity, and dissolved oxygen in Narrows Inlet.

between the up inlet flow of tide water and the down inlet flow of deeper water. The deep layer was relatively stagnant resulting in a low oxygen concentration. The slight oxygen maximum at 50 metres, if real, may be due to the tide water flowing up inlet at mid-depths.

November 1961

Layers I and II were present in November 1961 but the data does not extend to the bottom of the inlet and layer III is not apparent. The water in layer II was more uniform with respect to temperature, salinity, and oxygen than in July 1961. Also, the density of the water in this layer was greater in November. These changes are indicative of an increasing tide water density. Instead of flowing up-inlet near the top of layer II, the tide water seeks an intermediate level, thereby displacing upward the upper water in layer II.

March 1962

The data taken in March 1962 extends to the bottom of the inlet. The density of the water in layer II was greater than previously, and the oxygen content of the deep water was much higher. It is believed that the tide water sank right to the bottom of the inlet and flushed out the old low oxygen water.

May 1962

The profiles for May 1962 are very similar to those of March but the salinity in layer II was greater. This increase is indicative of continued flushing of the deep water after the March cruise. The oxygen content of the deep water is lower because of oxygen demand.

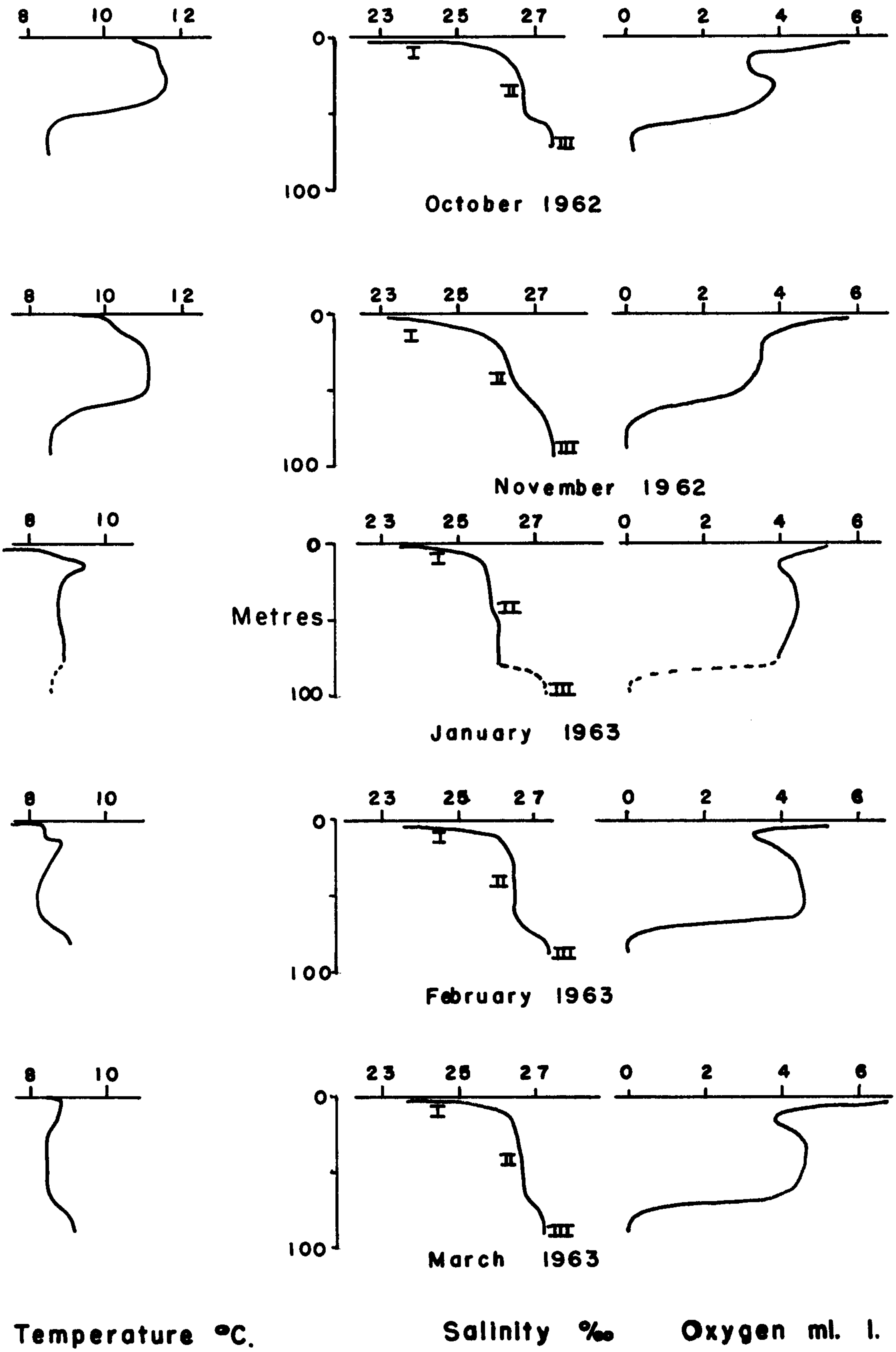


Figure 32. (continued) Vertical profiles of temperature, salinity, and dissolved oxygen in Narrows Inlet.

July 1962

The profiles for July 1962 are very similar to those for July 1961. The water in layer III was denser in 1962 because of the flushing in the winter of 1961-62. The oxygen content in the lower part of the deep layer was nearly zero which was a drop of about 3.5 ml/l since March. This large oxygen demand may be due to a reducing environment on the bottom; a result of undecomposed detritus falling from the surface layers.

October 1962

The vertical profiles for October 1962 indicate that the density of the tide water was increasing with time. This water seeks an intermediate level after entering the inlet. This resulted in highly oxygenated water intruding between 30 and 50 metres. This intrusion is evident in the oxygen maximum at 30 metres.

November 1962

The November 1962 profiles are similar to the October profiles except the characteristics of the water in layer II changed slightly. This change was due to a change in the characteristics of the tide water entering the inlet.

January 1963

During the cruise in January 1963 most of the inlet was blocked by thin ice. It was impossible to occupy the usual station and the data obtained does not extend into the deep zone. By extrapolation between the November 1962 and February 1963 data the dotted lines are drawn on the January 1963 profiles to represent the deep water characteristics. The profiles show that the density of the water in layer II has decreased since November, while the oxygen content has increased. Because the water in layer II is strongly influenced by the tide water, these changes are due to variations in the tide water characteristics.

February 1963 and March 1963

The vertical profiles for February and March 1963 are very similar and show little change since January 1963. The oxygen minimum centred at 10 metres in January, February, and March is thought to be due to the upward displacement of low oxygen water by the intermediate intrusion of tide water.

III DEEP SILLED INLETS

Jervis Inlet

The general features of Jervis Inlet have been described in the Introduction. Because of the deep sill in the inlet it is assumed that the general circulation pattern is estuarine in character. Thus the tidal flow does not noticeably affect the vertical density stratification in the inlet. In the following description of the data emphasis is placed on the difference in the temperature, salinity, and dissolved oxygen distributions between two cruises. It is assumed that, if two points A and B (say) are characterized by different properties, a flow from A to B between two cruises will be revealed by finding the properties of A at B on the later cruise. In this way a rough idea of the net circulation between two cruises can be found. It is concluded that an estuarine circulation is not always the dominant circulation pattern in the inlet. An estuarine circulation is caused and controlled by the amount of surface runoff. Because the surface runoff in Jervis Inlet is relatively small, other factors, such as changes in the meteorological and oceanographic conditions in the area, will produce flows that dominate the estuarine circulation.

March 1962

The average vertical profiles of temperature and salinity for March 1962 are shown in figure 33. The longitudinal profile of oxygen content (figure 33a) is given to emphasize the oxygen minimum situated at mid-depth near the head of the basin.

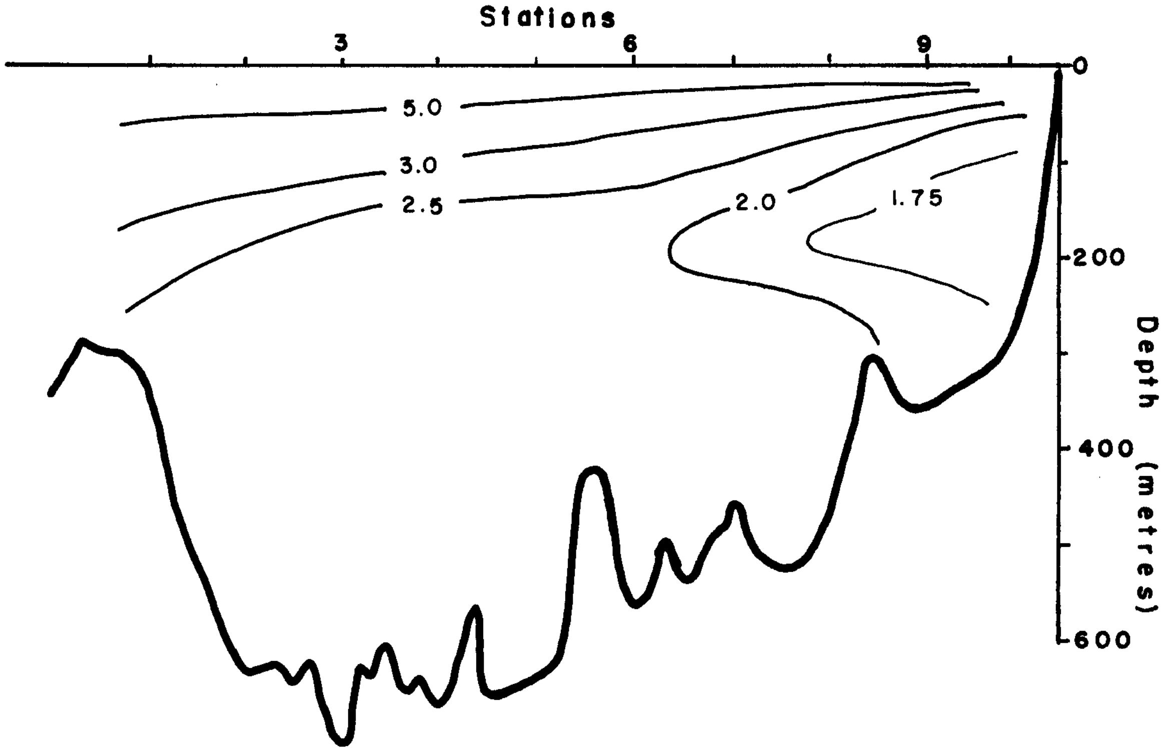


Figure 33a. Longitudinal section of dissolved oxygen in Jervis Inlet during March 1962.

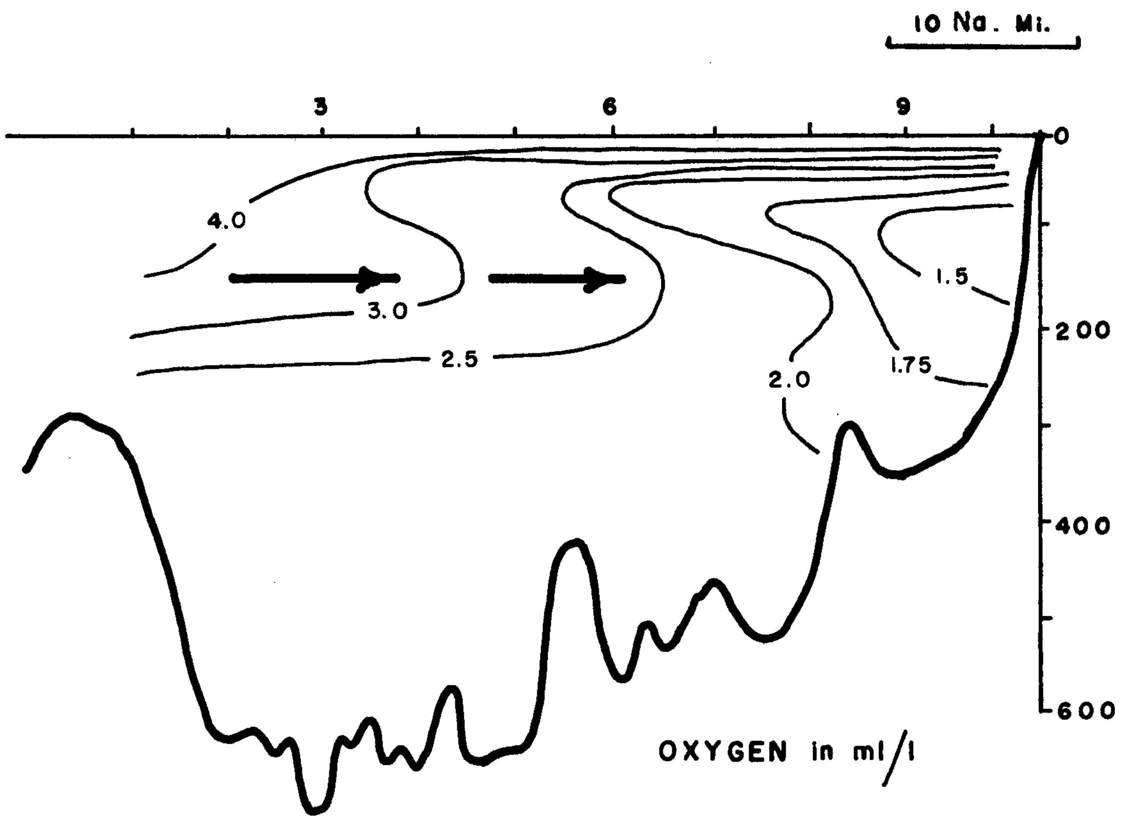


Figure 34a. Longitudinal section of dissolved oxygen in Jervis Inlet during May 1962.

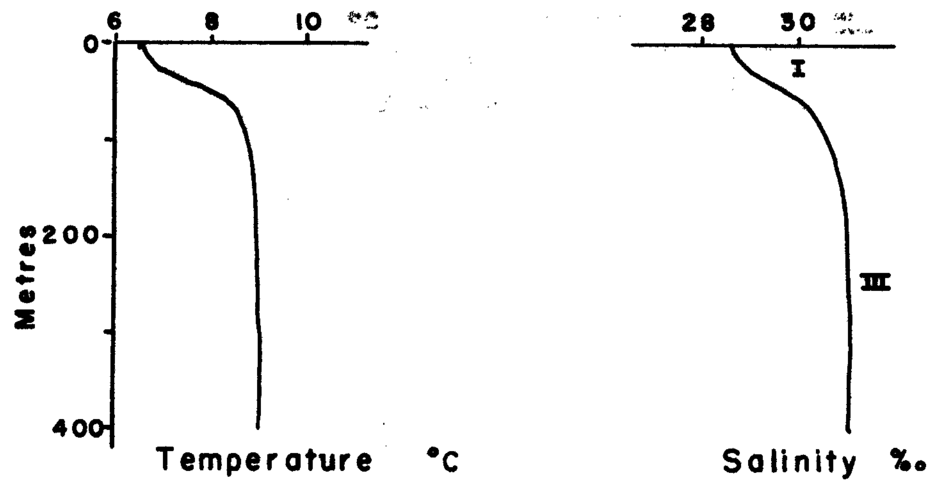


Figure 33. Average vertical profiles of temperature and salinity for Jervis Inlet during March 1962.

The surface layer (layer I) is defined by relatively low temperature and low salinity. The water below 150 metres (layer III) is nearly homogeneous with respect to temperature and salinity. The transition in water properties between the surface layer and the deep homogeneous layer is gradual, and the depth assigned to the surface layer is somewhat arbitrary. Loss of heat from the surface water by radiation, and dilution by runoff water are the causes of the low temperature and low salinity of the surface and intermediate layers. It is difficult to understand why the depth of this influence is so great. For example, the surface layer in Princess Louisa and Sechelt Inlets never becomes greater than 15 to 20 metres, while in Jervis it is 30 to 50 metres (figure 33) with noticeable influence up to 150 metres. This problem is discussed further on page 46.

The oxygen minimum centred at 200 metres at the head of the basin is defined by the water containing less than 2 ml/l of oxygen. This minimum layer is a characteristic feature of this inlet, having been observed during every visit.

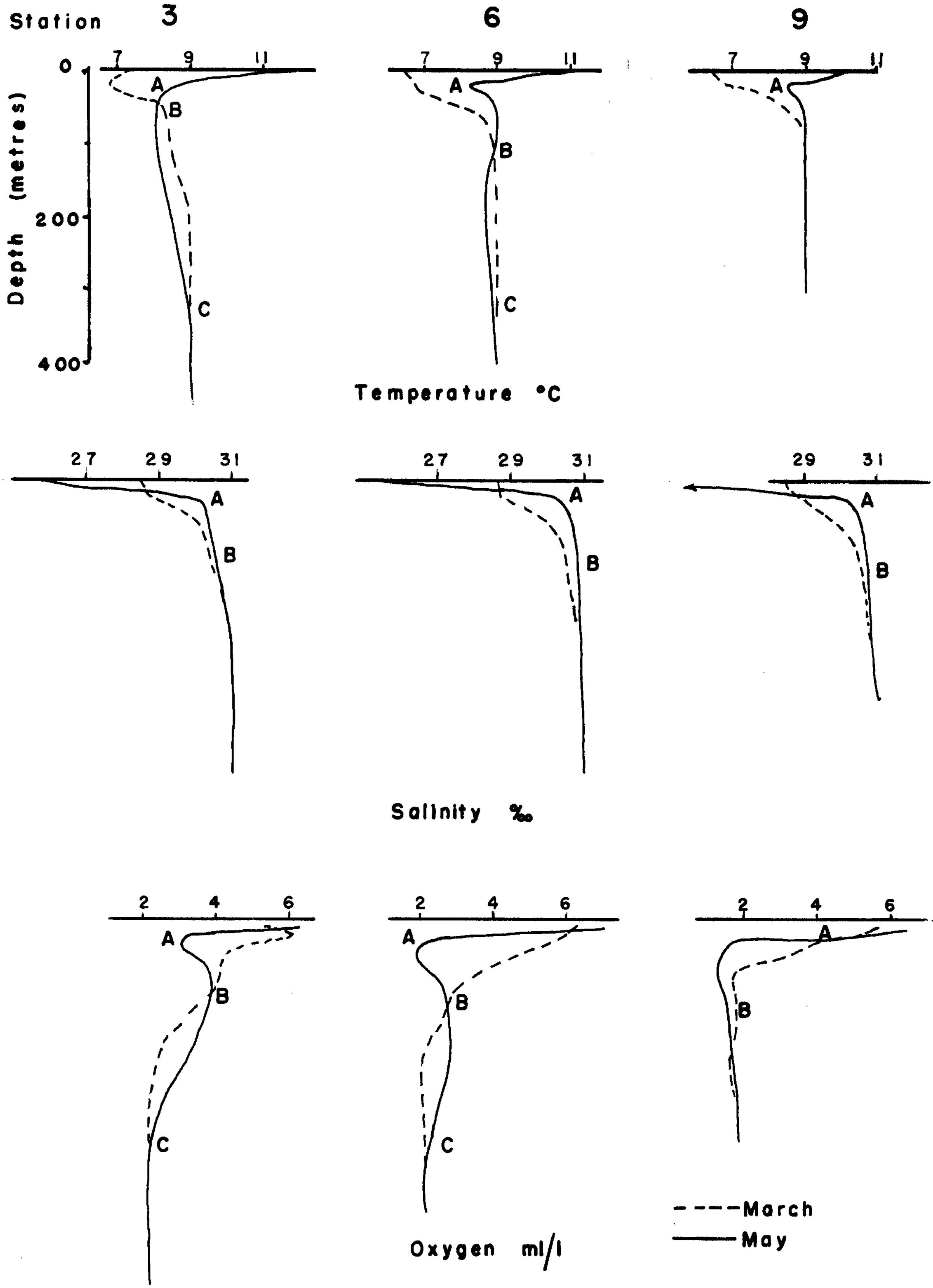


Figure 34. Vertical profiles of temperature, salinity, and dissolved oxygen at three positions in Jervis Inlet during March and May 1962.

May 1962

Vertical profiles for March and May of temperature, salinity, and oxygen are compared in figure 34, for three stations in the inlet. Because of lack of space and the possibility of confusion it is not practical to present profiles for all the stations. Stations Je. 3, 6, and 9 are given to represent conditions near the mouth, middle, and head of the inlet respectively.

The top 5 to 10 metres of the water column in May exhibit properties indicative of spring. The temperature is much higher than in March and the salinity much lower, indicating increased solar radiation and runoff. The oxygen content of the top 10 metres is also higher in May. This could be due to oxygen production by phytoplankton or associated with the runoff water.

The layer of water BC (figure 34) exhibits a marked decrease in temperature coupled with an increase in oxygen content between March and May. The only water in the inlet in March with such a temperature and oxygen content is in the surface layer. Because of the stability it is impossible for the surface water to descend to the layer BC. It is therefore assumed that this change is due to an inflow of water from Malaspina Strait. It is difficult to say how far up the inlet this "new" water has progressed for any horizontal flow will push indigenous water ahead of it. Station 9 exhibits slight changes in layer BC but this is probably due to replacement by water already in the inlet in March. The layer between the inflowing water and the surface layer (layer AB figure 34) is occupied in May by water displaced upward by the mid-depth intrusion. Because of the nature of the gradients before

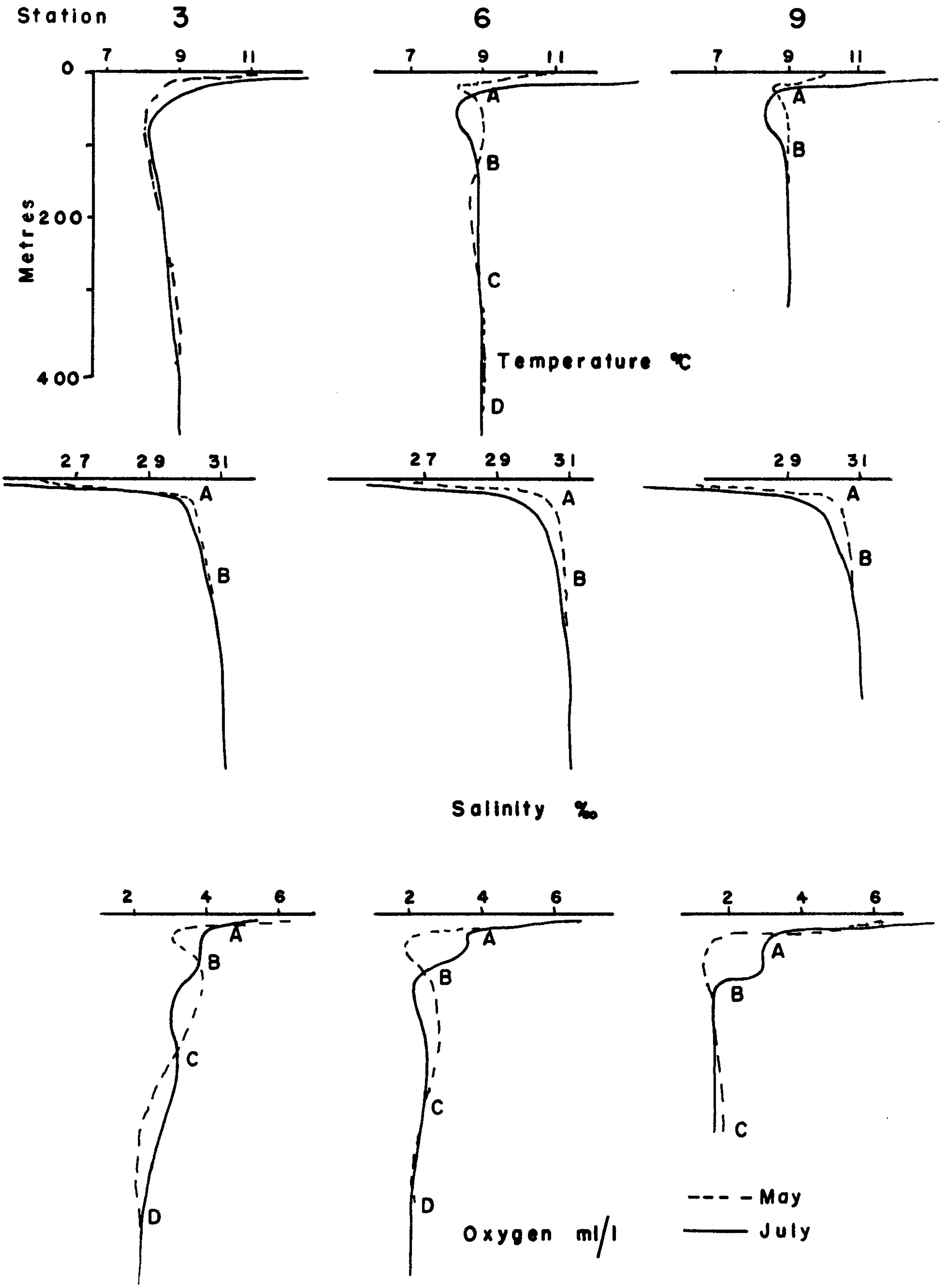


Figure 35. Vertical profiles of temperature, salinity, and dissolved oxygen at three positions in Jervis Inlet during May and July 1962.

the intrusion, layer AB reveals a loss of oxygen, a gain in temperature and a gain in salinity. The temperature minimum evident at 10 metres at stations 6 and 9 is a remnant of the bottom of the previous surface layer. In March the bottom of the surface layer rested at about 60 metres (figure 34), but the mid-depth inflow has pushed it up to about 20 metres. The surface layer in May defined by high temperature and low salinity is above 20 metres. Near the mouth (station 3 figure 34) the layer which exhibits the temperature minimum is not present. Either it has been eroded by exchange with the surface layer or the subsurface inflow has pushed it up into the surface layer to be carried out.

The longitudinal oxygen profile for May (figure 34a) when compared with the same profile for March (figure 33a) reveals a change in the position of the oxygen minimum. It appears that the mid-depth inflow of high oxygen water, indicated by the arrows has cut the minimum into two parts. The upper part has been pushed up near the surface, while the lower half remains much the same. In this way some of the water with oxygen content less than 2 ml/l joins the surface outflow, and leaves the inlet. The amount of inflow however, is not great enough to remove all of the oxygen minimum.

July 1962

The vertical profiles for May and July are compared in figure 35. The surface layer has become warmer due to increased solar radiation, and less saline due to increased runoff. Below the surface layer the three regions AB, BC, and CD are defined (figure 35). The regions AB and CD exhibit gains in oxygen content

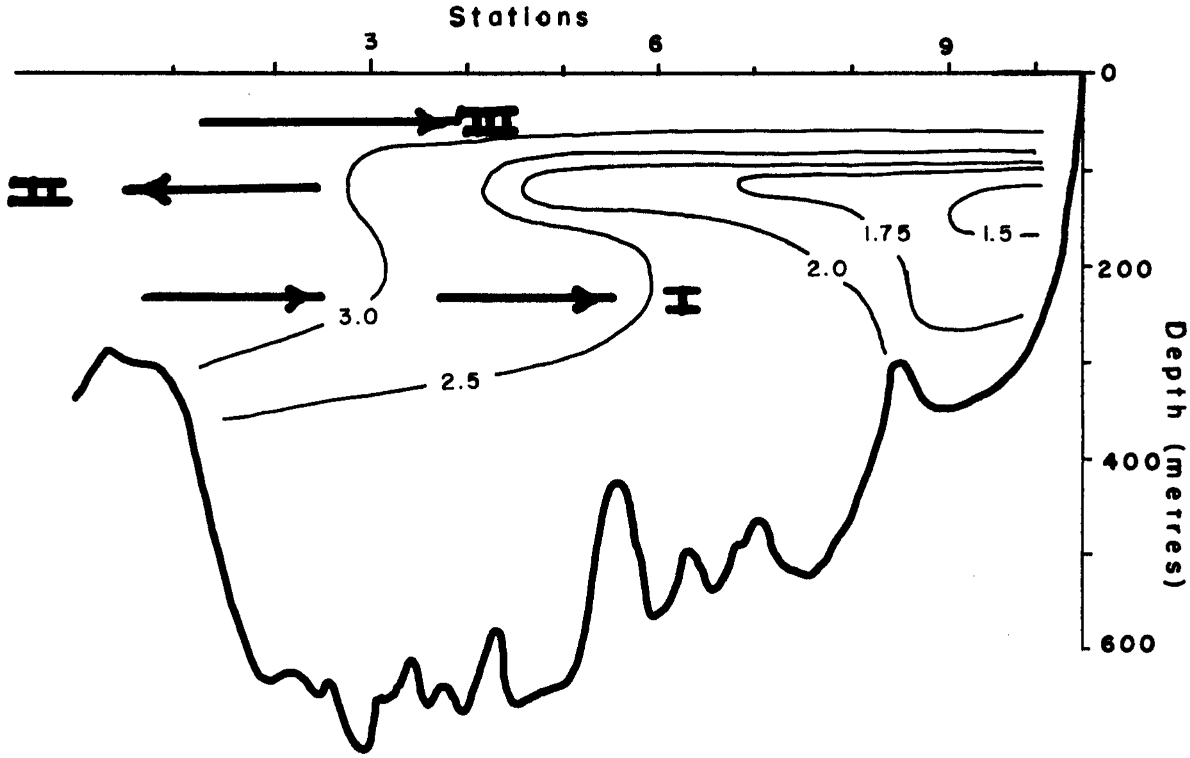


Figure 35a. Longitudinal section of dissolved oxygen in Jervis Inlet during July 1962.

10 Na. Mi.

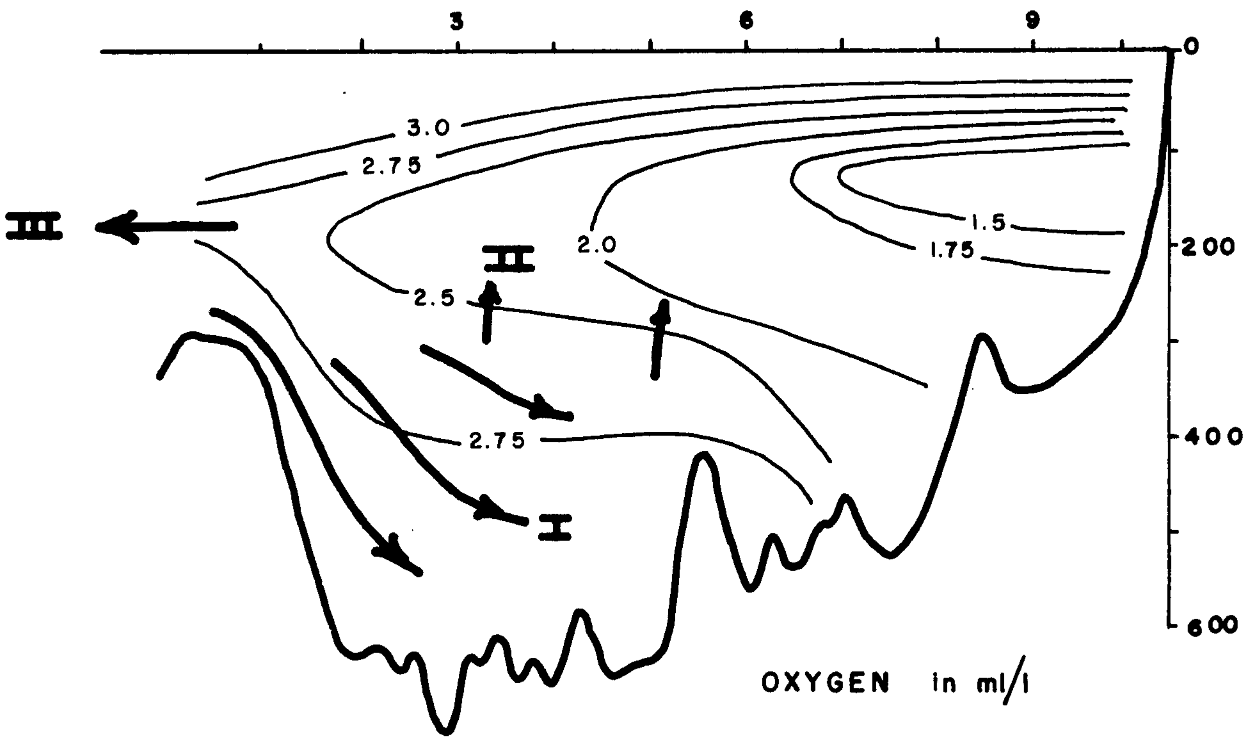


Figure 36a. Longitudinal section of dissolved oxygen in Jervis Inlet during October 1962.

since May while region BC shows a loss. The layers showing a gain in oxygen content are also associated with a loss in temperature, but the middle layer exhibits a slight gain in temperature. It is suggested that changes in the top and bottom layers (AB and CD) represent flows into the inlet, while the changes in the middle layer are a result of an outflow. Thus between May and July there has been an inflow at about 300 metres and at 50 metres. An outflow has taken place in a layer centred at 125 metres. The drop in salt content of about 0.2 to 0.5‰ in layer AB is due to the inflow just under the surface layer.

The oxygen distribution shown in figure 35a has changed as a result of these flows. The flow labelled I in the figure is the deep inflow, which has increased the oxygen content near the mouth at 300 metres. Arrow II represents the flow out of the inlet at 125 metres. This flow has taken the oxygen minimum with it. Flow III is the influx centred at 50 metres, which has forced the oxygen minimum to greater depths. Flows I and III seem to "squeeze" the intermediate layer out of the inlet.

October 1962

Between July and October 1962 there has been an inflow of water into region CD (figure 36). This "new" water is colder by 0.3 to 0.4 C^{o} , while the oxygen content is greater by 0.8 to 1.0 ml/l than the water which was replaced. The water which has been replaced by the deep inflow has moved up into region BC (figure 36a). This is why the oxygen content in the region BC is lower, and the temperature and salinity are higher in October. It is difficult to determine whether the inflow of water into region CD

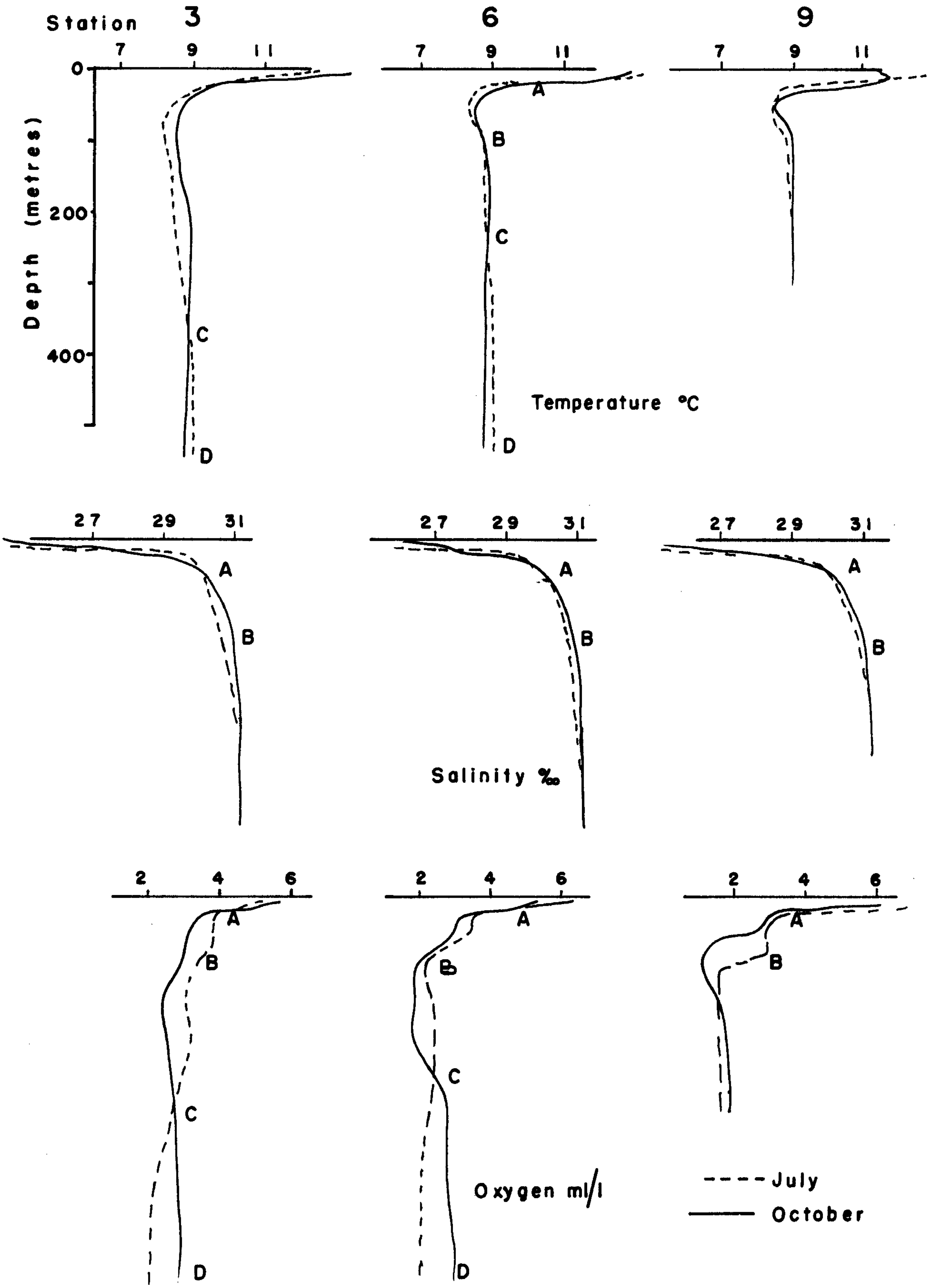


Figure 36. Vertical profiles of temperature, salinity, and dissolved oxygen at three positions in Jervis Inlet during July and October 1962.

has just balanced the outflow in the surface layer. If there has been an increased outflow in the surface layer or at some intermediate depth it is not obvious.

The surface layer in October has changed only slightly since July. It is a little thicker due to continued exchange with the water below the surface layer. The temperature of the top 5 metres is less, indicating a net loss of heat by radiation from the surface. Higher salinities in the top 5 metres indicate a decrease in runoff.

The arrows on the longitudinal oxygen profile (figure 36a) represent the net currents between July and October. The arrows labelled I represent the inflow of highly oxygenated water that has entered the deep zone below sill depth. Arrow II is the upward movement of water resulting from the deep inflow. This upward displacement has brought with it water of oxygen content less than was previously there. The oxygen minimum near the head of the inlet is higher in October due to the upward push from the deep influx. The volume of water containing less than 2 ml/l of oxygen is greater in October than in July. This decrease of oxygen content is attributed to increased oxygen demand in the inlet during the summer, and not to advection of low oxygen water from outside the inlet. The arrow labelled III represents a questionable flow. The 2.5 ml/l oxygen isopleth is found much further down inlet than in July. This is either due to the upward flow of the deep water or to a down inlet flow centred at about 175 metres. It is possible that both flows are present.

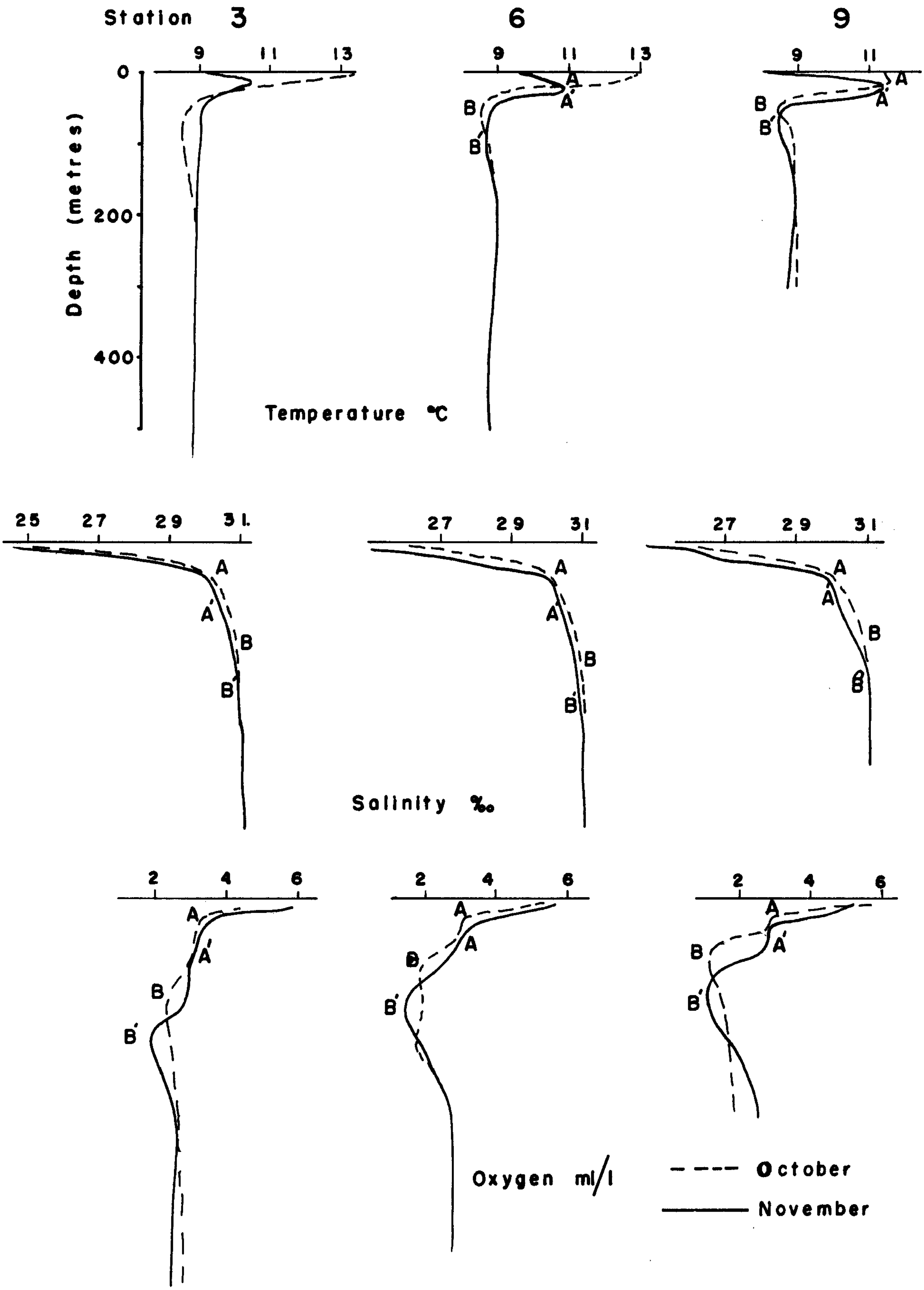


Figure 37. Vertical profiles of temperature, salinity, and dissolved oxygen at three positions in Jervis Inlet during October and November 1962.

November 1962

Vertical profiles for October and November are compared in figure 37. The high-oxygen low-temperature water that entered the deep zone between July and October is evident nearer the head in November (station 9 figure 37). This movement has brought water of higher oxygen content to the deeper layers in the upper half of the basin. This has tended to accentuate the oxygen minimum centred at 150 metres near the head. Another noticeable difference between October and November is that the whole water column above 150 metres seems to have been displaced downward about 20 metres. For example, notice how similar the profile sections marked A'B' are to the sections marked AB in figure 37. The section AB represents the structure in October while A'B' is that in November. It is suggested that there has been a mid-depth out flow centred at about 200 metres. This loss of water has caused the water above it to descend and the surface layer to thicken in order to compensate for the net loss of water from the inlet. The relation between the mid-depth outflow and the thickness of the surface layer is discussed further on page 46.

The change in the surface layer between October and November is shown best by the temperature profiles at station 6 (figure 37). The layer AB in October has been lowered to the layer A'B' by the loss of water at mid-depth. The top 5 to 10 metres has cooled due to increased loss of heat by radiation. This top region is considered the surface layer for it is the only water directly affected by the changes in solar heating and runoff. If the layer AB has descended to A'B' due to exchange there would be no

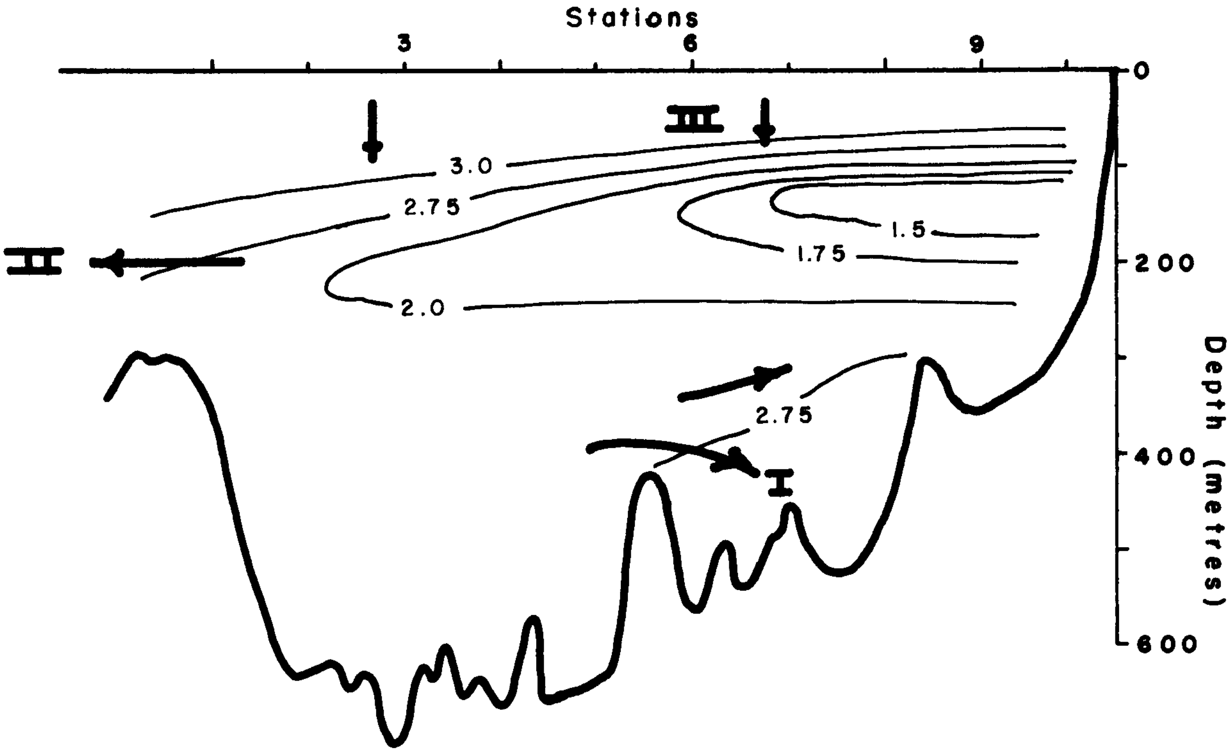


Figure 37a. Longitudinal section of dissolved oxygen in Jervis Inlet during November 1962.

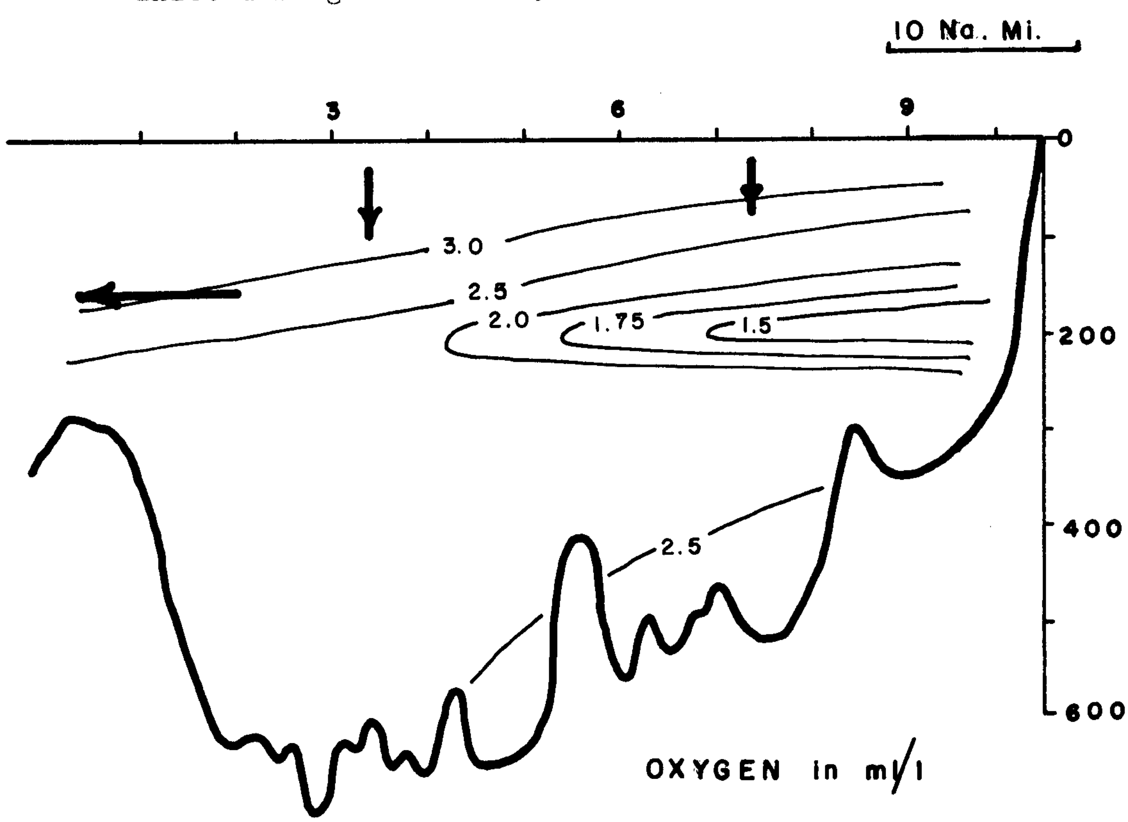


Figure 38a. Longitudinal section of dissolved oxygen in Jervis Inlet during January 1963.

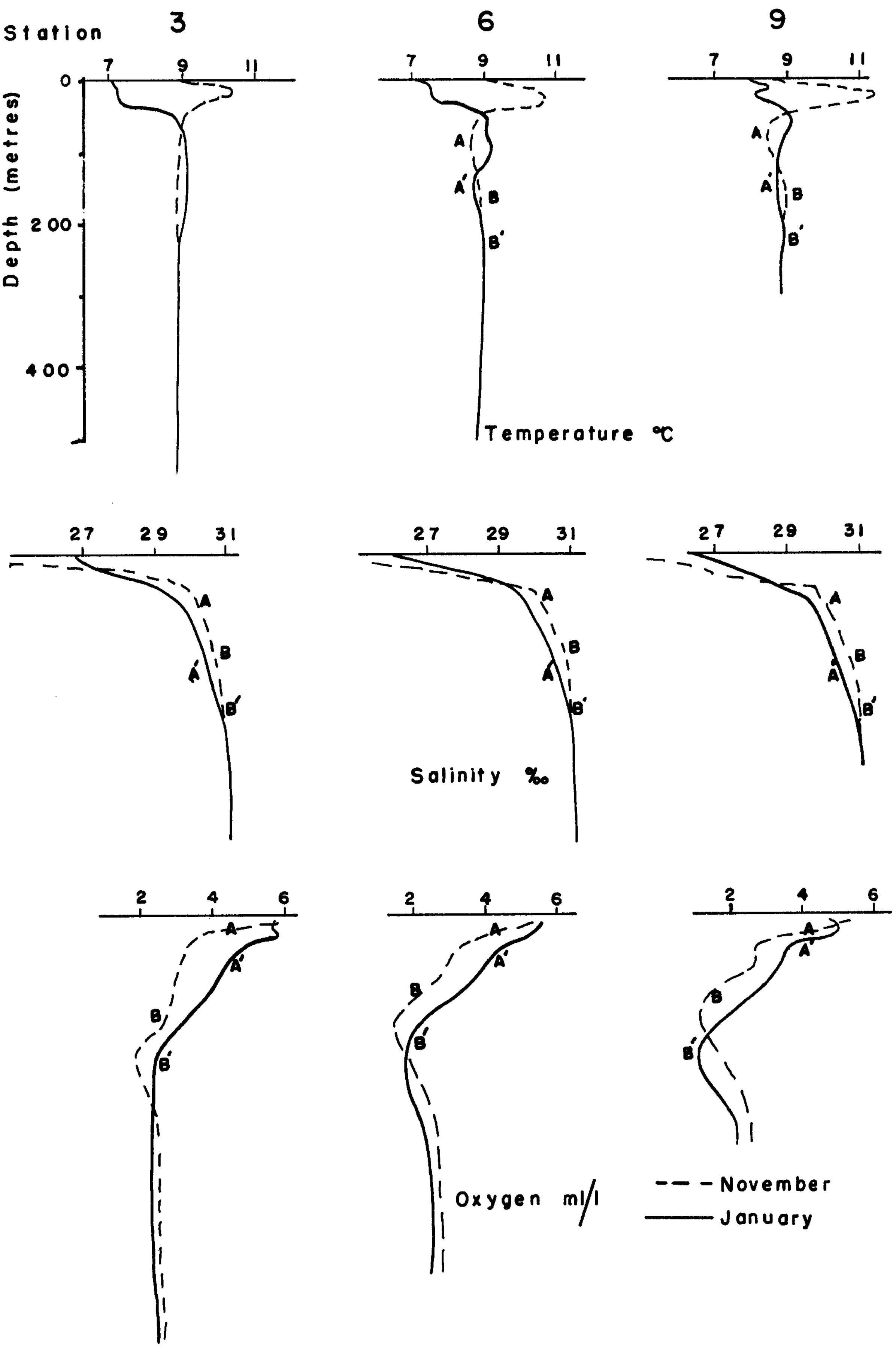


Figure 38. Vertical profiles of temperature, salinity, and dissolved oxygen at three positions in Jervis Inlet during November 1962 and January 1963.

temperature maximum at 15 metres.

Arrow I shown on the longitudinal oxygen profile (figure 37a) represents the tail end of the inflow of highly oxygenated water between July and October. Flow II represents the mid-depth outflow which has caused the water above 200 metres to be displaced down (arrow III).

January 1963

The changes in the vertical profiles between November and January are very similar to the changes noted between October and November. Notice in figure 38 how the layer labelled AB seems to have descended to A'B'. This downward displacement of part of the water column is again caused by an outflow at intermediate depths, with a compensating inflow into the surface layer. The surface layer could be defined as the top 50 metres, which seems too thick for any ordinary surface mixing process.

The longitudinal oxygen profile (figure 38a) shows the increase in depth by 50 metres of the core of the oxygen minimum between November 1962 and January 1963. The increase in oxygen content in the water above the oxygen minimum is also evident. The proposed mid-depth outflow is not too evident in this plot, for the 2 ml/l oxygen isopleth has retreated up inlet since November. It is supposed that the decrease in the volume of water containing less than 2 ml/l of oxygen is due to mixing with more highly oxygenated waters. The decrease in oxygen content in the deep water below sill depth (figure 38a) is attributed to the oxygen demand of organic material in the water.

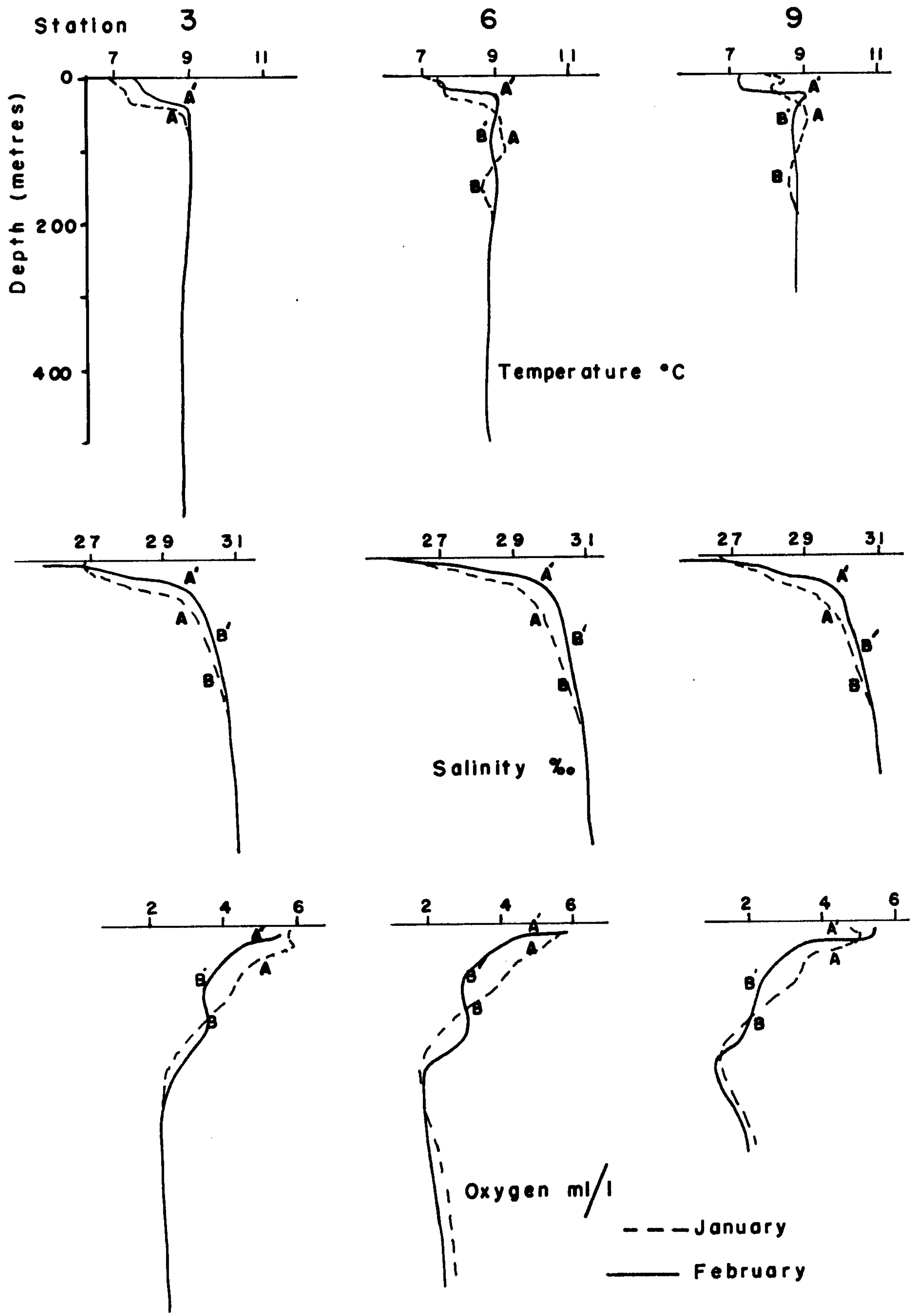


Figure 39. Vertical profiles of temperature, salinity, and dissolved oxygen at three positions in Jervis Inlet during January and February 1963.

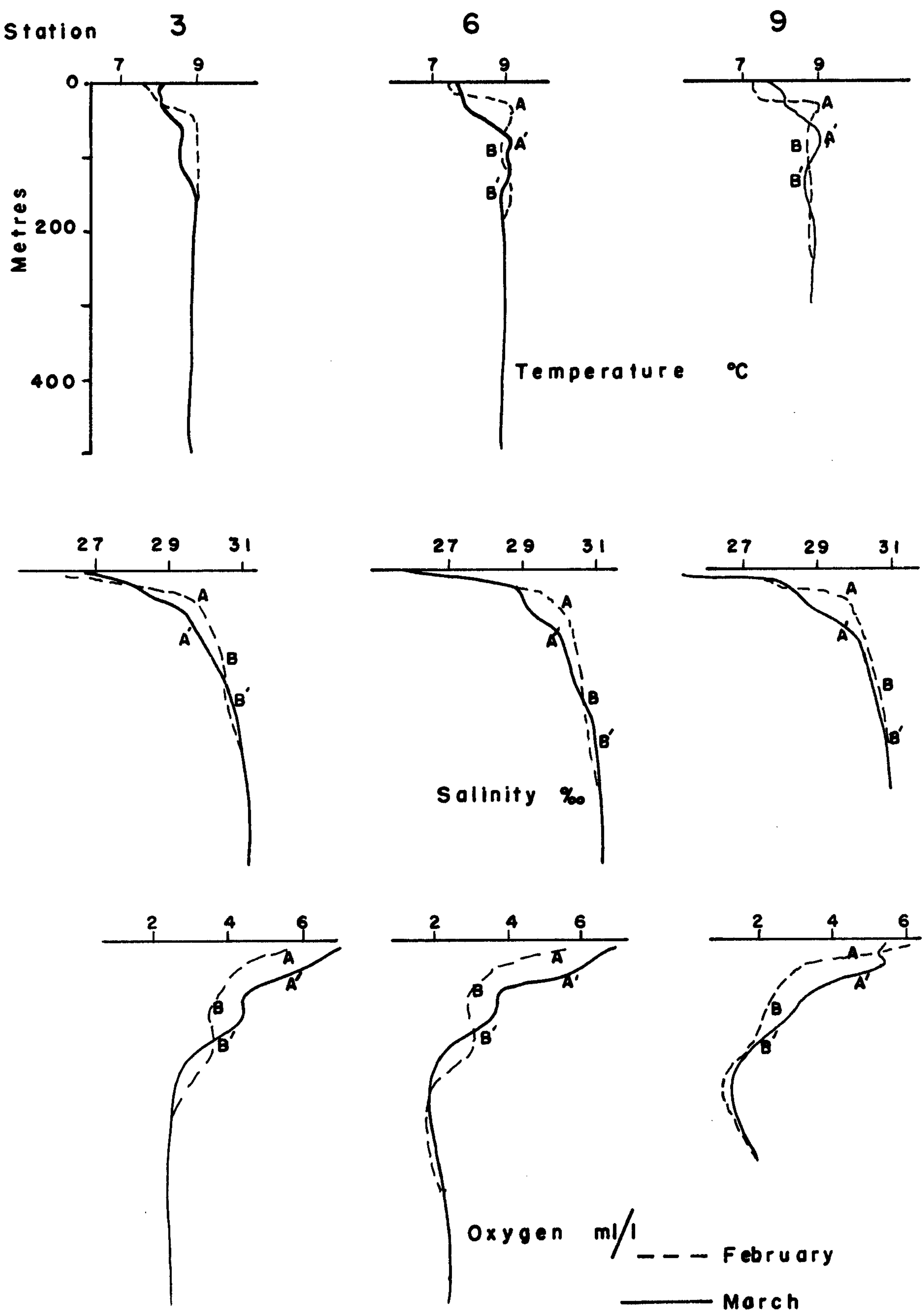


Figure 40. Vertical profiles of temperature, salinity, and dissolved oxygen at three positions in Jervis Inlet during February and March 1963.

February 1963

Comparison of the January and February profiles (figure 39) reveals that a mid-depth inflow has taken place. This inflow has displaced upward the water above it and thus produced a thinner surface layer. Region AB (figure 39) in January has lifted up to become layer A'B' in February. To compensate for the inflow, greater outflow of surface water has taken place. This has produced a thinner surface layer in February. The depth of the sub-surface intrusion is about 150 to 200 metres. This is most easily recognized by inspection of the vertical and longitudinal profiles of oxygen content (figure 39a). The intrusion is characterized by an increase in oxygen content between 150-200 metres, especially noticeable in the tongue of high oxygen water at 150 metres at stations 6 and 7 on the longitudinal profile.

March 1963

The changes in temperature, salinity and oxygen between February and March 1963 are very similar to the changes noted between November and January. The layer labelled AB in the February profiles (figure 40) has been displaced down to become layer A'B' in March. The surface layer consequently is thicker in March. The mid-depth outflow that caused the upper layers to descend occurred at 150 metres. This is evident by the oxygen decrease at this level (figure 40).

The longitudinal oxygen profile for March (figure 40a) shows the oxygen minimum near the head of the inlet in much the same position as it was in February (figure 39a). The values of oxygen content in the upper 150 metres are generally higher than in

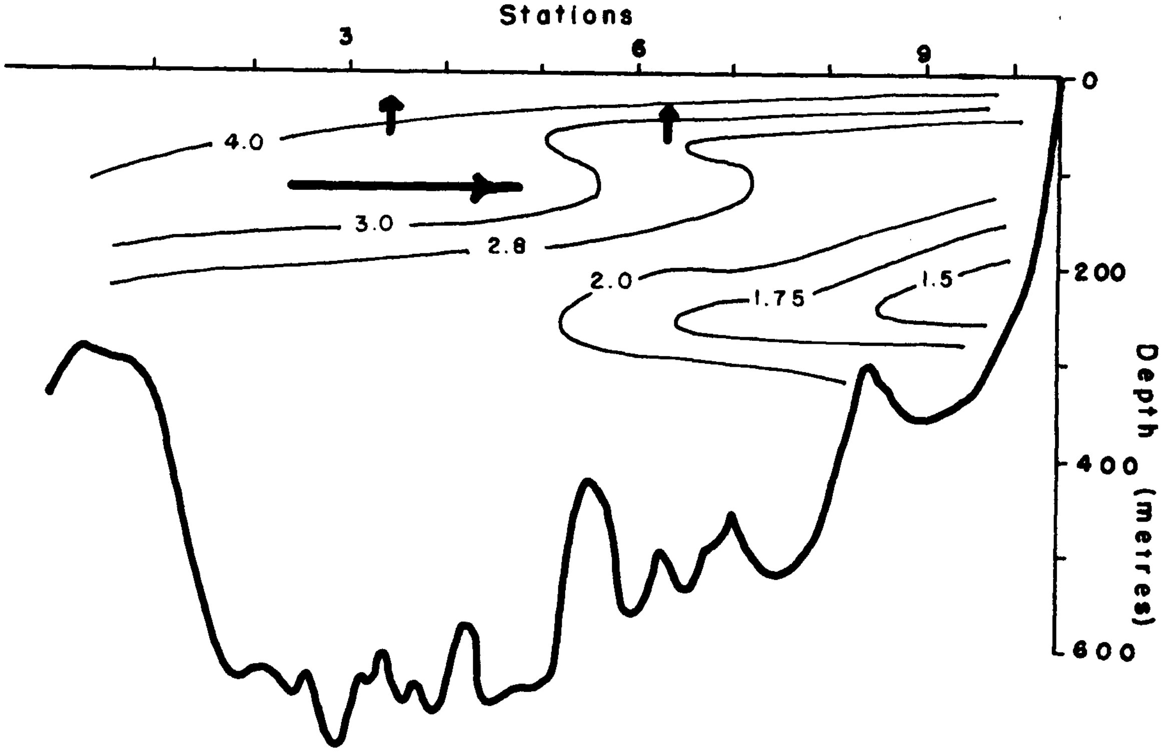


Figure 39a. Longitudinal section of dissolved oxygen in Jervis Inlet during February 1963.

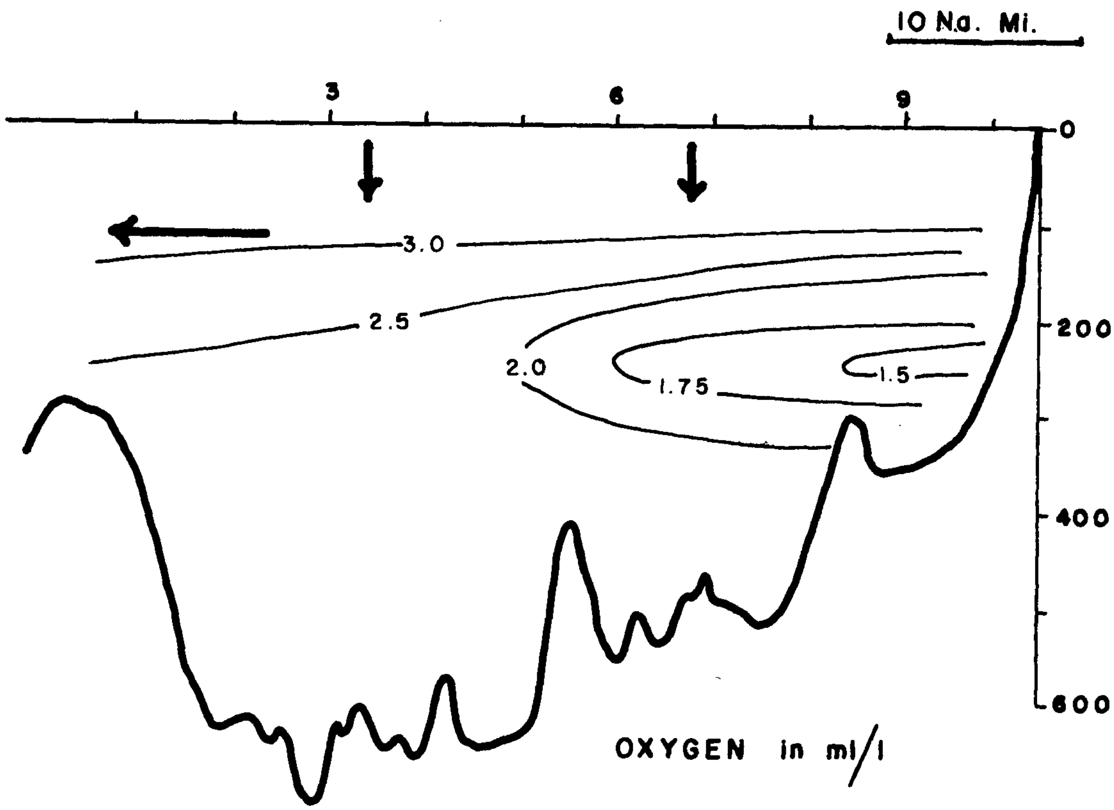


Figure 40a. Longitudinal section of dissolved oxygen in Jervis Inlet during March 1963.

February, due to the mid-depth outflow.

The Surface Layer and Mid-depth Flows

In this account it has been stated that a mid-depth outflow results in an increase in the thickness of the surface layer, also a mid-depth inflow results in a decrease in the surface layer thickness. Although it is implied that the flow is the cause of the change in thickness of the surface layer, it is not necessarily so. This question of which phenomenon comes first is usually referred to as the "chicken and egg" problem.

The salinity at 50 and 100 metres is plotted against time in figure 41. A rough estimate of the surface layer thickness is also shown. There is a strong negative correlation, from November 1962 to March 1963, between the salinity curve and thickness of the surface layer. When the salinity decreased in January and March the surface layer became thicker. The opposite is true in November and February.

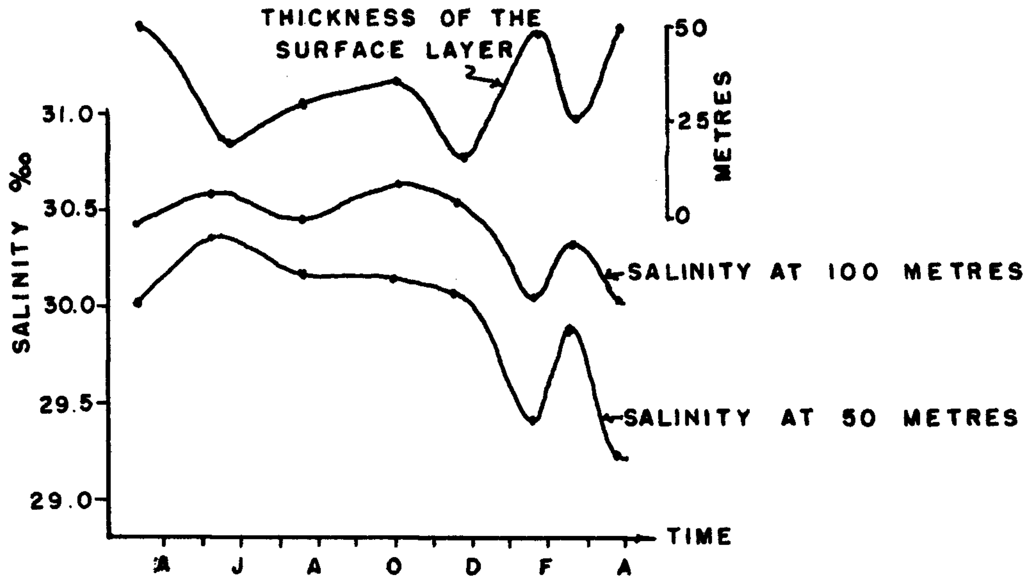


Figure 41. Salinity at 50 and 100 metres at station Je. 3, and the thickness of the surface layer plotted against time.

It has been observed, Pickard and Rodgers 1959, that "in the presence of an up-inlet wind" there is a flow, "up-inlet in the top 5-10 metres". The measurements which this statement refer to were taken in Knight Inlet, but it is assumed that the same phenomenon would occur in Jervis Inlet.

It is proposed that an up-inlet wind blowing for a prolonged period of time will stop, and possibly reverse, the normal down inlet flow of runoff water. This would thicken the surface layer, and raise the water level. To re-establish the water level a movement of water out of the inlet, at mid-depths, takes place. As this water leaves the inlet, the water above the outflow is displaced downward. Because the salinity increases with depth and oxygen content generally decreases, each level between the surface layer and the outflow experiences a drop in salinity and an increase in oxygen content. The changes in temperature are not so regular.

The mid-depth outflow will create, at its own level, a horizontal pressure gradient which tends to reverse the direction of the flow. This pressure gradient builds up until the flow reverses to create a mid-depth up-inlet flow. Then the water in the inlet above the flow is displaced upward, and to compensate for the gain in water volume the surface layer flows out of the inlet faster, thus decreasing its thickness. Thus an increase in salinity at mid-depth (50 to 100 metres) is associated with a non-estuarine sub-surface inflow, and a decrease in the thickness of the surface layer. Also a decrease in salinity at intermediate depths can be correlated with a mid-depth outflow and an increase in the thickness of the surface layer.

The oscillations (figure 41) appear to be greater in the winter of 1962-63. The winds that start the process may be the strong winds usually associated with the autumn months in southern British Columbia. It was observed on October 20, 1962 that the water level at Pender Harbour was extraordinarily high. This is attributed to the strong winds associated with Typhoon Frieda which entered the area at that time. This phenomenon may have been the cause of the variations in the thickness of the surface layer shown in figure 41, which in turn resulted in the oscillatory mid-depth flows. It would be interesting to take a series of oceanographic and meteorological observations in the Strait of Georgia and Jervis Inlet during a prolonged period of strong southerly winds. The data would be collected in the hope of correlating the wind vector, the depth of the surface layer, and the oceanographic conditions in the deep water. It is predicted that the depth of the surface layer will increase in the direction of the wind vector. The salinity will decrease in this direction, and at some mid-depth there will be a flow of water in the opposite direction.

Oxygen Minima

The changes in position and volume of the water in Jervis Inlet containing less than 2 ml/l of oxygen have been described. During the period of this study this mass of water formed an oxygen minimum at intermediate depths near the head of Jervis Inlet. The net flows suggested by the variations in position of this minimum have confirmed some of the suggestions made by Pickard (1961). He proposed that "small but frequent inflows of oxygenated saline water from outside may take place over the entrance sill and spread over the inlet bottom, so that the oxygen-deficient water is held at mid-depth". These flows occurred between March and May 1962 (page 40), May and July 1962 (page 41) and July and October 1962 (page 42). Although the last of these flows was the only one that sank to the bottom, all the mid-depth up-inlet flows tended to decrease the depth of the oxygen-deficient water. It has been suggested here (page 47) that mid-depth out flows also occur. One such flow took place between October and November 1962 (page 44). If such a flow occurs at the same depth as the core of the oxygen minimum, the minimum will appear to flow down inlet. If the depth of the down inlet flow is greater than the depth of the oxygen minimum, the oxygen-deficient water will be displaced downward.

The fresh water runoff in Jervis Inlet is relatively small, and the induced estuarine circulation is correspondingly weak. Because of the absence of a large continual up-inlet mid-depth flow, the oxygen deficient water is not replaced faster than it is formed by oxygen demand in the water. A large runoff inlet such as Bute does not possess an oxygen minimum as prominent as that found in Jervis, (Tabata and Pickard, 1957; Pickard, 1961).

In the shallow silled inlets oxygen deficient waters were found either in a mid-depth minimum or in the deep layer. It was suggested (page 31 and 32) that low oxygen waters in the deep zone are the result of stagnant conditions, and a mid-depth minimum is due to upward displacement of deep low-oxygen water by an intrusion into the deep layer of highly oxygenated water.

IV SUMMARY

The study of the variation in the distribution of temperature, salinity and dissolved oxygen during the period from July 1961 to March 1962 in the Jervis Inlet system has shown a marked difference in the circulation patterns in a shallow silled inlet and a deep silled inlet. It was proposed that a shallow sill forces the tide water to enter an inlet in a turbulent jet which produces a mass of homogeneous water near the mouth. The depth of this water is greater than the sill depth due to the Coanda effect. In general the tide water is of a different density than the indigenous water at the same depth and a horizontal pressure gradient resulting in horizontal flows is produced. If the tide water is less dense than the indigenous water the former will tend to flow up inlet on top of the indigenous water which tends to flow down inlet. If the tide water is denser than the indigenous water the tide water flows up inlet at an intermediate depth displacing upward the indigenous water. The water below the influcence of the tidal jet is relatively stagnant and displays a decreasing oxygen content. Flushing of the deep water occurs when the tide water is denser than all the water in the inlet. It was observed that a deep intrusion of this kind displaced upward the oxygen deficient water in the deep region, thereby producing an oxygen minimum at mid-depths. Because of the tidal jet, the temperature and salinity distributions in the shallow silled inlets, Princess Louisa, Sechelt, and Narrows are divided into essentially three layers. The surface layer diluted by runoff water extends to five or ten metres. The intermediate layer which is influenced by

the tidal jet extends to varying depths depending on the density of the tide water, and the deep layer extends from the bottom of the intermediate layer to the bottom.

The vertical structure of the water in the deep silled inlet (Jervis) is not influenced by the tidal flow. It was assumed that a weak estuarine circulation existed in Jervis due to the relatively small fresh water runoff into the inlet. A mid-depth oscillatory flow of unknown period during the winter of 1962-63 was described. It was proposed that strong south-westerly winds in the autumn, particularly those associated with Typhoon Frieda, caused the water level in Jervis to rise. To compensate for the increase in water volume a mid-depth outflow was created. This outflow produced a horizontal pressure gradient that tended to reverse the direction of the flow. When the flow reversed, the water level in the inlet again became greater and the surface outflow increased. A negative correlation between the direction of this mid-depth flow and the depth of the surface layer was noted.

The low oxygen content in the water at mid-depths near the head of Jervis Inlet was attributed to the weak estuarine circulation which results in a slow renewal of the water near the head.

V APPENDIX

Some Observations During May 1963

Observations were made in the Jervis Inlet system in May 1963, as part of the series of cruises. Because the cruise was taken at the time this thesis was in preparation the results were not used. However, the characteristics of the deep water in Princess Louisa Inlet have been plotted on figure 16. It is interesting to note that the rates of change of temperature and salinity between March and May 1963 appear to be the same as between February and March 1963. The rapid change between February and March was attributed to increased mixing in the deep layer due to the sinking flood tide water. In March and May the flood tide water was flowing up inlet near the surface and it was expected that the rates of change of temperature and salinity would decrease. More data between March and May might have revealed that the rate of change really has decreased. The oxygen content of the deep layer in May was slightly lower than in March. This is attributed to the oxygen demand in the water being greater than the supply by downward diffusion. The downward diffusion had increased in January because of the mixing caused by the sinking flood tide water.

The temperature and oxygen distributions in Sechelt Inlet were similar in May 1963 (not given) to those given for July 1961 (figure 19) except that the surface temperature was not as high in May 1963 nor the oxygen content of the deep layer as low. No mid-depth oxygen minimum was found but a slight structure in the temperature curve indicative of incomplete flushing during the previous winter was noticed.

The data for Jervis Inlet suggested that the oscillatory motion proposed on page 48 was still present.

References

Carter, N. M. 1934. Physiography and oceanography of some British Columbia fjords. Proc. 5th Pac. Sci. Cong., 1933, Vol I, pp 721-733.

Gilmartin, M. 1962. Annual cyclic changes in the physical oceanography of a British Columbia fjord. J. Fish. Res. Bd. Canada, 19(5): 921-974.

Newman, B. G. 1961. The deflection of plane jets by adjacent boundaries - Coanda effect. Boundary layer and flow control. Edited by G. V. Lachmann. Vol. I, pp 232-264. Pergamon Press, New York.

Pickard, G. L. 1961. Oceanographic features of Inlets in the British Columbia mainland coast. J. Fish. Res. Bd. Canada, 18(6): 907-999.

Pickard, G. L., and R. W. Trites, 1957. Fresh water transport determination from the heat budget with applications to British Columbia inlets. J. Fish. Res. Bd. Canada 14(4): 605-616.

Pickard, G. L., and K. Rodgers, 1959. Current measurements in Knight Inlet, British Columbia. J. Fish. Res. Bd. Canada, 16(5): 635-678.

Pritchard, D. W. 1952. Estuarine Hydrography. Advances in geophysics. Vol. I, pp 243-280. Academic Press Inc., New York.

Rouse, H. 1959. Advanced mechanics of fluids. John Wiley & Sons Inc. New York.

Strickland, J. D. H. and T. R. Parsons, 1960. A manual of sea water analysis. Fish. Res. Bd. Canada Bull. No. 125, 185 pp.

Tabata, S., and G. L. Pickard, 1957. The physical oceanography of Bute Inlet, British Columbia. J. Fish. Res. Bd. Canada, 14(4): 487-520.

Trites, R. W. 1955. A study of the oceanographic structure in British Columbia inlets and some of the determining factors. Ph.D. thesis, University of British Columbia, Vancouver, B.C.

Tully, J. P. 1949. Oceanography and prediction of pulp mill pollution in Alberni Inlet. Fish. Res. Bd. Canada Bull. No. 83, 169 pp.