THE OCEANOGRAPHY OF CHATHAM SOUND, BRITISH COLUMBIA

by

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ABSTRACT

A detailed analysis of data taken on an oceanographic survey of Chatham Sound in the spring and summer of 1948 is presented. The primary purpose of the survey was to determine, if possible, whether there was any obvious characteristic of the water in the region which could be correlated with the known migration of salmon to the spawning grounds up the Nass and Skeena Rivers.

The path taken by the fresh water between the river mouths and the more open waters of Dixon Entrance and Hecate Strait is shown to depend on the volume of fresh water discharged from the rivers. The rivers reach their peak discharge in late May or early June and during this period the amount of fresh water in the sound is 3 - 4 times the average.

The effect of tides on the distribution of properties is also discussed. Anchor stations occupied for periods varying from 10 - 40 hours indicates that as a rule there is a good correlation between tidal, salinity, and temperature cycles.

Dynamic calculations giving velocities, volume and fresh water transports have been made. During normal river discharge conditions, the agreement with the observed velocities, and fresh water discharge determined from gauge readings, suggests that even in these coastal waters there is an approximate balance between the horizontal pressure gradients and the coriolis force associated with the motion. Stations at the mouth of Portland Inlet exhibit an apparent balance at all times which suggests that transverse inertial and frictional forces are slight compared with the transverse pressure gradient and coriolis force. Evidence of a variation in geopotential slope as the result of tidal variation is proposed.

The relatively large tidal amplitudes together with the wide and rapid fluctuations in river discharges make it exceedingly difficult to obtain reliable synoptic observations over the entire Sound.

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I INTRODUCTION:

Most of the early work in physical oceanography was directed toward the determination of structure and circulation in the open ocean. However in recent years there has been an increasing interest in the oceanography of inshore waters, particularly in bays and estuaries, which from the standpoint of fisheries and industries is of extreme importance.

The history of oceanography since 1938 along the west coast of Canada was reviewed by Tully (1949). Hutchinson and Lucas (1928,1931) have described the general distribution of temperature, salinity, pH, and phytoplankton in the Strait of Georgia. These investigations were initiated in order to determine the extent and influence of the Fraser River on temperature, salinity, currents, and plankton, which are probable factors in determining salmon migrations. Carter (1934) has described the characteristics of inlets and fiords in the southern part of the British Columbia coast. Tully (1936) has done considerable work on Nootka Sound and the three Inlets directly contiguous with it. In this paper has has discussed the characteristic tidal circulation in the Inlets and the possible inverse correlation between temperature and the depth of tidal circulation in those inlets having a threshold. More recently Tully (1949) has made a quantitative study of the behavior of fresh water entering the sea through Alberni Inlet. In this study he constructed a hydraulic model of the harbour and head of the Inlet and from this he has been able to study the effect of river discharge, wind, and tide on the rate of dissipation of fresh water seaward, and to predict the probable extent and degree of pollution of the Inlet caused by a proposed pulp-mill.

An oceanographic survey of Chatham Sound was carried out by the Pacific Oceanographic Group during the spring and summer of 1948. The primary purpose of the survey was to determine, if possible, whether there was any obvious characteristic of the water in this region which could be correlated with the known migration of salmon to the spawning grounds up the Nass and Skeena Rivers. To do this required a knowledge of the physical and chemical properties of the water in the proximity of the Rivers and to determine the extent of the fresh water before it is finally so diluted with sea water that it can no longer be detected.

Cameron (1948) has discussed briefly the mean distribution of fresh water in Chatham Sound during the periods of maximum river discharge in early June, and the normal river discharge conditions in mid-August, on the basis of the 1948 survey.

The present thesis is concerned with a detailed analysis of the data obtained during the 1948 survey.

Cameron (1951) has also made use of some of the data taken at the mouth of Portland Inlet to demonstrate that the mass distribution is in approximate balance with the deflecting force of the earth's rotation. Relative currents calculated under this assumption were found to agree in magnitude and direction with the currents measured during the survey. Fresh water transports deduced from volume transports compared favourably with the River discharges. From these calculations it appeared that lateral friction in coastal waters of this type is of secondary importance, and that synoptic surveys may be interpreted in terms of the stationary circulation theory of Sandstrom and Helland-Hansen.

II HYDROGRAPHY OF CHATHAM SOUND:

Chatham Sound is situated in the northern part of British Columbia and borders on Alaska (fig. 1). It is a semi-enclosed basin with an area of approximately 600 square miles, into which the water of the Nass and Skeena Rivers discharge. Several large passages and channels provide communication with the more open waters of Dixon Entrance and Hecate Strait. The largest and deepest of these is the un-named passage north of Dundas Island, which

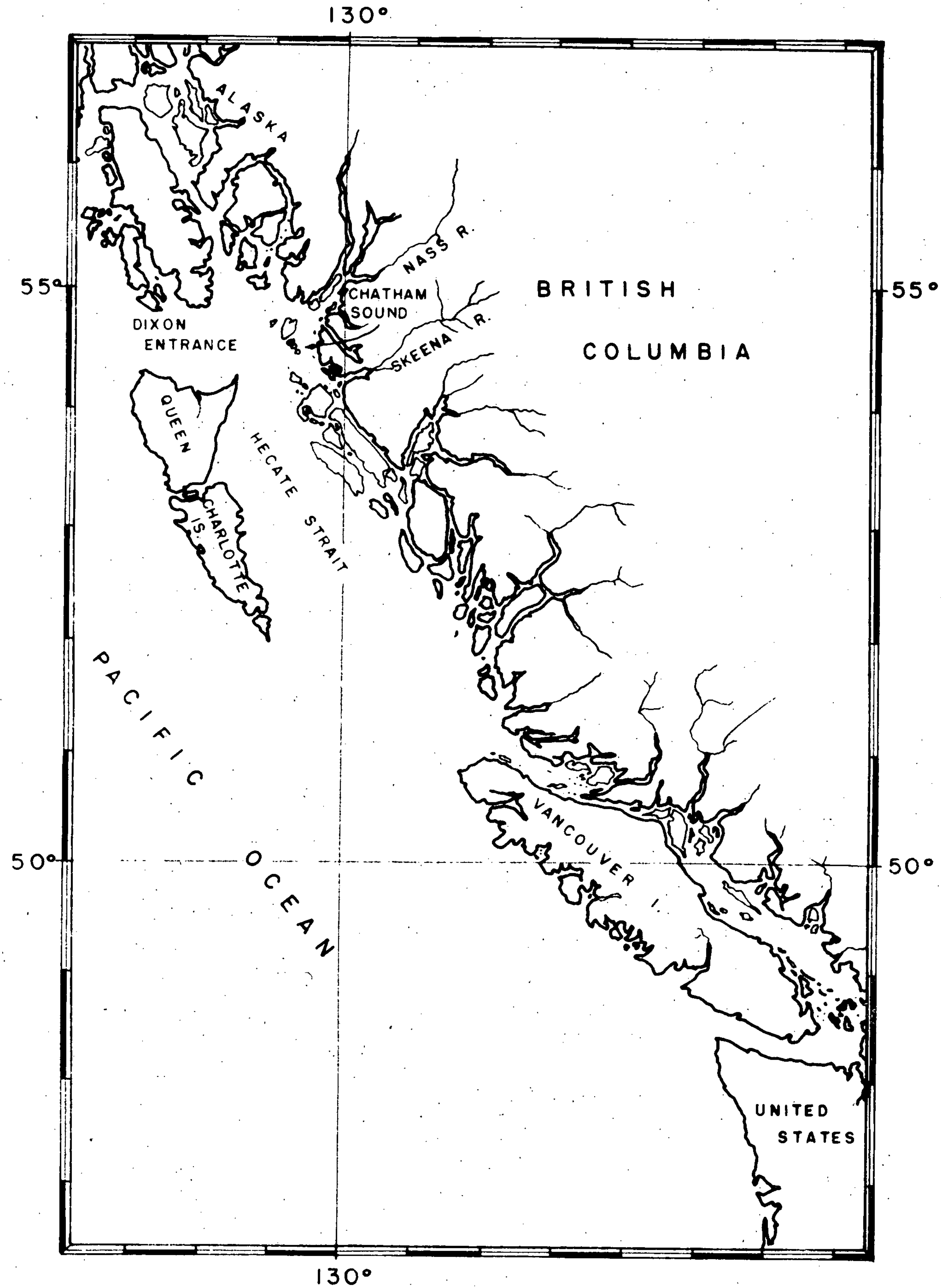
130°
ALASKA
NASS R.
CHATHAM SOUND
SKEENA R.
BRITISH
COLUMBIA
55°
DIXON ENTRANCE
QUEEN CHARLOTTE IS.
HECATE STRAIT
PACIFIC OCEAN
VANCOUVER I.
50°
UNITED STATES

FIG. I

in this study will be referred to as "Dundas Passage" (fig. 2). Hudson Bay, Brown, Bell, and Edye Passages open directly into Dixon Entrance and Hecate Strait. Ogden Channel, between Porcher and Pitt Islands, and Grenville Channel, between Pitt Island and the mainland, provide a more indirect communication with the sea.

The Sound contains many rocks, reefs, and shoals, and its depth for the most part is less than 100 fathoms. It is only in the northern end where depths greater than 100 fathoms are found. Portland Inlet extends inland for some 25 miles from the northeast corner of the Sound. There is no sill across the mouth and depths in the Inlet are comparable to those in the northern end of the Sound (greater than 300 fathoms in some cases).

The Sound can be considered as a large reservoir which is supplied with fresh water from the Nass and Skeena Rivers, and with sea water from Dixon Entrance and Hecate Strait. Its average salinity therefore, is greater than that of fresh water and less than the normal salinity of the adjacent ocean. Chatham Sound constitutes an estuary in the modern sense of the word but the addition of an extra river and the irregular boundaries of the Sound make it considerably more complicated than the simple, two dimensional estuary of which most of the inlets in the coast are examples.

III SOME FACTORS INFLUENCING THE CIRCULATION:

(a) Rivers:

Fresh water inflow is an essential feature of an estuary and hence a description of the rivers which contribute this fresh water is important.

The Nass and Skeena are the only two important rivers which discharge into Chatham Sound. Skeena River water reaches the Sound directly through Inverness and Marcus Passages, and to a lesser extent through Arthur Passage, while Nass River water first discharges into Portland Inlet and thence into Chatham Sound.

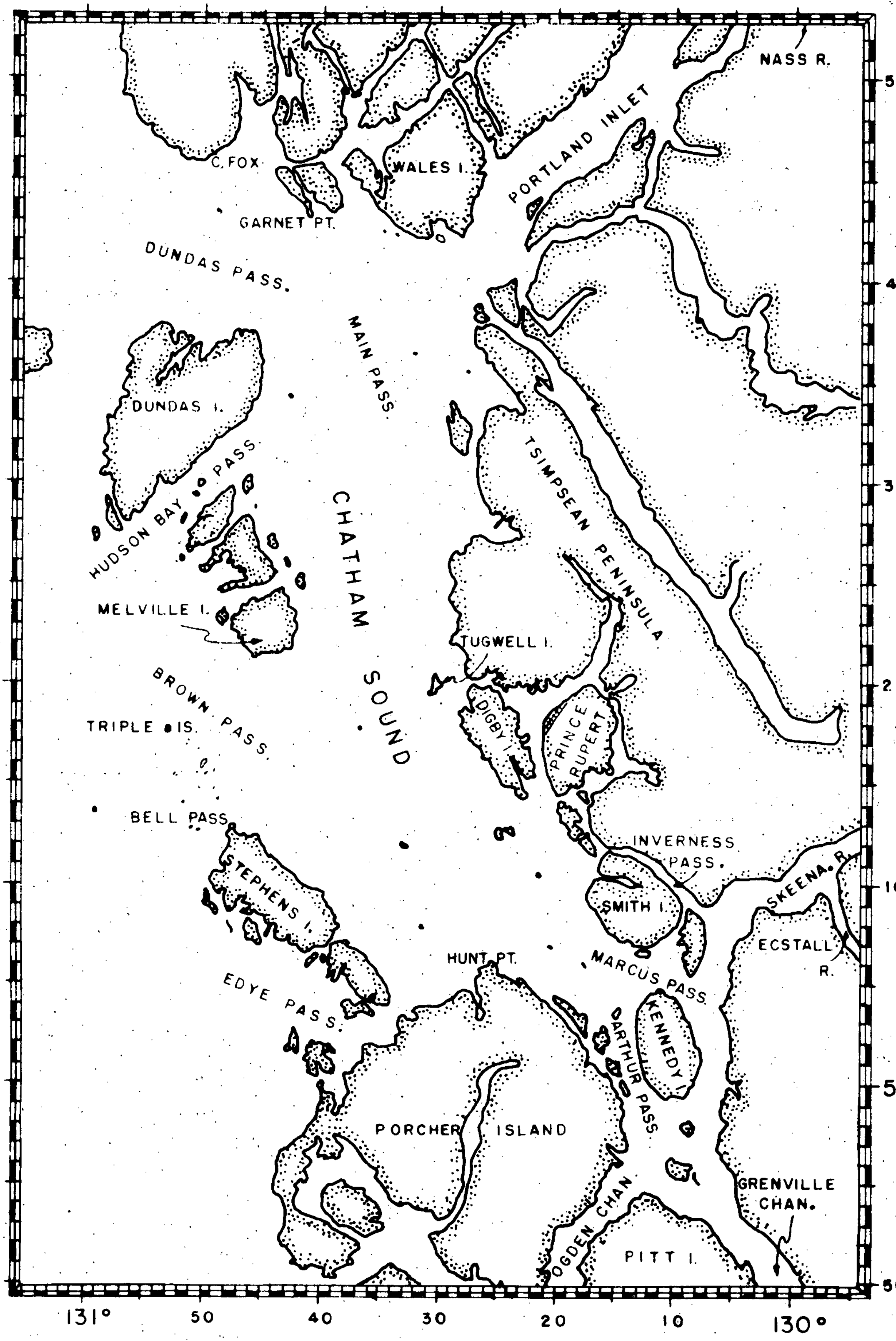
NASS R.
PORTLAND INLET
C. FOX
WALES I.
GARNET PT.
DUNDAS PASS.
MAIN PASS.
DUNDAS I.
HUDSON BAY PASS
CHATHAM SOUND
TSIMPSEAN PENINSULA
MELVILLE I.
TUGWELL I.
BROWN PASS.
TRIPLE IS.
DIGBY I.
PRINCE RUPERT
BELL PASS.
INVERNESS PASS.
STEPHENS I.
SMITH I.
SKEENA R.
ECSTALL R.
HUNT PT.
MARCUS PASS.
EDYE PASS.
KENNEDY
ARTHUR PASS.
PORCHER ISLAND
GRENVILLE CHAN.
OGDEN CHAN.
PITT I.
50
40
30
20
10
54°
50
131°
50
40
30
20
10
130°

FIG. 2

These Rivers drain a total area of approximately 21,900 square miles of which 6,900 is drained by the Nass and the remaining 15,000by the Skeena. The Dominion Water and Power Bureau maintains records of river discharges taken from gauge readings on the Nass River at Aiyansh, 45 miles upstream from the River mouth, and on the Skeena River at Usk, approximately 90 miles upstream from the mouth.

The mean monthly and mean yearly discharges in cubic feet per second for the Nass and Skeena Rivers have been tabulated and are presented in Table I. This table indicates that as a rule, the mean yearly discharges for these Rivers are very nearly equal. However it should be pointed out that these figures are only approximate, since the records, which were commenced in 1927 for the Skeena and in 1928 for the Nass, are not continuous, but contain several deficiencies. The notable exceptions are for the period 1932-36 when the Skeena was not gauged, and similarly for several years no figures are available for the Nass during the months of December, January, February and March. These rivers reach a mean monthly maximum in June of three to four times their yearly mean, and a minimum in March of less than one-fifth their mean. The Skeena however has the wider fluctuations.

Table I also indicates that for the year 1947-48 the Skeena discharge was 20% greater than average while the Nass discharge was about 10% lower than its average. However, the total discharge for both rivers together is only slightly higher than the average.

The maximum discharge for the Skeena was recorded on May 28th 1948, when it reached a figures of 330,000 cubic feet per second. This was more than three times the average peak and broke all previous records. The maximum discharge of the Nass was likewise abnormally high, although it was not a record. Daily discharges of the Nass and Skeena Rivers from May to September, 1948 are plotted in figure 3.

Table I

Discharges in Cubic Feet Per Second for the
Nass and Skeena Rivers at Aiyansh and Usk Respectively

Month	Mean Discharge Nass (1928-48)	Skeena (1927-48)	Nass (1947-48)	Skeena (1947-48)
Oct.	30,100	26,830	26,000	26,400
Nov.	19,680	15,140	9,510	14,500
Dec.	9,850	10,170	5,120	8,230
Jan.	7,270	6,930	5,760	8,660
Feb.	6,480	5,560	3,310	6,070
Mar.	4,390	4,840	2,780	3,690
Apr.	15,120	14,420	3,920	6,050
May	44,550	64,240	56,000	127,000
June	71,990	86,470	78,800	103,000
July	59,221	52,890	41,900	42,000
Aug.	44,420	31,170	37,400	28,100
Sept.	30,260	22,690	37,900	37,300
Mean (year)	28,610	28,450	25,700	34,300

(b) Tides:

The tides in Chatham Sound are classed as semi-diurnal, mixed, there being two high waters and two waters each day, none being of equal height.

Tide tables published by the Hydrographic and Map Service of Canada give the time and height of each high and low water at Prince Rupert. Time and mean height differences of high and low water for various parts of the Sound are given with reference to Prince Rupert harbour. However, time differences are only of the order of a few minutes and height differences are less than 2 feet.

In this thesis the four points on the tidal cycle for which times and heights are recorded will be denoted as higher low water (H.L.W.), lower high water (L.H.W.), lower low water (L.L.W.), and higher high water (H.H.W.).

The tidal range in the Sound is relatively large having a mean value of about 20 feet. As a result of this large amplitude, large volumes of water must move into and out of the Sound resulting in tidal currents in the various passages of the order of 1 to 2 knots.

(c) Meteorology:

Twice daily observations of cloud coverage, wind speed and direction are recorded at Triple Island by the Meteorological Service. During the period of the 1948 survey the average direction of the wind lay between north and west, and the average speed was 10 to 15 miles per hour. Detailed meteorological data are also recorded at Prince Rupert, and in addition to this, observations of weather conditions were made at each station during the survey.

IV COLLECTION OF DATA:

The oceanographic research vessel H.M.C.S. "Ehkoli" was used to make this survey. Observations were commenced on the 19th of May and continued to the 10th of September, 1948. Initially a network of stations was established in the Sound, but additional stations were incorporated, some changed, and some dropped during the course of the survey as more pertinent locations were established. One survey of parts of Dixon Entrance, Hecate Strait, and the entrance to two of the Alaskan passages in the vicinity of Chatham Sound was made to determine the general oceanographic features of the area. Occasionally, more intensive investigations were made of small areas, such as the immediate approaches to the Skeena.

Salinity observations were made by titrating samples of water drawn from selected depths, using Ekman water sampling bottles. Observations were made for the most part at depths of 0,3,6,12,18,24,30,36,48,60, and 90 feet.

However at certain stations observations were made to a depth of only 60 feet, while at others, the observations extended to 150 feet. Following the normal oceanographic procedure, each geographical position at which observations were made will be referred to as a "station", and each lowering of the bottles or instruments at a station, as a "cast". Temperature measurements were obtained largely with a bathythermograph, although some temperatures were recorded using Richter and Wiese reversing thermometers, primarily for calibration of the bathythermographs. Approximately 1000 bathythermographs casts were made.

Approximately 6000 samples of water were obtained and titrated aboard ship to determine the salinity. The Mohr method of analysis was employed, to obtain the chlorosity of the sample, salinity being determined from conversion tables.

Seven anchor stations were occupied for periods varying from 10 to 40 hours. Temperature and salinity observations of the water column were made for all stations at intervals of 1 to 2 hours, and at 3 of them current observations were made at various depths between the surface and 60 feet, using a current drag.

V METHODS OF ANALYSIS OF DATA:

For each station, salinities, temperatures, and in some cases densities were plotted against depth. Temperature-salinity plots were also made for each station.

(a) Salinity:

In an estuarial problem a knowledge of the horizontal and vertical distribution of salinity is essential in determining the circulation.

For a scalar quantity such as temperature or salinity, the processes which tend to change its value may be divided into two groups:

(1) External processes, which are active only at the boundary surface of the fluid (e.g. river inflow, precipitation, sea inflow).

(2) Internal processes, which are active anywhere in the fluid (e.g. mixing).

At subsurface levels and away from boundaries, salinity and temperature are conservative properties. The term "conservative" is used to denote that changes in the values of the quantities are affected (except at boundaries) by processes of diffusion and advection only.[1] This implies that if no mixing or diffusion at subsurface levels takes place, any flow of the fluid must be along the lines of constant property. Departures from this type of flow are indicative of diffusion or advective processes occurring. Very often plots of salinity or temperature have tongue-like distributions, which suggest that there is some flow in the direction of the tongue and therefore, in the steady state some flow occurs across the isolines at the end of the tongue.

In estuaries such as the type considered here, mixing is very extensive and consequently there must be considerable flow across the isolines, particularly in the vicinity of the river mouths.

(b) Temperature:

At any particular time, the horizontal variation of temperature over the sound was found to be slight and hence little use was made of temperature topography plots. Cross-sections of temperature might have been useful, but very few were available, owing to the layout of the stations. Temperature observations however, have been used indirectly in calculating densities and dynamic heights.

(c) Temperature-Salinity Relations (T-S diagrams):

Helland-Hansen (1916) first introduced the use of a temperature-salinity diagram to identify oceanic water masses and demonstrated that for any given water mass, a plot of temperature against salinity resulted in a characteristic

1 Sverdrup et al, The Oceans, Prentice Hall, p. 158

curve. This method then, offers a means of identifying various water masses and their possible origins. The use of T-S diagrams however depends on the conservativeness of temperature and salinity.

T-S curves were plotted for each station, but did not prove to be of primary value in this problem, because, as mentioned previously temperature variations were small and their significance not apparent.

(d) Fresh Water Concentration:

In this study it was found convenient to introduce the expression, "fresh water concentration" (c), to represent the percentage of fresh water that a given sample of water contains. The value of c of course depends on the value chosen for the salinity of undiluted sea water. This salinity which has been chosen arbitrarily as 31.30 ‰ results in a few instances where c is negative. Since emphasis are placed on relative differences, this is not considered to be a serious deficiency.

The relationship expressing the concentration of fresh water (c) at any depth (z) is given by:

$$c_z = 1 - \frac{(S \text{‰})_z}{31.30} \qquad (1)$$

Thus water with a salinity of 10 ‰ has a fresh water concentration of 0.68, i.e. it contains 68% fresh water and 32% sea water.

The mean concentration of fresh water in any depth interval can then be evaluated from the relation:

$$C = \frac{1}{z} \int_0^z c \, dz \qquad (2)$$

(vertical axis is taken as positive downward)

C was evaluated at each station for the upper 60 feet. The integration was performed by the use of a planimeter, to measure the area between the salinity-depth curve and the 31.30 ‰ line.

Plots of C have been used extensively in this study, because they seemed to give a good indication of the mean flow of fresh water seaward, and appeared to offer a distinct advantage over plots of salinity in indicating mean flow. Very often horizontal plots of salinity at some particular depth, contained many tongues of high or low salinity water, while a plot a few feet deeper, contained few or no tongues. These local invasions of high or low salinity water, which contributed little to the mean flow, tended to be "smoothed out" in C plots.

(e) Dynamics:

(1) Equations of motion:

One of the fundamental laws of mechanics states that the acceleration of a body equals the sum of the forces per unit mass, acting on the body. This law is applicable to every part of a fluid and may be expressed mathematically, in rectangular co-ordinates relative to the earth, using a left-handed co-ordinate system with the z axis positive downward, as:

$$\frac{du}{dt} = -\alpha\frac{\partial P}{\partial x} + 2\Omega\sin\phi\, v - 2\Omega\cos\phi\, w + F_x \qquad (3)$$

$$\frac{dv}{dt} = -\alpha\frac{\partial P}{\partial y} - 2\Omega\sin\phi\, u + F_y \qquad (4)$$

$$\frac{dw}{dt} = -\alpha\frac{\partial P}{\partial z} - 2\Omega\cos\phi\, u + g + F_z \qquad (5)$$

where u, v, and w, represent velocities in the x, y, and z directions, respectively

α = specific volume (If ρ = density, then $\alpha = \frac{1}{\rho}$)

p = pressure

Ω = angular velocity of earths rotation

ϕ = latitude

g = acceleration due to gravity

F_x, F_y, F_z = friction, etc.

(2) Velocities, assuming gradient flow:

If it is assumed that the vertical velocity is negligible, accelerations, equal to zero ($\frac{du}{dt}$, etc. = 0), and friction, etc. can be neglected, then the equation of motion reduces to:

$$\alpha \frac{\partial P}{\partial x} = 2\Omega \sin \phi v \qquad (6)$$

$$\alpha \frac{\partial P}{\partial y} = -2\Omega \sin \phi u \qquad (7)$$

These equations express a balance between the deflecting force due to the earth's rotation and the horizontal pressure gradient. From these relations, the velocities necessary to maintain these pressure gradients can be calculated by determining the slope of the pressure surfaces.

The above equations can be applied directly to determine the mean velocity perpendicular to a line joining two stations. If these stations are represented as A and B, then the equations may be reduced to the form:

$$v_1 - v_2 = \frac{10(D_B - D_A)}{2\Omega \sin \phi L} \qquad (8)$$

where, L = distance between A and B, v_1 and v_2 = velocities at levels 1 and 2 respectively, and D_A and D_B are the dynamic heights at stations A and B respectively, expressed by the equations:

$$D_A = \int_{P_1}^{P_2} \alpha_A \, dp \qquad \text{and} \qquad D_B = \int_{P_1}^{P_2} \alpha_B \, dP \tag{9a,b}$$

α may be expressed as the sum of two terms:

$$\alpha = \alpha_{35,o,p} + \delta \tag{10}$$

where, $\alpha_{35,o,p}$ = specific volume of water with a salinity of 35‰, temperature of 0°C, and a pressure p, and δ=specific volume anomaly.

All that it is necessary to calculate then, is the dynamic height anomaly expressed by the relation:

$$\Delta D = \int_{P_1}^{P_2} \delta \, dP \tag{11}$$

so for computation, (8) takes the form:

$$v_1 - v_2 = \frac{10(\Delta D_B - \Delta D_A)}{2\Omega \sin\phi \; L} \qquad \text{or} \qquad v = \frac{10}{2\Omega \sin\phi} \frac{\partial \Delta D}{\partial x} \tag{12a,b}$$

(3) Volume transports:

The volume transport through an elemental area of cross-section is given by:

$$t = v \, dx \, dz \tag{13}$$

substituting equation (12b) into (13) gives:

$$t = \frac{10}{\lambda} \frac{\partial \Delta D}{\partial x} \, dx \, dz \tag{14}$$

where, $\lambda = 2\Omega \sin \phi$

To get the total volume transport, (14) must be integrated vertically and horizontally, giving:

$$T = \frac{10}{\lambda} \int \partial \Delta D \, dz \qquad (15)$$

Substituting for ΔD from (11) gives:

$$T = \frac{10}{\lambda} \iint \delta \, dp \, dz \qquad (16)$$

Between two stations, A and B, the volume transport is given by:

$$\begin{aligned} T &= \frac{10}{\lambda} \int (\Delta D_A - \Delta D_B) dz \\ &= \frac{10}{\lambda} \left[\int \Delta D_A \, dz - \int \Delta D_B \, dz \right] \end{aligned} \qquad (17)$$

or, using the form of the equation introduced by Jakhellen (1936), one obtains:

$$T = \frac{10}{\lambda} (Q_A - Q_B) \qquad (18)$$

where

$$Q = \iint \delta \, dp \, dz \qquad (19)$$

Thus the volume transport between two stations depends only on the geopotential anomalies at the two stations, and is [illegible] independent of the distance apart, or the distribution of mass between the two stations.

(4) Fresh water transport:

The fresh water transport through an elemental area may be written as:

$$f.w.t. = v \; c \; dx \; dz \qquad (20)$$

where, c = concentration of fresh water passing through the area dx dz.

Integrating this, gives:

$$\text{F.W.T.} = \iint v \; c \; dx \; dz \tag{21}$$

or,

$$\text{F.W.T.} = \frac{10}{\lambda} \int c \, \partial \Delta \, D \; dz \tag{22}$$

However, this equation cannot be integrated as simply as for volume transports, unless a relationship between c and $\partial \Delta D$ can be established. It can however, be integrated by assuming that the gradient of fresh water concentration at each level, between two stations, is uniform. At each level p, this requires the use of the arithmetical mean fresh water concentration $\bar{c}$:

$$\bar{c} = \frac{C_{pA} - C_{pB}}{2} \tag{23}$$

$\bar{c}$ is then substituted for c in equation (22) and the integration performed in the usual manner, giving:

$$\text{F.W.T.} = \frac{10}{\lambda} \int \bar{c}(\Delta D_B = \Delta D_A) dz \tag{24}$$

Fresh water transports determined for various sections can be compared with one another and with the known inflow of fresh water from the Nass and Skeena Rivers.

VI AVERAGE FRESH WATER DISTRIBUTION AND SALINITY PATTERN:

The average fresh water distribution and salinity observed in the Sound during normal river conditions will be discussed first, so that the patterns and distributions observed at other times may be compared with them.

For the month of August both the Nass and Skeena Rivers have discharges very nearly equal to their yearly mean. A network of stations in the Sound was occupied during the period from August 10 to 19. For the first 4 days the southern half of the network was occupied, once each day, the timing of the observations being so arranged that at the end of 4 days each station had been occupied at 4 different stages of the tide, i.e. low flood, high flood, high ebb, and low ebb. In order to present an average picture the observations at each station were averaged. Similarly observations for the northern half of the network were taken during August 16 to 19. The average distribution of fresh water is presented in figure 4. The concentration in the Sound was between 1.1 and 9.9 %, the highest value being observed at station 29, located just south of Garnet Point.(fig. 5), and the lowest at station 47, located near Triple Island. A secondary maximum of 8.8 % was observed at station 41, off Inverness Passage.

Due to the earth's rotation, the flow of fresh water into the Sound f rom the Nass and Skeena Riversat normal levels, shows the tendency to turn to the right which is common to all river outflows in the Northern Hemisphere. From the pattern illustrated, it is evident that very little Skeena River water flows out through Brown, Bell, or Edye Passages. Instead, the net seaward flow of Skeena River water takes place up the east side along the shore of Digby Island and continues northward past Tugwell Island and along the mainland coast of the Tsimpsean Peninsula.

The Nass River water tends to be concentrated along the north shore of the Sound,moving out past Wales Island, through Dundas Passages, and finally into Dixon Entrance and the various passages and channels along the southeastern Alaskan coast.

In figure 6 the average surface salinity pattern during the same period is presented. Salinity varied from less than 24‰ at station 42, located southwest of Inverness Passage, to greater than 30‰ at station 47. While this pattern indicates the same general flow in the southern end of the Sound as the plot of fresh water concentration, the isohalines are more wavelike in the northern end and suggests that there is some flow of Nass water at the surface toward the south along the eastern shore of Dundas Island. However, examination of the salinity pattern at 6 feet and at deeper levels indicates that this southward tendency is confined to the upper few feet. The extension of the tongue towards Hudson Bay Passage suggests some seaward movement of fresh water through this passage. This suggestion is also indicated in the fresh water concentration plot.

It would seem then, that although a thin surface layer of Nass water extends southward, most of the fresh water in the southern and central part of the Sound is derived from the Skeena River.

One concludes therefore, that during normal river conditions, there is little seaward movement of fresh water through Brown, Bell and Edye Passages or through Ogden and Grenville Channels. Most of the Skeena River water moves northward along the Tsimpsean Peninsula, merges with the Nass River water and finally the greater part leaves the Sound through Dundas Passage, with possibly a small amount passing through Hudson Bay Passage.

VII SURVEYS:

The surveys of Chatham Sound will now be discussed in chronological order.

(1) May 19 - May 21:

The first set of observations was commenced on May 19 and extended to

May 21. This was a general survey of the Sound, in which most stations were occupied twice - once during the flood tide and once during the ebb.

Surface salinities, salinities at 6 feet, and fresh water concentrations have been plotted. Figure 7 illustrates the pattern of fresh water concentration and salinity at 6 feet for the flood and ebb phases of the tide. The patterns observed are very similar to those illustrated for normal river discharge conditions.

(a) Flood:

Fresh water concentration ranged from less than -1.0 % at the station near Hunt Point to greater than 11.0 % at the northern end of Grenville Channel. The salinity plots agreed very closely with those of fresh water distribution, the salinity varying /from 22 ‰ at the northern end of Grenville Channel to 31 ‰ near Hunt Point.

(b) Ebb:

While the effect of tide on the distribution of salinity or fresh water does not reveal itself very markedly in these plots, still a difference can be seen by noting the shift in the 8 % C line. The most marked shift was in the southern end of the Sound, where the 8 % isoline moved about 5 miles southward during the ebb tide, and replaced the 0 % isoline. In the northern part of the Sound the 8% isoline also shifted a few miles further off Portland Inlet and was replaced by the 10 % isoline. The change in salinity pattern between ebb and flood tide was of the same order of magnitude as for the fresh water concentration.

Ideally, if there was no net flow of water in the Sound over a tidal cycle, then observations taken midway on the flood and ebb tide would reveal the same distribution of fresh water. The fact that this is not observed indicates a net flow during a tidal cycle. There must be a net seaward movement of fresh water, equal to the river discharge, otherwise accumulation would result. However the small variation in salinity and fresh water concentration, near Edye Passage, suggests a net northerly tidal set through it.

The slightly higher concentration of fresh water in the southern part of the Sound, compared with the normal, was due to the increase in Skeena River discharge, which had been increasing steadily from about May 10 (fig. 3), The Nass did not show a comparable increase in discharge. These patterns then, correspond closely to the average conditions shown previously for the mid-August survey.

(2) May 25 - May 28:

This network of stations extended only over the southern end of the Sound. However it indicates a considerable change from the May 19 - 21 survey.

In figure 8, the mean fresh water concentration and mean salinity at 6 feet are presented. The 8 % C line stretched in a more nearly east-west direction, compared with the north-south direction on May 19 - 21, and even extended outside Melville Island. The 14 % C line was almost coincident with the position of the 8 % line on May 19 - 21. The mean fresh water concentration varied from less than 2 % in Bell Passage to greater than 21 % just seaward of Inverness Passage.

The salinity pattern at 6 feet was very similar to the fresh water concentration plot. However, the surface salinity was quite different, especially in the region just north of Edye Passage and along the northeast shore of Stephens Island. A very thin layer of water relatively low salinity had evidently spread out over the area from the Skeena.

Tidal effects were almost completely masked by the effect of the large increase in river discharge. However, the station near Hunt Point still showed a variation in fresh water concentration of about 1.5 % from high to low water (increasing during the ebb).

This set of observations evidently represents a transient state in which the circulation in the Sound was changing from normal conditions to that corresponding to maximum fresh water discharge.

(3) June 1 - June 4:

In this period the northern part of the sound was surveyed. Each station was occupied 4 times during the survey - once each day, and at different stages of the tide. The mean distribution of fresh water is presented in figure 9(a). The highest concentration of 22.6 % was found at station 29, and the lowest of 9.8 % at station 27 located just off the northwest coast of Dundas Island. This change represents an increase in fresh water to more than double that during normal conditions. The mean surface salinity is presented in figure 9(b). Its pattern is similar to the fresh water concentration plot, the range of values being from less than 11 ‰ at station 29 to 21 ‰ at station 27.

The fact that the lines of constanct C still portrayed the same general pattern as under normal conditions, does not necessarily imply that all the fresh water from the Nass was moving seaward through Dundas Passage. Although the bulk of the fresh water was moving seaward through this passage, the increase in fresh water discharge resulted in increased flow across the lines of constant property, and hence it is probable that there was considerable movement toward the south and west, especially in a thin surface layer.

Plots of fresh water concentration were made for each phase of the tide (low flood, high flood, high ebb, low ebb) and were found to exhibit quite different patterns from the mean. Large but inconsistent variations were noted in each. It appears that during this period observations taken at the same phase of tide but on different days could not be used to give a synoptic picture.

Plots of fresh water concentration were made for each day regardless of tide. It was evident that the resulting patterns were more reasonable than those plotted using only data taken in the same tidal phase but on different days. In these plots (fig. 9 (c),(d),(e),(f)), the highest fresh water concentration of 28.6 % occurred on June 1 at station 29. This maximum is associated with the peak discharge of the Nass which occurred 3 - 4 days earlier.

The June 2 plot indicates a decrease in the maximum C to 25.2 %. It also shows a southward extension of the isolines into the central part of the Sound which indicates that this large cell of relatively fresh water had a southward, as well as a westward component.

On June 3 there was a further decrease in fresh water concentration, and a more marked southward movement.

By June 4, this large cell of exceedingly high fresh water concentration had almost completely disappeared.

It would appear that this large body of brackish water, observed on June 1, had moved part way out into the Sound by virtue of the hydraulic head established in Portland Inlet, due to the increase in river discharge. Since the rate of drop in river discharge was about equal to the rate of rise, this resulted in a body of water of very high fresh water concentration being partially isolated. The dispersal and removal of this water resulted from energy supplied from any one or all of the following sources:

(a) energy stored as momentum which this body had at the time of isolation.

(b) energy possessed by virtue of its higher potential than the surrounding more saline water.

(c) tidal enery.

(d) Wind.

In this case (a) and (b) will result in cross-isobaric flow which will be directed in the main westward through Dundas Passage and to a lesser extent southward into the central part of the Sound. Undoubtedly (c) and (d) will play their part also, but to what extent is not known.

(4) June 8 - 18:

From June 8 to 11 the northern part of the Sound was surveyed, the stations as before, being occupied once each day at different tidal phases. Similarly during June 14, 15, 17, and 18, the southern part of the Sound was surveyed.

The observations at each station were averaged for the purpose of getting a mean picture corresponding to maximum fresh water discharge conditions. (At the gauge stations the river flows had actually passed their peaks but were still about 4 times their mean. In the Sound the effect of the maximum flow was still being felt.) The mean distribution of fresh water presented in figure 10 indicates that the concentration varied from 5.2 % at station 47 to 18.1 % at station 41. A secondary maximum of 16.9 % was located at station 26, off the northeast corner of Dundas Island.

The Sound had for the most part a fresh water concentration of 10 - 15 % as compared with the normal conditions of 1 - 6 %. Considerable quantities of fresh water were reaching Hecate Strait and Dixon Entrance through all the passages. Nass water appears to have extended southward as far as Melville Island which suggests that there was little Skeena water reaching the northern part of the Sound. However, Dundas Passage appears to be still transporting seaward more fresh water than any other passage.

Plots of fresh water concentration and salinity distribution were made for each stage of the tide, however, as mentioned previously, it was apparent that the large increase and unsteadiness of river discharge completely masked any tidal effects which might have been present.

Plots of C for each day were drawn and found to have a measure of continuity from day to day. They are presented in figures 11(a),(b),(c), and (d).

On June 8 the minimum, 6.9 % was at station 29, and the maximum, 17.8 % was at station 25, near Hudson Bay Passage. A tide line was observed to extend northeast from Dundas Island towards Wales Island. This intruding, more saline water, apparently pinched off relatively fresh water located along the north shore of Dundas Island. The presence of this tide line, and the displacement of the maximum fresh water concentration, southward, was quite possibly due to wind effects. During June 7 and 8, northwest winds with speeds of 25 - 30 miles per hour were recorded at Triple Island. It is probable then, that these winds were tending to force more saline water into Dundas Passage and consequently forcing fresh water flowing out from Portland Inlet, southward.

On June 9 the minimum C of 3.8 % was at station 24, and the maximum of 16.6 % at station 26. This indicates an apparent return northward of the cell of maximum fresh water concentration, which, in part, may have been due to the gradual subsidence of the wind and the circulation returning to normal.

The june 10 plot indicates an increase in fresh water concentration to a maximum of 22.1 % at station 26. This increase can be correlated with the increase in discharge of the Nass River of 44 %, which occurred between June 7 and 8.

On June 11 the maximum C of 18.6 % was located at station 26, which is in reasonable agreement with the drop in river discharge between the 8th and 9th.

Fresh water concentrations for June 14, 15, 17, and 18 are plotted in figures 14 (a),(b),(c), and (d) respectively.

On June 14, a minimum of 5.6 % was observed at station 47, located near Triple Island, and a maximum of 15.9 % at station 50, located in the south-central part of the Sound. There is evidence of a considerable flow of fresh water through Edye, Bell, and Brown Passages.

On June 15 the minimum of 5.3 % was still at station 47 but the maximum of 17.4 % was at station 41.

The distribution on June 17 indicates a decrease in the minimum at station 47, to 2.6 %, while the maximum at station 41 has increased to 23 %. It is quite possible that an even higher value was reached on June 16. This increase may have been due in part to the increase in Skeena River discharge of approximately 12 % between June 10 and 11. However the apparent increase may also have been due partly to the effect of the tide. Station 47 was occupied near high water, whereas station 41 was occupied near low water, consequently, minimum and maximum values, respectively, due to tidal effects would be expected at these stations. Since these are relatively shallow area, it would be expected that a larger variation in salinity would occur between high and low water, than in an area where depths are greater and horizontal salinity gradients, less.

The plot of June 18 indicates an increase in the minimum C to 7.1 % and a decrease in the maximum to 16.9 %. This decrease in the maximum, may as on the previous day have been due partly to tidal effects, or it may have been due to the decrease in river discharge. In this instance, tidal effects seem more likely to have given rise to the apparently large changes in distribution of fresh water in the Sound.

From the plots presented for the period June 8 to 18 the large daily variations are obvious. These variations were due principally to the large unsteady fresh water discharge. The observations in the southern part of the Sound, however, suggest that some tidal effects were appearing.

(5) June 21 - June 26:

During this period a general survey was made in part of Hecate Strait, Dixon Entrance, and the entrance to some of the passages in south-eastern Alaska. From this survey it appears that little of the fresh water discharged from Chatham Sound, was reaching the Pacific Ocean through Hecate Strait. Fresh water concentrations as high as 9.2 % were observed some 50 miles north-west of Cape Fox, and in Dixon Entrance concentrations of approximately 7 % were observed some 35 miles west of Dundas Island. Concentrations west of Triple Island decreased to less than 1 % within 10 miles.

(6) July:

During June 2 to 7 inclusively, and July 22 and 23, 4 anchor stations were occupied. The results of these will be presented and discussed later.

(7) August 3 - August 5:

During this period stations in the north and central part of the Sound were occupied, some three times, some twice and some only once. The data from those stations occupied more than once were averaged. The fresh water distribution for this period is presented in figure 13(d). The concentration varied from 3.5 % at station 27 to 18 % at the station just south of Cape Fox, while a secondary maximum of 16.6 % was observed at station 30, located just south of Wales Island. The high concentration near Cape Fox suggests one of two possibilities:

(a) Relatively fresh water was entering the area through passages north of the Sound.

(b) An accumulation of relatively fresh water, that was possibly moving out of the area.

It is instructive to compare the distribution of fresh water on August 3 with that on the 5th (figures 13(a) and (c) respectively). On August 3, C varied from 7.8 % at station 31 to 17.0 % at station 33 and on August 5 it varied from 6.0 % at stations 21 and 22 to 18.0 % at station 31. The change in pattern was undoubtedly due largely to two factors:

(a) Differences in tidal phases

(b) Variations in fresh water discharge.

Comparison of the two sets of data between Melville and Tugwell Islands indicates that there has been a decrease in fresh water concentration from the 3rd to the 5th. However, both sets of data were taken on the same tidal phase. This suggests that (b) was the predominant factor here. In the area southwest of Digby Island an even larger decrease in fresh water concentration is noted. The observations on the 3rd were made midway on the flooding tide, while on the 5th, observations were made immediately after high water. This suggests that the observed change was possibly the result of both (a) and (b).

Station 31, located at the mouth of Portland Inlet was occupied near low water both times, but the concentration was 18 % on the 5th compared with 7.8 % on the 3rd which suggests that (b) was the important factor.

During the few days prior to this period of August 3 - 5 the Nass discharge was increasing while that of the Skeena was decreasing. This fact supports the suggestion that the large observed fluctuations of fresh water in the Sound were mainly due to variations in river discharge.

(8) August 10 - August 19:

The mean distribution of fresh water and surface salinity during this period has been discussed in section VI. Here as in the June 8 - 18 survey, plots were made for each tidal phase. Although the fresh water discharged into the Sound from day to day remained relatively constant the time interval over which the survey was made, appears too long to allow a synoptic picture to be drawn. Evidence of this appears upon examination of a station located near Tugwell Island which was occupied during both parts of the survey. It illustrates that the variation in fresh water concentration for similar stages of the tide but on different days, was greater than the maximum variation between high and low water.

Plots of fresh water concentration have been made for each day regardless of tide. The patterns in the southern half varied only slightly from the average, and have not been illustrated. However those in the northern half indicate relatively large variations from the average. These plots are shown in figures 16 (a), (b), (c) and (d).

On August 16 C varied from 4.1 % at station 26 to 12.7 % at station 29. The interesting feature of this plot is the tongue of relatively high fresh water concentration extending westward towards Hudson Bay Passage, which suggests some movement in this direction.

The distribution of fresh water on August 17 has changed considerably from the previous day. The 6 % C line best illustrates the observed change. It has now been displaced further northward in the Sound to be replaced by more saline water. However there has been an increase in fresh water concentration along the Tsimpsean Peninsula. The maximum C, 10.5 %, observed at station 36, in the middle of Dundas Passage has decreased from the previous day.

The August 18 plot exhibits little change from that of the 17th in the central part of the Sound but the maximum was again observed at station 29. It seems most probable that this maximum represents a new cell of brackish water which has moved out of Portland Inlet and the water, which had the highest concentration the previous day, has moved out of the area.

On August 19 C varied from 4.3 % at station 25 to 8.7 % at station 29. This was the minimum variation observed in the Sound during the 4 day survey.

These individual surveys then, indicate a rather large variation from the average distribution and suggest more clearly the tendency for some southwestward movement of fresh water. This is also indicated in the average distribution of fresh water (fig. 4) as noted from the "shape" of the 5 % C line.

It should be pointed out that during this period the Skeena River water contributes considerable to the distribution of fresh water in the central and northern part of the Sound. Consequently, the patterns of fresh water concentration observed cannot be interpreted on the basis of Nass River discharge alone.

(9) September 8 - September 10:

This was the last survey made during the expedition and consisted of a fairly complete coverage of the Sound. Surface samples and B.T. casts were usually made for 3 positions between stations, consequently a fairly detailed surface salinity pattern is available.

The average fresh water concentration is presented in figure 15 (c). C varied from 0.0 % in the south central part of the Sound to 15.9 % at station 29. The pattern was very similar to the average presented for August 10 - 19, but had a much higher fresh water concentration. The 10 % line approximately replaced the 7 % of August 10 - 19 and a similar displacement of the other lines was observed. There were indications also of some flow through Brown Passage.

The presence of quite saline water just off Inverness Passage compared with the mean may in part be due to the tide because observations in the southern part of the Sound were made at high water ± 3 hours, whereas those in the approximate latitude of Tugwell Island were made at low water ± 3 hours. This fact then, would explain the abnormal distribution of fresh water in this part of the Sound. The general higher fresh water concentration however, is attributed to the increase in discharge of both the Nass and Skeena during the first 5 days of September.

The surface salinity pattern is illustrated in figure 15 (a). The salinity likewise was lower than the average of August 10 - 19, varying from 19 ‰ at the station just south of Kennedy Island to 31.9 ‰ at station 45 located just north of Edye Passage. The explanation of the distribution in the southern part is similar to that given for the distribution of fresh water. In the northern area a cell of low salinity water was present near station 52. A tongue of low salinity water also extended from Portland Inlet. The cell of brackish water appears to have moved into the area since the previous day, consequently the pattern illustrated is quite possibly not synoptic. It is more likely that this cell of low salinity water was, on the previous day, the tongue of water which is indicated to be moving out of Portland Inlet. The decrease in salinity was presumably due to the sudden increase in Nass River discharge during September 3 and 4.

In figure 15(b) the salinity pattern at 6 feet is shown. It is interesting to note that while the patern is very similar to that of fresh water concentration (fig. 15(c)), it shows a marked difference from the surface salinity pattern (fig. 15(a)), especially in the northern part of the Sound. The cell of low salinity water indicated in the surface pattern is entirely absent at 6 feet. This portrays the shallowness of the cell of brackish water.

The September 8 - 10 survey can be summarized as follows:

(1) The average fresh water concentration in the Sound was greater than that presented for average river discharge conditions. This correlates with the observed river discharges.

(2) The observations cannot be considered as synoptic. Thecrowding of the isolines in the southern area was accentuated due to differences in tidal phases. The shallow brackish layer in the northern area is associated with the increase in Nass River discharge. The cell observed on the 10th is associated with the tongue which extended from Portland Inlet on the 9th.

(3) The fresh water concentration pattern is a fair approximation to the mean distribution during this period.

These observations on September 10 concluded the survey of Chatham Sound.

VIII ANCHOR STATIONS:

During the course of the survey, 7 anchor stations were occupied. The locations of these are shown in figure 5.

Observations of temperature and salinity in the water column were made at intervals of 1 to 2 hours. From these observations the dominant factors determining the structure of the water, and its variations should appear.

The salinity and temperature of the water in the Sound at any particular place and time are determined by;

(1) river discharge

(2) tide

(3) wind

(4) interval waves

(5) insolation and cooling

(6) evaporation and precipitation

(7) currents outside the area, but which influence the water in the Sound

Of these factors, the first four are predominant in controling the salinity.

Anchor station 80:

Station 80, located just south of Digby Island was the first to be occupied. Observations were commenced on July 2 and continued for approximately 25 hours, with observations made at intervals of about 1 1/2 hours. Figure 16 shows the variation of salinity with time at the surface, 18, 30, and 36 feet and in the same diagram the variation of fresh water concentration with time is shown. (The tide curve as well, is illustrated.)

The surface salinity curve follows that of the tide very closely, illustrating that the tide is the predominant factor at this time in determining the fluctuations at the surface.

The salinity variation at 18 feet exhibits little or no correlation with tide. The transition zone between the upper brackish layer and the deeper more saline water, which is indicated by the sharp vertical salinity gradient, is observed to be at this depth. Considerable mixing and transfer of water must be occurring across the boundary between these layers, which apparently masked any tidal effects. (Presumably most of the energy supplied for mixing is derived from tidal forces, but this secondary effect is not of necessity in phase with the tide.)

The variations in salinity at 30 and 36 feet, and in fresh water concentration in the upper 60 feet, all follow the tide curve closely. It is evident from these curves that a fair degree of correlation exists between the curves of salinity, fresh water concentration, and tide.

The relationships of the depth of the 27‰ salinity line and the 50° F isotherm, versus time were also drawn. These showed essentially the same fluctuations as have been illustrated for the variations at a particular depth. While in each case the period of oscillation was about equal to that of the tide the phase of the salinity, fresh water concentration, and temperature curves lagged that of the tide by about 90 degrees.

The curves then all exhibit the same general tendencies, making it evident that the tide was the principal factor in controlling these variations.

Anchor station 81:

On July 4 and 5 station 81 was occupied over a period of 24 hours. Similar diagrams as for station 80 have been made and a few of these are illustrated in figure 17 from which the following items are noted:

(1) Surface salinity variation is small, showing no tidal periodic tendencies.

(2) Salinity at 18 feet doesn't show any tidal variations.

(3) Salinity variations at 30 and 36 feet again correspond fairly closely with the tide curve.

(4) Variation in fresh water concentration follows the tide curve closely.

(5) In each case where correlations existed the phase of the salinity, temperature, and fresh water concentration curves were advanced in phase relative to the tide curve by 60 - 90 degrees.

Plots of depth versus time for the 52° F and 26‰ isolines (not illustrated) also agrred closely with the tide curve.

The small variation in surface salinity with time as compared with that of station 80 is to be expected since it is located further from a fresh water supply and consequently the horizontal gradient of salinity was smaller. It also suggests the possibility of a net flow over the tidal cycle.

Anchor station 82:

On July 5, 6, and 7, station 82 was occupied for a period of 40 hours. The variations in salinity of the water column with time is illustrated in figure 18 (a) and in figure 18 (b) the variation of salinity with time at various d epths is shown. These plots do not show any correlation with tidal cycles. Figure 18 (c) shows the variation in depth of the 29‰ salinity line, and the 49° F isotherm together with the variation in fresh water concentration. Each of the curves are observed to correlate very closely with one another, though not with tide. The complicated variationscould be accounted for by internal waves alone but it is quite possible that the structure indicated was the result of a combination of several factors (e.g. tide, river discharge, wind, and internal waves).

On July 22 and 23 station 82 was again occupied for a period of 25 hours and as during the previous occupation, no correlation with tide was evident. Surface salinity fluctuated more widely than on July 5, 6, and 7. No explanation for this difference appears.

Anchor station 113:

On August 7 and 8 the ship was anchored at station 113 for a period of 25 hours. This station is located very close to station 80 and therefore for comparison, the two stations can be considered as identical.

Surface salinity variations, etc., are illustrated in figure 19 (a). These curves are ssen to have a variation with a period similar to that of the tide, however the surface salinity is approximately 180 degrees out of phase with those of tide, and of salinity and temperature at 18 and 36 feet. Such a phase difference could be explained if the surface and deeper currents were in opposite directions. Surface salinity fluctuations from high to low water were much greater than during the July 2 and 3 occupation of station 80. The wider fluctuations are due possibly to the decrease in Skeena River discharge, which would also result in greater surface salinity gradients in this region at this time than during higher river discharge levels.

While the variation in salinity, temperature, and fresh water concentration at station 82 exhibits no correlation with the tidal cycle, variations at all other stations do show an approximate correlation with that of the tide. These complicated fluctuations of salinity and temperature could have been due in addition to tide, to any one or a combination of different factors such as wind, river discharge, and internal waves. Sufficient data of an intensive nature are not available to determine the relative importance of the various factors.

Anchor stations 75 and 76:

On August 24 and 31 stations 75 and 76 respectively were each occupied for a period of about 12 hours. These stations were occupied primarily for current observations, but salinity and temperature observations were also made. Salinity and fresh water concentration variations are illustrated in figures 20 (a) and 21 (a). The variations agreed closely with the tidal phase, however the brief periods of occupation prevent conclusive deductions from being drawn.

IX CURRENT OBSERVATIONS:

Occasionally surface current observations were made at some of the hydrographic stations occupied during the surveys. More detailed direct observations were made at anchor stations 113, 75, and 76, occupied on August 7 and 8, 24, and 31, respectively. Measurements were made at the surface, 15, 30, and some at 60 foot depths using current drags.

Calculations of currents from temperature and salinity observations have also been made. The results of these calculations will be presented and discussed later (section XI).

Temperature and salinity observations also made at these stations have been presented and discussed previously (section VII).

Station 113, August 7 - 8:

Observations of velocity were made at the surface and at a depth of 30 feet. The predominant flow was observed to be in the direction 315 ° T. Figure 19 (b) illustrates the surface velocity along this line. The surface current varied from a value of -0.40 ft./sec. at 2 hours before lower high water to a maximum of 2.9 ft./sec. about 2 hours before lower low water. The mean velocity along this line during a 24 hour period was 1.0 ft./sec. Velocities at 30 feet were similar in phase to those at the surface, although the range was somewhat greater, varying from 0 to 4.0 ft./sec.

Station 75, August 24:

On August 24 station 75 was occupied for a period of approximately 12 hours. Hodographs of the velocities at half hour intervals for 0, 15, 30, and 60 feet are presented in figure 20 (c). These indicate that the resultant flow at all depths down to 60 feet was approximately in the direction 315 ° T. The mean current in the direction of resultant flow over approximately a 12 hour period (HLW to LLW) was 0.94 ft./sec. at the surface, 0.69 at 15 feet, 0.40 at 40 feet, and 0.17 at 60 feet.

In an estuary which is effectively two-dimensional a flow of the deep more saline water towards the head of the estuary is required in order to maintain the observed salinity structure in the upper layer. Tully, in his study of Alberni Inlet observed that this up-inlet flow occurred well above 60 feet. It is possible that since this area of Chatham Sound cannot be considered in two dimensions, the necessary flow of the deep water is from the southeast, consequently resulting in a net flow in the same direction as that at the surface. Alternately, it is quite possible that a flow of water at depths greater than 60 feet was in the reverse direction to the surface current. Exmination of the salinity profile indicates that there was still some dilution due to fresh water at 60 feet.

For comparison of this station with station 113 currents at the surface and 60 feet in the direction, 315 ° T are presented in figure 20 (b).

Station 76, August 31:

On August 31 the ship was anchored near Wales Island, off Portland Inlet. Cameron (1951) has reported on the results of these observations.

The seaward velocity at the surface and 60 feet is illustrated in figure 21 (b). The surface current was seaward over the period of observation, fluctuating in speed near lower high water, reaching a maximum at higher low water, and decreasing to zero at higher high water. The average seaward velocity averaged over a period of 12 hours was 0.81 ft./sec.

The seaward velocity averaged from lower high water to higher low water was 1.1 ft./sec. The current at 60 feet was less and different in phase. The average velocity was 0.25 ft./sec. making a mean difference in seaward velocity between the surface and 60 feet of 0.56 ft./sec.

Further use of these current observations will be made later.

X SALINITY STRUCTURE AND MIXING MECHANISM:

If the vertical distribution of salinity at one position is examined it will be found that the water is arranged in a series of sheets or strata. The upper layer is the least saline, while at greater depths the water becomes more and more saline and in general undiluted sea water is found within 100 feet of the surface. Although, in each case, the total range in salinity from surface to bottom, is usually of the same order of magnitude, the number of distinct layers observed, will vary with position and time. While the two layer system, having a transition region, where the salinity gradient increases sharply from low salinity at the surface layer to higher salinity in the deeper water, is the most common, there may be as many as 4 or 5 sheets. In each case they are arranged in the order of increasing density with depth. This stratification occurs, because, in large bodies of water, sufficient energy to mix the waters completely, is not available. Work has to be done against gravity to move the deep saline water up to the surface zone. A parcel of water, then, may retain its salinity for long periods of time unless sufficient energy is available to mix it with the surrounding water. Three factors, tide, river discharge, and wind are capable of supplying energy for mixing. Of these the tide is probably the most important factor.

Tully, (1949) in his study of Alberni Inlet, has observed some interesting relationships between the estuarine properties and both the tidal motions and river discharge. He has observed that a linear relationship exists between tidal velocities and the increase in sea water per unit volume of fresh water in the upper layer, and has deduced the decreasing proportion of fresh water toward the mouth of the inlet to be the result of the rate of mixing, due to the tide alone.

"From visual observation of the numerous eddies and rips that are present in the Skeena, near its mouth, one might conclude that in this locality at least, the water would be fairly uniform from top to bottom. But examination of the vertical distribution of salinity shows that this is not the case." (Cameron, 1948) In figure 22 the distribution of fresh water in a vertical section through the main channel of the Skeena River, from a position near the southern tip of Kennedy Island to a point just off the Ecstall River mouth, is presented. The section was made during a flooding tide on September 7, and illustrates conditions during the influx of sea water into the river.

The most outstanding feature of the section is the general inclination of the lines of constant fresh water concentration. For example the 50 % c line intersects the bottom 4 miles upstream from its position at the surface. It is noted also that the isolines are not equally spaced. The greatest change in horizontal concentration at the surface appears just seaward of Inverness Passage, between stations 113 and 97. Along the bottom the greatest horizontal gradient is near station 97. The regions where concentrations change rapidly with distance, represent boundaries established by the movement of water through Inverness and Marcus Passages. As a result of these passages, there must be some flow across the main channel at all stages of the tide. When the tide is flooding, sea water enters the river through the three channels, moves in under the river water, lifting it to its high tide level and effectively damming up the river water. The influx of sea water increases mixing, however, the cross-section presented indicates that it is far from complete.

At high tide, upstream from Inverness Passage, the surface water is nearly fresh, while the bottom waters are considerably more saline. During the ebb tide the whole water column from top to bottom is moving seaward. Inverness Passage being furthest upstream and somewhat shallower than the other passages, discharges water into the sound, of relatively high fresh water concentration. Marcus Passage is further to seaward and therefore discharges more saline water than Inverness Passage. The most saline water of all, discharges through the main channel. Thus the passages contain decreasing amounts of fresh water from north to south.

During the next flooding tide the water in each passage is pushed upstream by the invading sea water and the regions where these streams of different fresh water concentration join, are marked by diffuse boundaries in which the fresh water concentration changes rapidly with distance. Although extensive mixing of water occurs across these boundaries, they are not completely obliterated, being continually reformed by the effect of cross channel flow in these regions.

Boundaries of this type are also found in the open stretches of the Sound and frequently can be identified, not only by the determination of salinity, but by an abrupt change in the colour of the water. The water discharged from the Nass and Skeena is brackish and muddy. Since it is lighter than the more saline water of the Sound, it remains at the surface and tends to move seaward because of continuous contribution of fresh water from the rivers. Mixing with the underlying water proceeds slowly and the brackish water spreads out laterally as it enters the Sound.

Tidal oscillations are superimposed on the mean seaward movements of f fresh water. While the exact nature of the tidal movements is not known, some resultant effects have actually been observed. Very often it has been noticed that at the boundary between the river water and sea water, floating debris, such as seaweed, bark, or even logs stretch for several miles. These narrow, clearly marked lines, are known as "tide lines". The fact that the floating debris remains together indicates that there is a convergence of surface water from both sides, toward the line. Consequently mixing and sinking must be occurring at the boundary.

The surface water is never completely bounded by a continuous line marking the boundary where sinking occurs. Tidal currents vary in direction and magnitude and mixing of the more saline water with the brackish water proceeds irregularly and at widely separated localities. On this account, several tide lines may be present at various positions in Chatham Sound at the same time.

An example of the character of the water below the surface in the vicinity of a tide line is illustrated in figure 23. This line was observed on the surface during the survey of July 21, and extended from a point just northwest of Dundas Island northeast toward Garnet Point. The section was made just before high water in a line from Cape Fox to the north end of Dundas Island (between station 28 and 27). The figure illustrating the fresh water concentration shows that a relatively brackish (> 15 % fresh water) layer of water extended across the passage, decreasing gradually in depth toward the south. At the position of the tide line the surface salinity increased abruptly, the surface water having a fresh water concentration to the south of the line of approximately 6 %.

Examination of the temperature section also reveals the sinking of water at the tide line. This temperature distribution shows that sinking in the direction of the tongue (arrows), and gradual mixing between the upper and lower layers of water was occurring.

In the section made on the same line just after high water, this tongue of warm water had completely disappeared, apparently the result of extensive mixing.

The examples cited above, then, represent the chief mechanism whereby the brackish and more saline waters are mixed.

XI DYNAMICS:

At the present time the dynamics of the circulation of the open ocean are better understood than those of inshore waters. In the deep ocean the circulation may be determined with some accuracy by the use of the geostrophic equation, indicating that the predominant forces are those due to the horizontal pressure gradient and the coriolis force. This permits the calculation of currents from observation of temperature and salinity.

Estuaries, however, present a more complicated problem since the extent to which the simplifying assumptions that are legitimate when treating the open ocean, is questionable. The net flow of fresh water seaward, and the observed increase in salinity of the upper layer in the seaward direction, indicate that large pressure gradients along the direction of mean flow exist. The relative importance of inertial and frictional forces in balancing these pressure gradients is not known with any degree of certainty. In shallow estuaries the bottom may introduce an important frictional effect and greatly influence the rate and degree of turbulent mixing. The kinematic requirements placed on the flow, by the complicated boundaries must also be met.

For the case of long, narrow estuaries which can be treated in two dimensions the seaward decrease in fresh water concentration in the upper layer requires a net upward transport of the deep more saline water, which in turn requires a net horizontal flow of this water in the reverse direction to that of the upper layer. Therefore some depth of no net horizontal motion between the two layers must exist. However, Chatham Sound presents a more complicated problem. The irregular coastline, the wide variations in depth, and the introduction of fresh water from two separate sources require a three-dimensional treatment. While the same movement of deep water, as in long narrow estuaries, must of necessity be occurring, it is only in narrow restricted localities where the actual mean flow can be inferred without making observations in that part of the water column.

Superimposed on the mean motion in an estuary are the acceleration and presure forces established by the tidal oscillations. While the resultant periodic changes in sea level due to tidal forces are well known, the detailed effects of the tide in estuarine waters are not clearly understood. The problem is further complicated by the occurrence of non-periodic variation in river discharge and wind.

It appears then, that in the immediate future at least, a formal solution to the equation of motion will not be forthcoming. Therefore, simplifing assumptions will have to be made in an attempt to get a partial solution to the problem, and perhaps indicate more clearly future methods of attack.

Recent investigations of Chesapeake Bay by Pritchard (1952) have indicated that certain assumptions regarding the flow in this estuary are justified. He has observed a characteristic lateral gradient in salinity (across the estuary) and a characteristic slope in the surface of no net motion. He suggests that this lateral salinity distribution, resulting in a mean lateral pressure gradient, is in the main balanced by the coriolis force related to the mean longitudinal motion (sea ward). Extensive observation at 3 cross-sections in the James River estuary have shown that more than 75 % of the coriolis force associated with the mean longitudinal motion is balanced by the lateral pressure gradient related to the lateral salinity gradient. This same tendency for the development of a lateral salinity gradient has been observed at stations 30 and 31, located at the mouth of Portland Inlet. Cameron (1951) has reported on these observations. On the assumptions of geostrophic flow and no motion at 90 feet, surface velocities, volume transports, and fresh water transports, were calculated for 12 occupations of these stations. Surface velocities agreed in magnitude and direction with those measured at an anchor station nearby (station 76). Fresh water transports were also considered to be in reasonable agreement with Nass River discharges measured at Aiyansh. If it is assumed that the upward transfer of salt occurs by virtue of the fresh water discharged into the Inlet, then it would be expected that a decrease would occur when fresh water transports decreased. On the contrary the calculations indicated that although the fresh water transport decreased in proportion to river discharge, no change in volume transport occured. If this is actually the case, then it means that there must be an increase in the volume of salt water transported upward equal to the decrease in fresh water transported. The reason for this apparent increase in the upward transfer of salt, is not evident.

(b) Presentation and discussion of calculations:

The calculations of surface velocities, volume and fresh water transports were made by Cameron for the occupations of stations 30 and 31 only. These are presented in table II. The average surface velocity calculated for the 12 occupations was 0.75 ft./sec. This is in good agreement with observation made at anchor station 76, on August 31, which indicated an average net seaward velocity over a 12 hour period of 0.81 ft./sec.

In the present study dynamic calculations have been extended over most of the Sound. Similarly surface velocities, volume and fresh water transports have been deduced. These calculations were made with the thought of getting quantitative values of fresh water transports from section to section, and hence possibly obtain values for the quantity of fresh water from each river passing through a particular section.

Table II[Δ]

Seaward Surface Velocities, Volume and Fresh Water Transports, Out of Portland Inlet (Calculated From Dynamic Height Data at Stations 30 and 31, Assuming no Motion at 90 Feet)

Date	Surface Seaward Velocity (ft./sec.)	Volume Transport (cu. ft./sec.)	Fresh Water Transport (cu. ft./sec.)
June 1	0.76	500,000	172,000
2	0.20	251,000	73,500
3	0.35	604,000	126,000
4	1.03	336,000	117,000
8	0.81	284,000	75,000
9	1.66	570,000	130,000
10	0.29	185,000	22,300
11	1.62	384,000	107,000
Aug. 16	0.29	366,000	35,200
17	0.68	450,000	40,500
18	0.57	207,000	22,000
19	0.74	647,000	48,500

June 1 - June 4:

Calculations for June 1 data indicate a seaward velocity between stations 30 and 31 at the mouth of Portland Inlet of 0.76 ft./sec. and a fresh water transport of 172,000 cu. ft./sec. Calculations between stations 24 and 25 across Main Passage give a northerly surface velocity of 0.86 ft./sec. and a fresh water transport of 137,000 cu. ft./sec. Between stations 26 and 29 across Dundas Passage a westward surface velocity of 2.3 ft./sec. and a fresh water transport of 398,000 cu. ft./sec. was calculated. In view of the

Δ From Cameron (1951) Transverse Forces in a British Columbia Inlet assumptions involved, these calculated values appear reasonably consistent.

For June 2 similar calculations were made. These gave a seaward velocity between stations 30 and 31 of 0.20 ft./sec. and a fresh water transport of 73,500 cut. ft./sec., and between stations 24 and 25 a northward surface velocity and fresh water transport of 0.44 ft./sec. and 154,000 cu. ft./sec., respectively. Between stations 26 and 29 a westward surface velocity of 0.31 ft./sec. and a transport of approximately 400,000 cu. ft./sec. were calculated. These transports, especially between station 26 - 29 and 24 - 25 have larger values than would be expected for the mean. However, it is quite possible that these values are real since the tide was ebbing when stations 25, 26 and 29 were occupied.

Calculations of velocity and transports for June 3 and 4 were also made but only those for stations 30 and 31 are illustrated (table II). The irregular values calculated for the other sections demonstrated that during such large and unsteady discharges of fresh water the assumption of the steady state is not justified.

June 8 - June 11:

Average dynamic height anomalies during this period, in the upper 90 feet were calculated from temperature and salinity observations averaged for the four occupations of each station. These are presented in figure 24 (a). The highest anomaly of 1.85 dynamic feet is at station 26 located near the north-east corner of Dundas Island while the lowest is 1.44 at station 27 located near the northwest corner of Dundas Island. Comparison of this plot with that of the average fresh water concentrations during the same period (fig. 10) reveals a close similarity in pattern.

If it were assumed that flow was entirely along the lines of constant anomaly then a very strong transverse flow would be indicated. It seems more reasonable to conclude that, in fact, a large component of flow took place across the lines of constant anomaly. The highest mean maximum located at station 26 is associated with the peak discharge of the Nass which was recorded at Aiyansh some 8 - 10 days earlier. This dynamic topography obviously does not represent a steady state, since from the pattern illustrated, there is no way to maintain the high dynamic height observed at station 26. This "high" would be tending to reduce itself to the potential of the surrounding water by radial outflow and by mixing with more saline water.

The flow out of Portland Inlet during this period was undirectional with a mean surface velocity of 0.84 ft./sec. and a mean fresh water transport of 99,000 cu. ft./sec. Assuming a three day lag for the passage of fresh water from Aiyansh to the mouth of Portland Inlet gives an average discharge of the Nass of 91,000 cu. ft./sec. during this period.

While many of the transports calculated between various pairs of stations during this period were unreliable, it is of interest to note some of these calculations. Between stations 21 and 22 calculations showed a surface velocity of less than 0.1 ft./sec., a net volume transport of less than 1,000 cu. ft./sec. and a fresh water transport of 8,000 cu. ft./sec. to the south. A reversal in the direction of flow above 24 feet relative to 90 feet, accounts for the net volume transport being less than the fresh water transport. The small transport of fresh water compared with those calculated in the northern end of the Sound appears significant and suggests that there is little or no Skeena River water moving northward along the Tsimpsean Peninsula. It is quite possible that this is the case during the freshet period when the Nass River water may effectively act as a barrier to Skeena River water thus forcing it to move seaward through Brown, Bell, and the other southern Passages.

August 10 - August 19:

The average dynamic height anomalies relative to the 60 foot level were calculated in the same manner as for June 8 - 11, These are plotted in figure 24 (b). Anomalies varied from less than 0.86 dynamic feet at station

47 located near Triple Island, to greater than 1.25 at station 29 located just south of Garnet Point. The pattern is very similar to that shown for fresh water concentration during the same period (fig. 4).

Table III shows the average surface velocities, volume and fresh water transports between various stations in the Sound. The maximum average surface velocity was calculated to be 0.73 ft./sec. westward between stations 41 and 44. The surface current measured directly at stations 113 and 75 (located near station 41) was found to have a mean value over a tidal cycle of 1.0 ft./sec. Bearing in mind that 0.73 ft./sec. represents an average across the entire section and that the velocities near station 41 are probably higher than at station 44, the agreement appears satisfactory.

The average fresh water transport between station 30 and 31 was found to be 31,000 cu. ft./sec. compared with the corresponding discharge at Aiyansh of 40,000 cu. ft./sec.

Table III

Average Surface Velocities, Volume Transports, and Fresh Water Transports (Assuming no Motion at 60 Feet) Between Several Stations in Chatham Sound, August 10-19, 1948

Stations	Surface Velocity (ft./sec.)	Direction	Volume Transports (cu. Ft./sec.)	Fresh Water Transports (cu.ft./sec.)
30 - 31	0.42	West	296,000	31,000
26 - 29	0.63	West	423,000	51,000
24 - 25	0.19	North	229,000	23,000
48 - 49	0.34	North	249,000	17,000
41 - 44	0.73	West	700,000	58,000
46 - 48	0.14	West	205,000	5,000

In most cases the calculated fresh water transports seem reasonable. One exception was between stations 41 and 44 where a value of 58,000 cu. ft./sec. was calcuated. This appears to be too large in view of the fact that the mean Skeena discharge at Usk from the 6th to the 9th inclusively was 33,000 cu. ft./sec. Possibly this large value was due to the assumption of a linear gradient of fresh water between the two stations, whereas it is possible that the fresh water tended to be concentrated near station 41.

The fresh water transport between stations 24 and 25 was calculated to be 23,000 cu. ft./sec. Between stations 21 and 22 a flow of fresh water of only 17,000 cu. ft./sec. was indicated. It is quite probable that this difference may be accounted for by a considerable flow of fresh water between station 21 and the mainland. On the basis of these calculations and the previous discussion of fresh water distribution it is evident that about 70 % of the Skeena River discharge was moving northward in Chatham Sound along the Tsimpean Penninsula and out through Dundas and Hudson Bay Passages, 15 % was leaving the Sound through Brown and Bell Passages, and the remaining 15 % was escaping through Edye Passage, Ogden and Grenville Channels.

September 9 - September 10:

On September 9 and 10 stations 24, 25, 26, 29, 30, and 31 were occupied. Calculation of surface velocities and freshwwater transports, assuming no motion at 90 feet, are summaried in table IV.

Table IV

Stations	Surface Velocity (ft./sec.)	Direction	Fresh Water Transport (cu. ft./sec.)
30 - 31	0.59	West	29,000
26 - 29	1.0	West	182,000
24 - 25	0.39	North	68,000

These calculations appear to be in reasonable agreement with river discharges and surface velocity measurements.

(c) Variation in geopotential slope at the mouth of Portland Inlet:

Superimposed on the mean flow seaward oof the surface layer, are tidal movements. If the coriolis force associated with the longitudinal motion is, in the main, balanced by lateral pressured gradients, then a periodicity in the geopotential slope equal to the tidal period should occur. On the basis of the calculations made for stations 30 and 31 (table II) Cameron points out that a periodicity equal to the tide is not evident. However, since the differences in dynamic heights are determined by 2 to 4 foot differences in the level of the isohaline surfaces, then internal waves of comparable magnitude could mask any periodicity resulting from tides. Although these calculations indicate a undirectional flow out of the Inlet for the 12 occupations, two abnormally low values occur in the surface velocities and transports, notably on June 2 and June 10. Both of these sections were made on the flood tide a few hours prior to high water. It is suggested then that these low values may represent instances in which the effect of the tide is noticeable.

On August 4 stations 30, 34, and 31, were each occupied twice. The first section was made during the first hour of the flood tide, while the second section was made from 1 to 2 hours before low water. The directions and velocities of the current at the surface, assuming no motion at 60 feet, are presented in table V. Sation 34 is located approximately midway between stations 30 and 31. During the time the first section was made surface velocities were directed up the Inlet, with an average value between stations 31 and 34 of 0.83 ft./sec. and between stations 34 and 30 of 0.13 ft./sec. The analysis demonstrated that during the time the second section was made the direction of flow had reversed and the greatest flow seaward was between stations 30 and 34 where an average value of 0.49 ft./sec. occurred. The velocity between stations 34 and 31 was 0.08 ft./sec.

Table V

Direction and Magnitude of Surface Current (Assuming No Motion at 60 Feet) at the Mouth of Portland Inlet, August 4, 1948

Stations	Time (P.S.T.)	Velocity (ft./sec.)	Direction
31 - 34	0710	0.83	Up-inlet
34 - 30	0735	0.13	Up-inlet
30 - 34	1725	0.49	Down-inlet
34 - 31	1745	0.08	Down-inlet

While this change in geopotential slope might have been due to tides, other factors, especially wind, could have caused this shift in the distribution of mass and consequently give a calculated up-inlet flow of surface water.

If a tidal periodicity in the dynamic heights does actually occur, then cross-inlet inertial and frictional forces must exist. However the data for the majority of the occupations implies that the coriolis force and the transverse pressure gradient approximately balance each other. The relatively narrow, constant width of Portland Inlet would only require small accelerations and velocities to effect this transverse movement. The relatively low velocities required would keep the transverse shear small.

Insufficient data are available to determine the effect of the tide on the distribution of mass in the Sound.

XII SUMMARY AND CONCLUSIONS:

Data have been presented to show the distribution of fresh water and sur face salinity in Chatham Sound during the period from May to September, 1948. The results of salinity, temperature, and current observation at anchor stations, as well ad dynamic calculation, have also been described.

From the study of these surveys the following conclusions have been drawn:

(1) During normal river discharge conditons, only a small proporiton (<30 %) of Skeena River water reaches Dixon Entrance and Hecate Strait, through the central and southern passages. Approximately 15 % appears to be escaping through Brown and Bell Passages. The other 15 % escaping through Edye Passage, and Ogden and Grenville Channels. The bulk (>70 %) of Skeena River water moves northward past Tugwell Island, along the Tsimpsean Peninsula, merges with the Nass River discharge, and finally leaves the Sound through Dundas Passage and to a lesser extent through Hudson Bay Passage.

(2) The peak discharge of both rivers is reached in late May or early June. The concentration of fresh water in the Sound is 3 - 4 times the average. Fresh water leaves the Sound through all the passages and channels, although Dundas Passage transports the largest amount of any single passage. During this period, Nass River water extends as far south as Melville Island.

(3) It seems quite probable that during freshet conditions, the presence of increased amounts of Nass River water in the northern part of the Sound, acts as a barrier, preventing any extensive movement of Skeena water northward past Tugwell Island. The fact that there is evidence of a fairly effective barrier during this particular year, when the peak discharge of the Skeena was much greater than the normal peak, while the Nass did not reach the same relative abnormal height suggests that during average freshet conditions, the Nass may act as an even more effective barrier to Skeena River water than has been indicated in the 1948 survey.

(4) Observations extending over a period of several days cannot be considered as synoptic when the rivers fluctuate; hence diagrams showing the distribution of fresh water or salinity in the entire Sound, for which data on several days separation have been used, cannot as a rule be considered

properly synoptic.

(5) Anchor stations reveal, that, in most cases variations in salinity, temperature, and fresh water concentration correlate with tidal variations. Departures from these tidal variations are due to any one or a combination of, variations in discharge of fresh water, wind, and internal waves.

(6) Dynamic height anamaly plots give essentially the same pattern as fresh water concentration. An apparent balance exists between coriolis force and transverse pressure gradients at the mouth of Portland Inet. There also is an apparent balance in the Sound during normal discharge conditions. However during freshet conditions cross-isobaric flow is quite probably dominent. Calculations of transports, assuming a steady state, led to anomalous values which appeared obviously erroneous.

(7) From the various surveys there appears to be an average time lag of from 2 - 5 days from the time a particle of water was at Aiyansh until it reached station 30, at the mouth of Portland Inlet, the time required being a minimum during maximum fresh water discharges.

The average time lag between Usk and station 41, located south of Digby Island, appears to be of the order of 3 - 6 days, varying with the discharge. Naturally factors such as variation in wind and tide would decrease or increase these times as the case may be.

(8) During periods of unsteady river discharges large cells of relatively fresh water appear to be discharged into the Sound. These are gradually dispersed as they move seaward, by spreading out laterally and mixing with more saline water. Energy to do this is supplied by the tides, winds, and the potential and momentum of the fresh water itself.

(9) Direction, strength, and duration of the wind are quite probably of considerable importance in causing wide variations from the average.

(10) The discussion of the data has indicated clearly the difficulties involved in obtaining a reliable synoptic picture of an estuary of this size and type. Since usually only one ship is available to carry out a survey, the area which can be covered in a short period of time is limited. While a

general survey of the entire area is required in order to determine the gross features of the distribution of properties and of the circulation, surveys covering a smaller area but of a more intensive nature are required if a clearer understanding of the relative importance of the several factors influencing the circulation is to be obtained. The observations at the anchor stations in the survey illustrate the important role which the tides play in determining the distribution of salinity and temperature at any particular time. A more accurate evaluation of the part played by the tidal currents in transport of fresh water could be obtained if observations (salinity, temperature, currents) across selected sections were taken over a period of several tidal cycles.

In the 1948 survey the observations were made down to depths of 90 or 150 feet at most. A better understanding of the dynamics of the circulation would result if observations were extended, where possible, to deeper levels. From these a knowledge of the depth of no net motion, and the movement and relative magnitudes of the net shoreward transport of the deeper water in the various passages, could be gained. The direct observation of currents would serve, apart from their primary value of indicating the circulation, as a check on dynamic calculations and would ascertain with clarity the degree to which geostrophic flow exists in coastal waters of this type.

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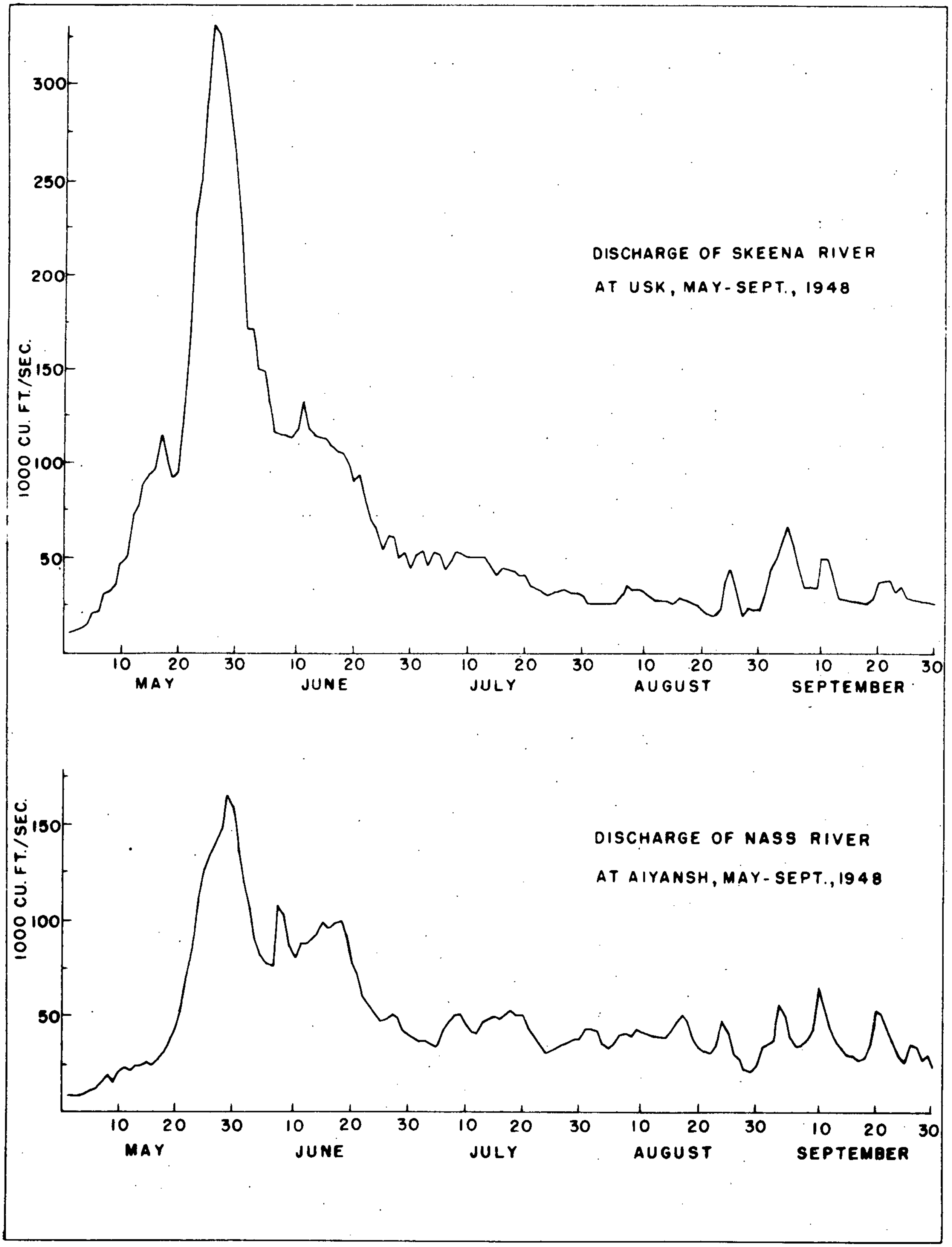
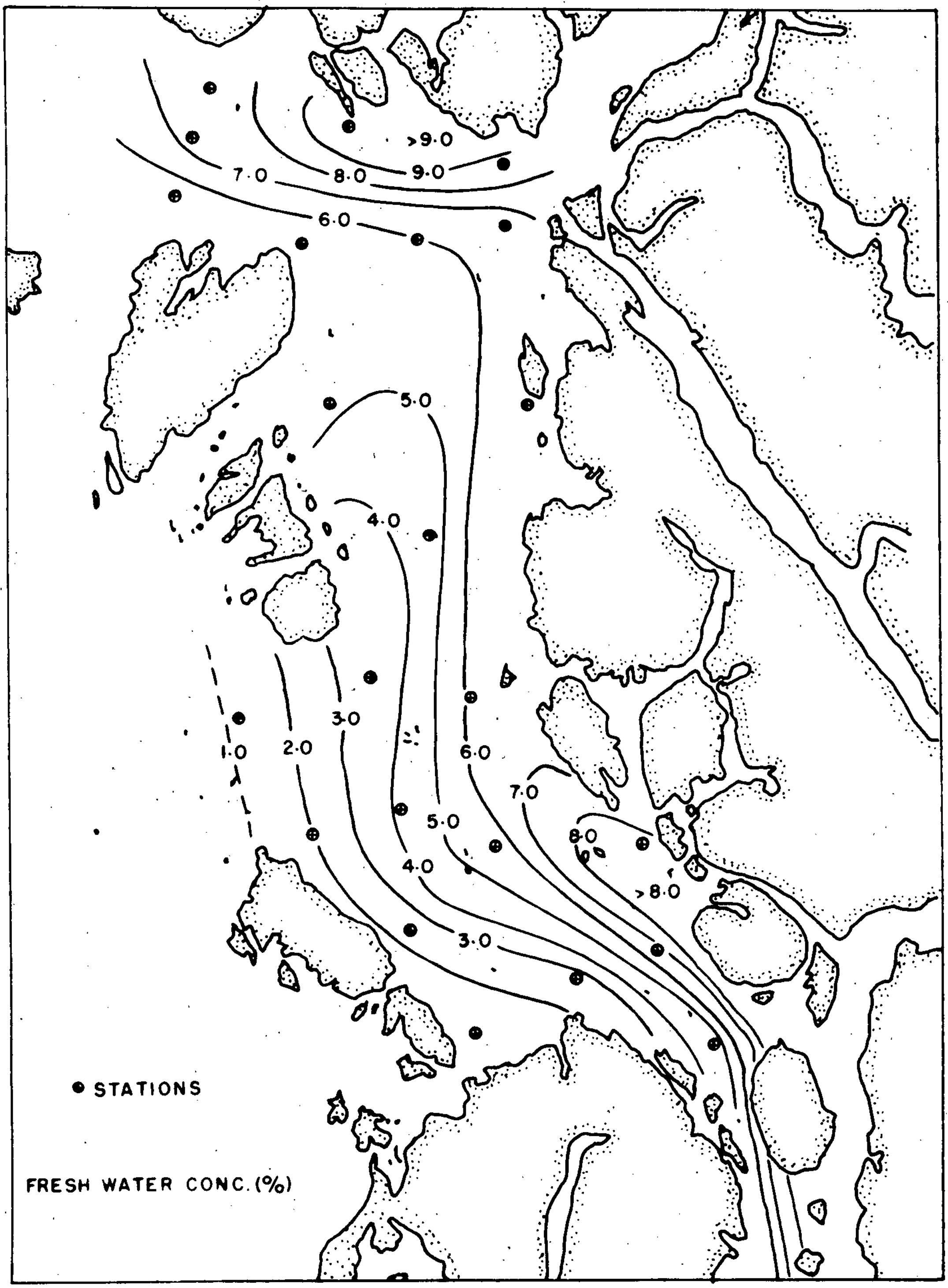


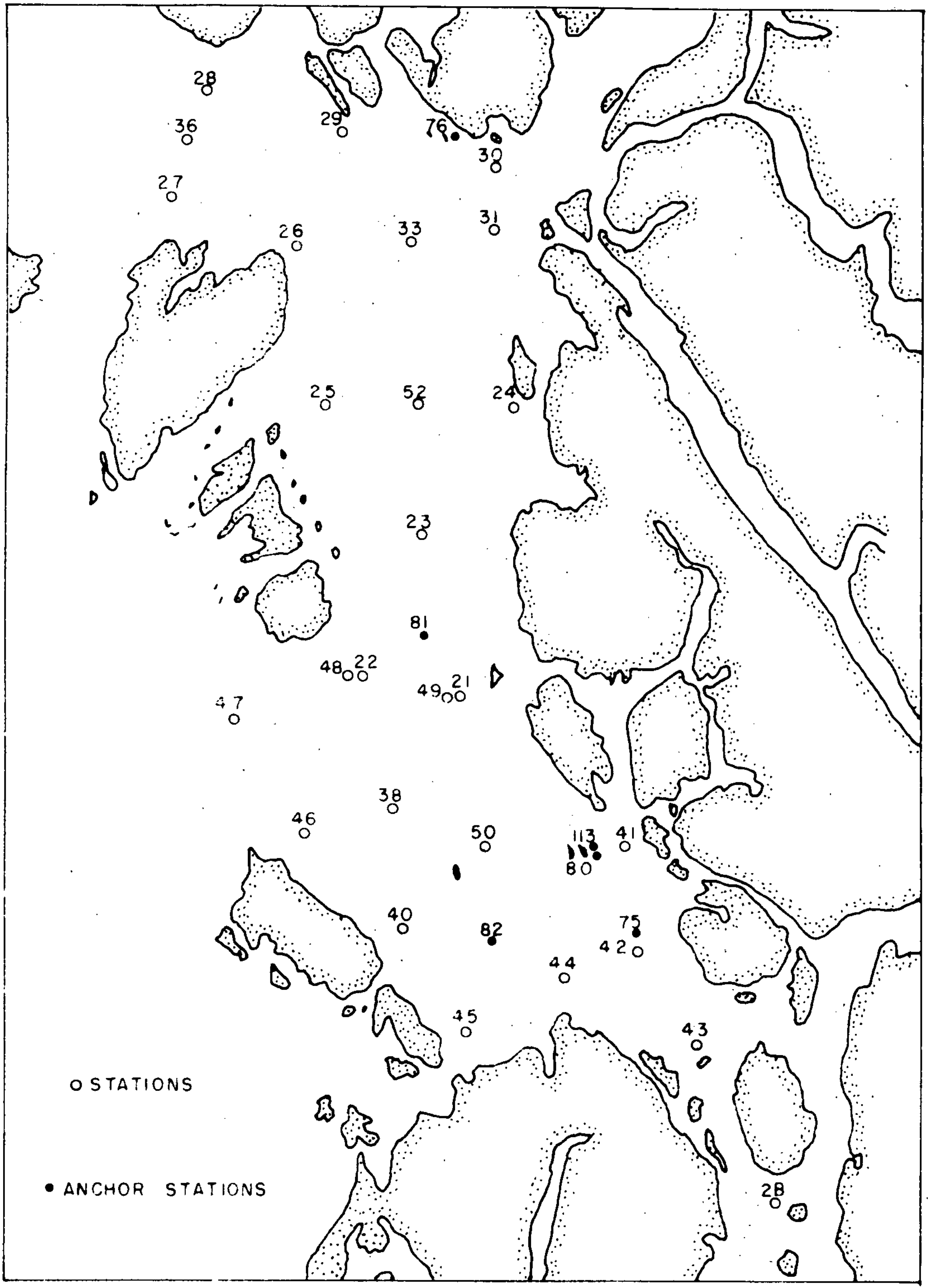
DISCHARGE OF SKEENA RIVER
AT USK, MAY-SEPT., 1948
1000 CU. FT./SEC.
300
250
200
150
100
50
10 20 30 10 20 30 10 20 30 10 20 30 10 20 30
MAY
JUNE
JULY
AUGUST
SEPTEMBER
DISCHARGE OF NASS RIVER
AT AIYANSH, MAY-SEPT., 1948
1000 CU. FT./SEC.
150
100
50
10 20 30 10 20 30 10 20 30 10 20 30 10 20 30
MAY
JUNE
JULY
AUGUST
SEPTEMBER

FIG. 3



% FRESH WATER IN UPPER 60 FT. DURING NORMAL RIVER CONDITIONS, AUGUST 10 - 19, 1948

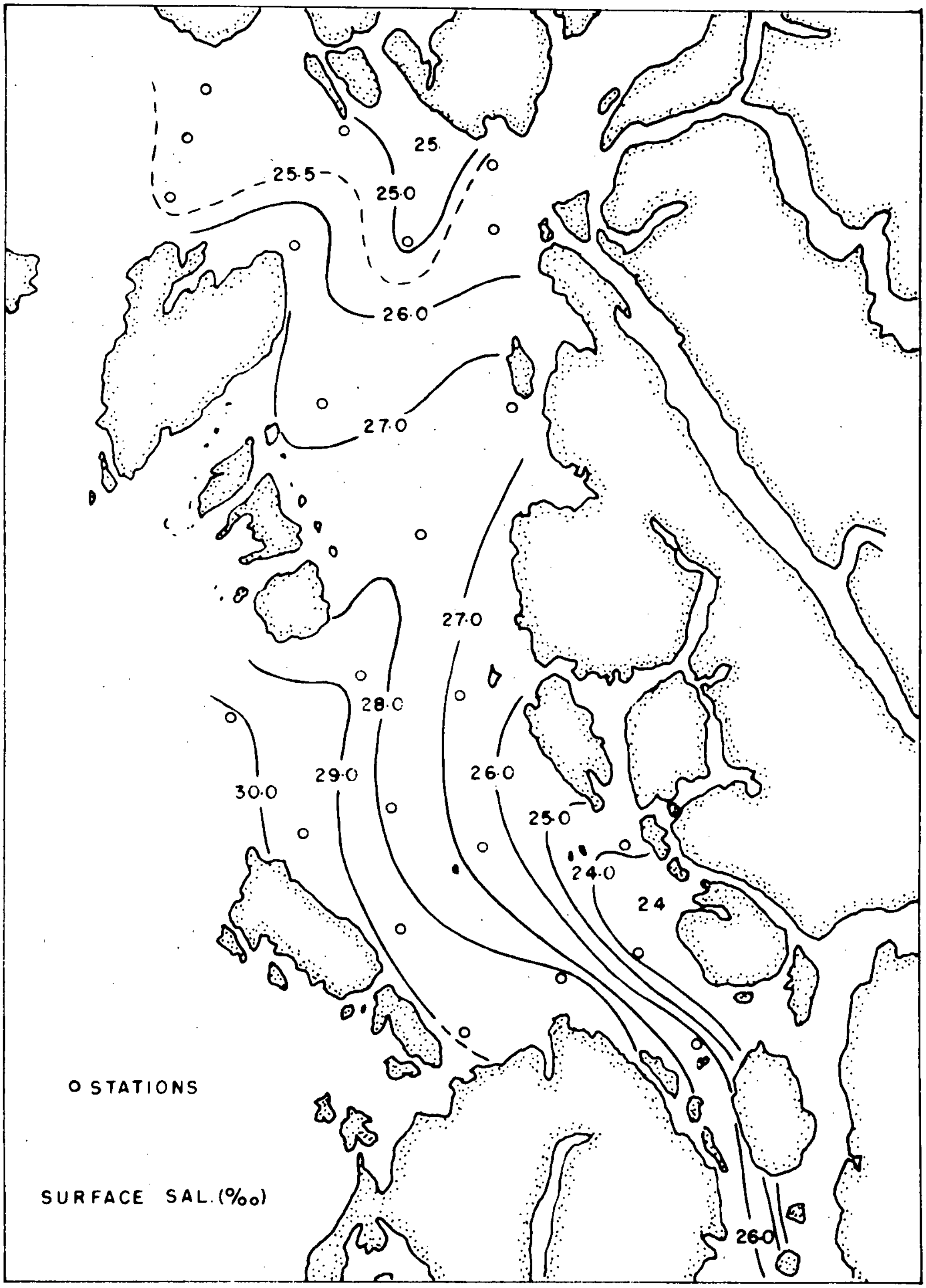
FIG. 4



LOCATIONS AND NUMBERS OF STATIONS MOST FREQUENTLY OCCUPIED

DURING SURVEY, MAY.- SEPT., 1948

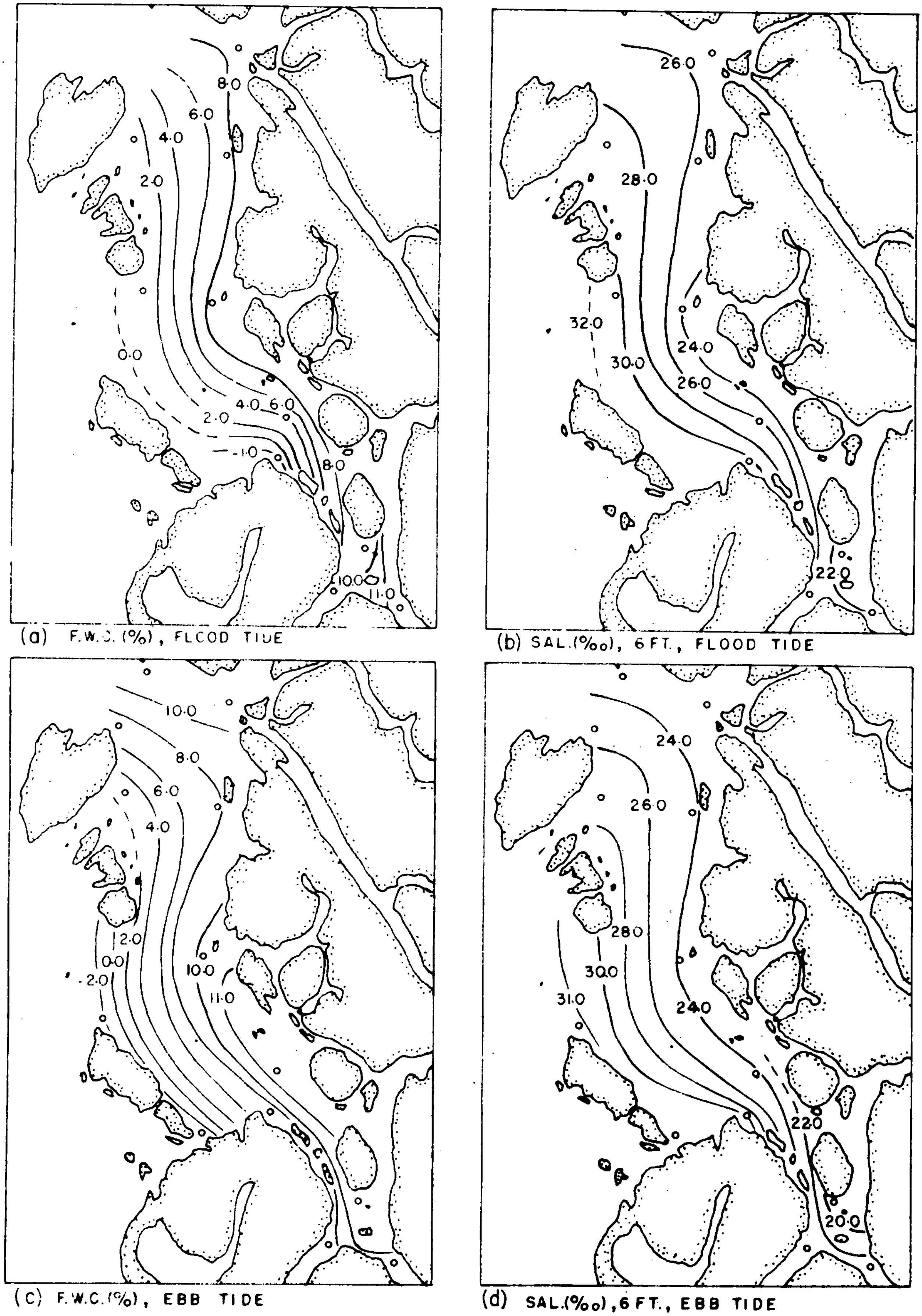
FIG. 5



SURFACE SALINITY PATTERN DURING NORMAL RIVER CONDITIONS

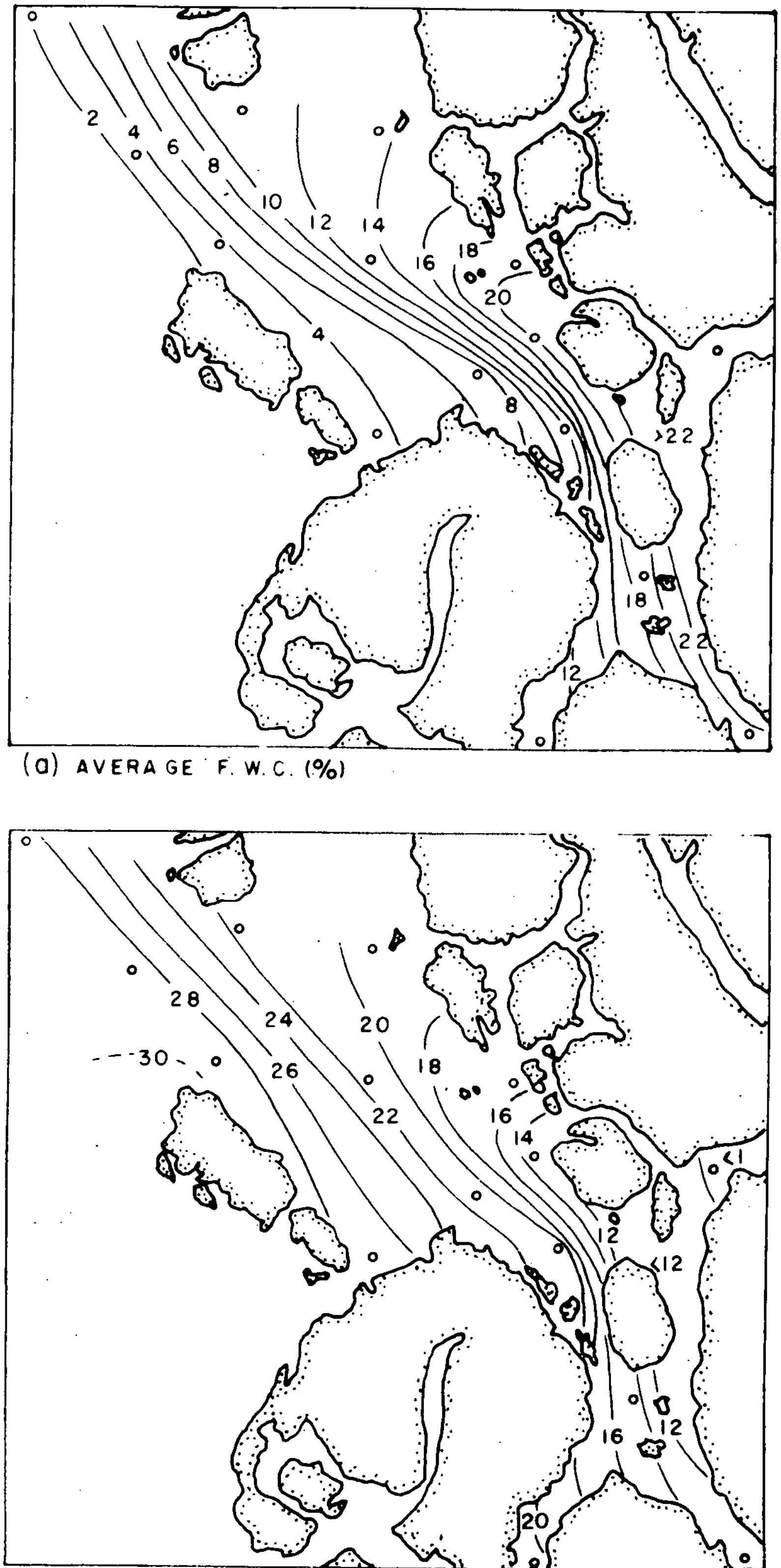
AUGUST 10-19, 1948

FIG. 6



SALINITY PATTERN AT 6 FT, AND FRESH WATER CONC., MAY 19-21, 1948

FIG. 7

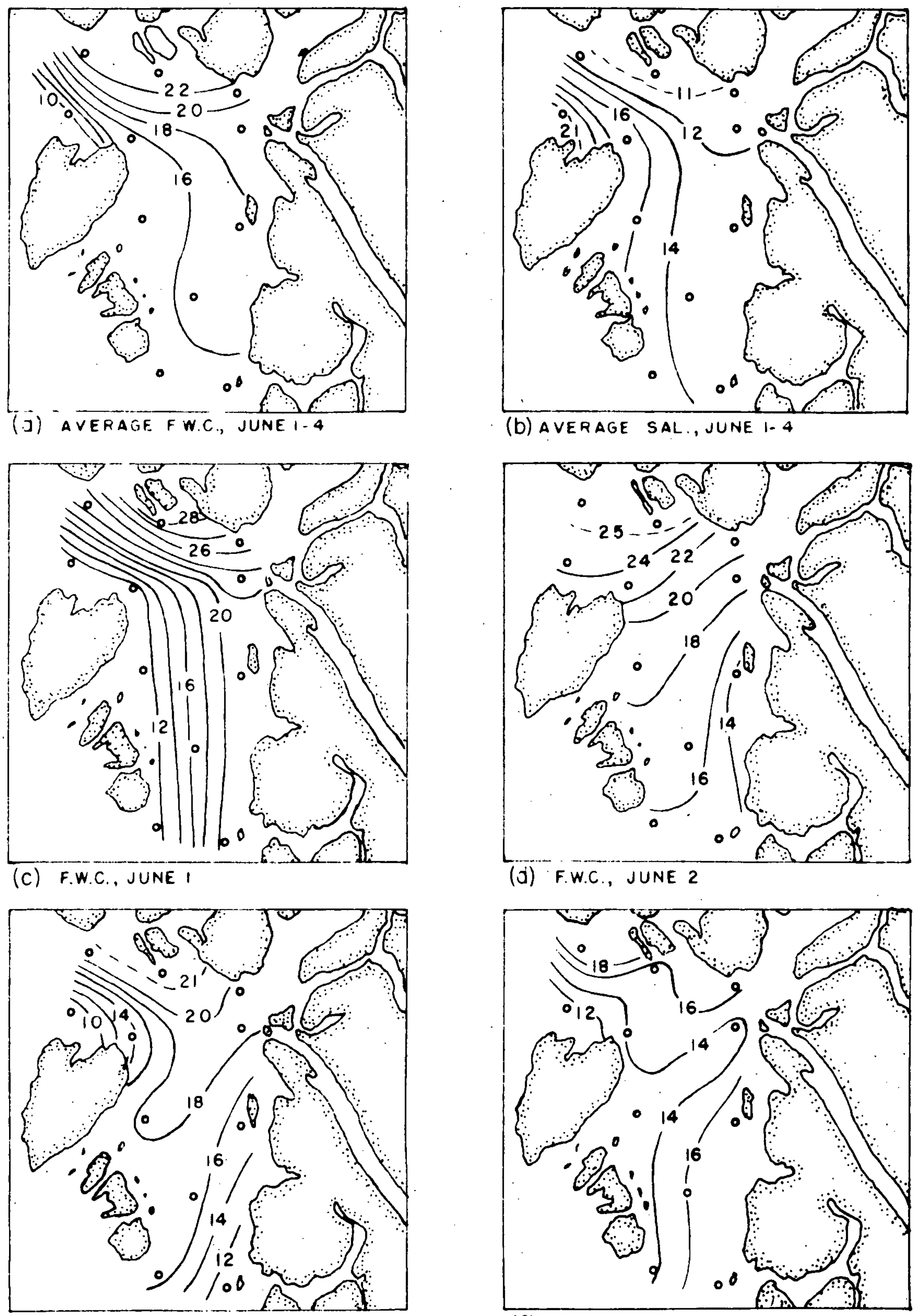


(a) AVERAGE F. W. C. (%)

(b) AVERAGE SALINITY (‰), 6 FT.

AVERAGE SALINITY PATTERN AT 6 FT, AND FRESH WATER CONC., MAY 25-28, 1948

FIG. 8



(a) AVERAGE F.W.C., JUNE 1-4

(b) AVERAGE SAL., JUNE 1-4

(c) F.W.C., JUNE 1

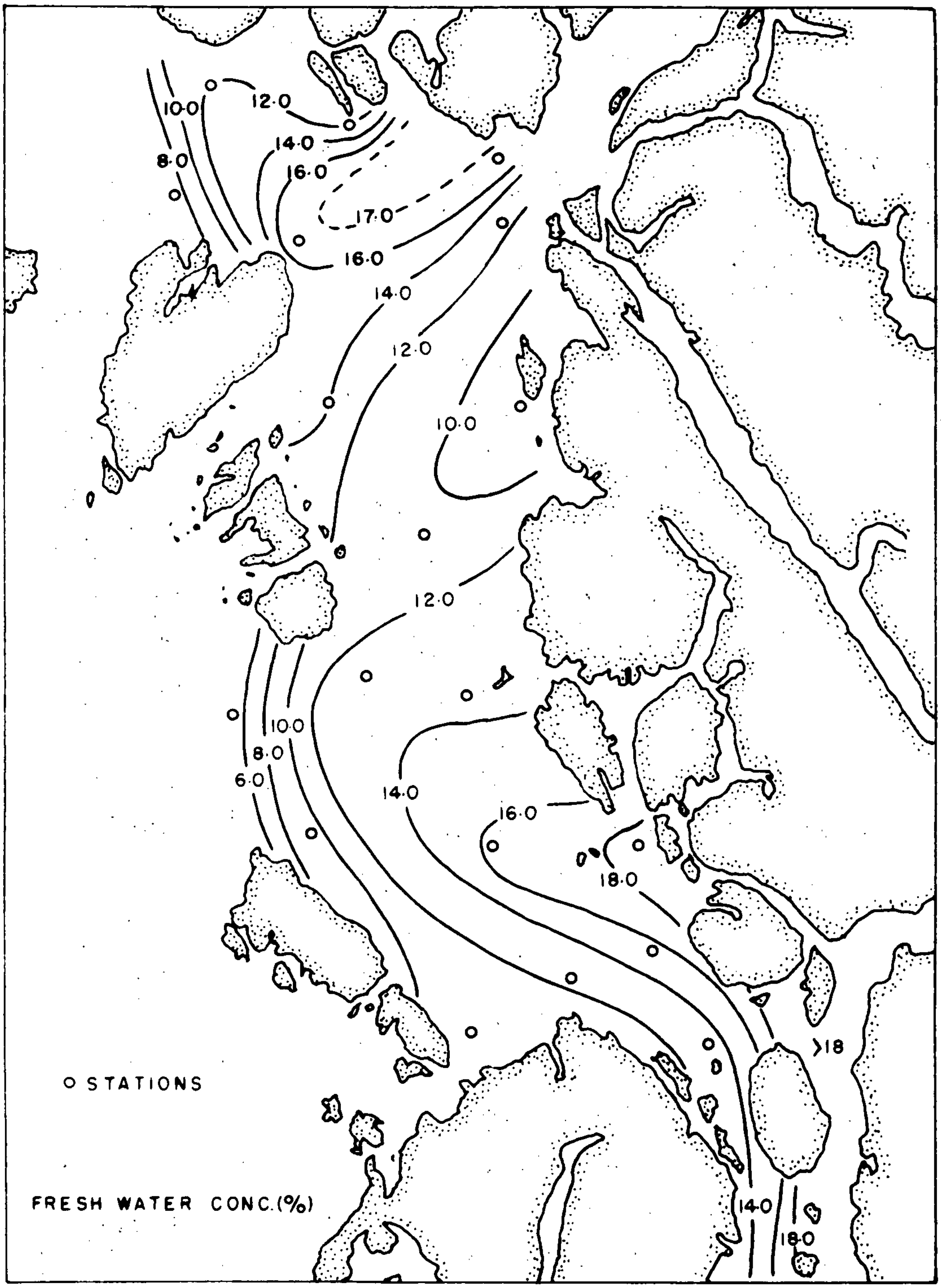
(d) F.W.C., JUNE 2

(e) F.W.C., JUNE 3

(f) F.W.C., JUNE 4

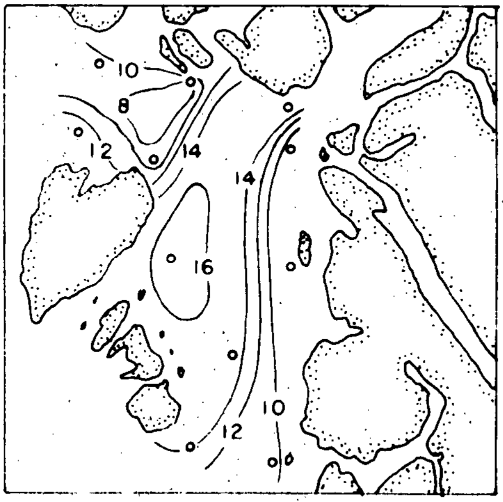
FRESH WATER CONC., AND SURFACE SALINITY, JUNE 1-4, 1948

FIG. 9

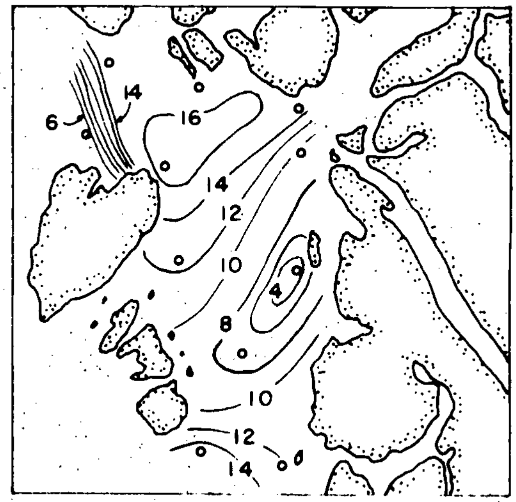


(%) FRESH WATER IN UPPER 60 FT. DURING FRESHET CONDITIONS, JUNE 8-18, 1948

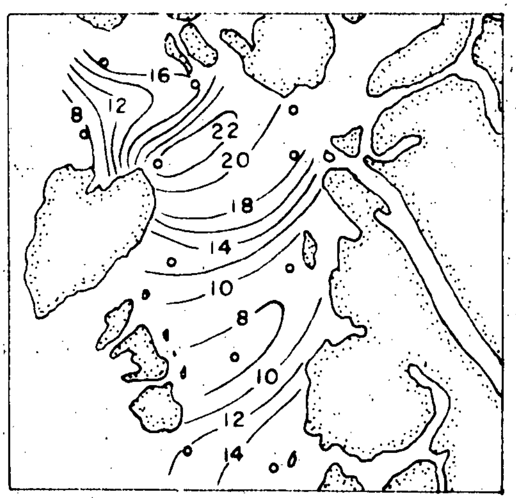
FIG. 10



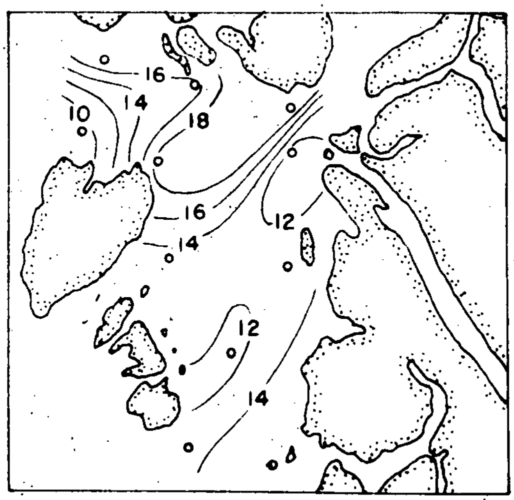
(a) F. W. C., JUNE 8



(b) F. W. C., JUNE 9



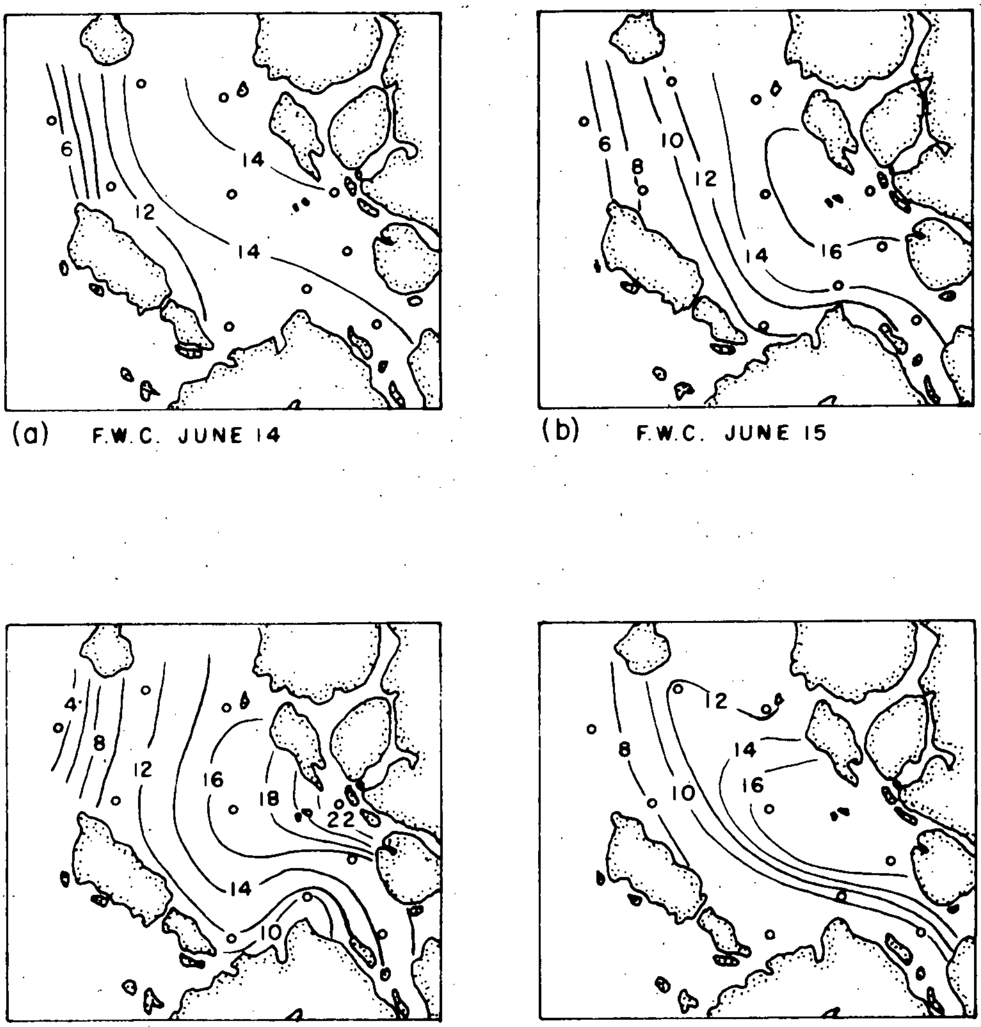
(c) F. W. C., JUNE 10



(d) F. W. C., JUNE 11

FRESH WATER CONC., JUNE 8, 9, 10, AND 11, 1948

FIG. 11.



(a) F.W.C. JUNE 14

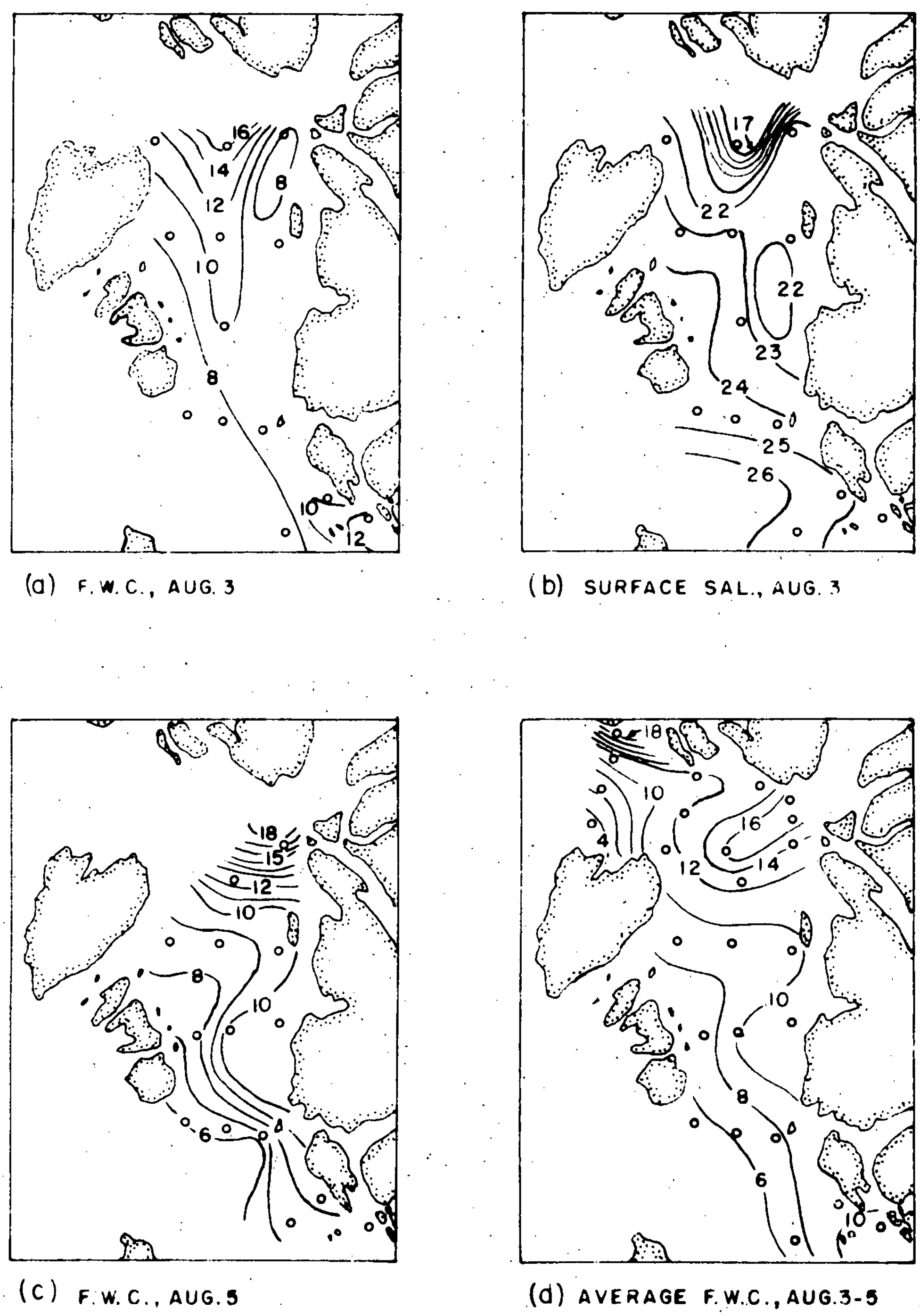
(b) F.W.C. JUNE 15

(c) F.W.C. JUNE 17

(d) F.W.C. JUNE 18

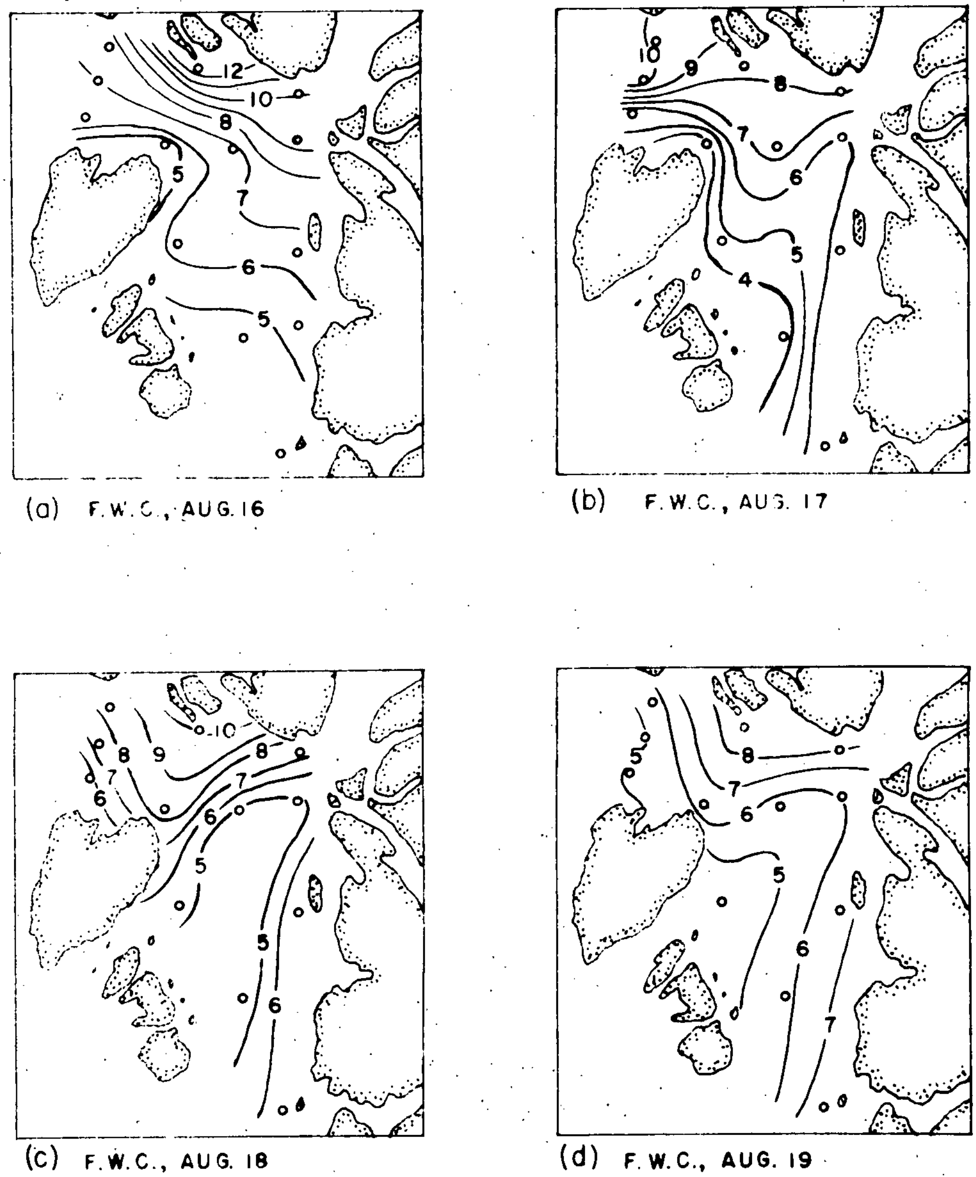
FRESH WATER CONC. (%), JUNE 14, 15, 17, 18, 1948

FIG. 12



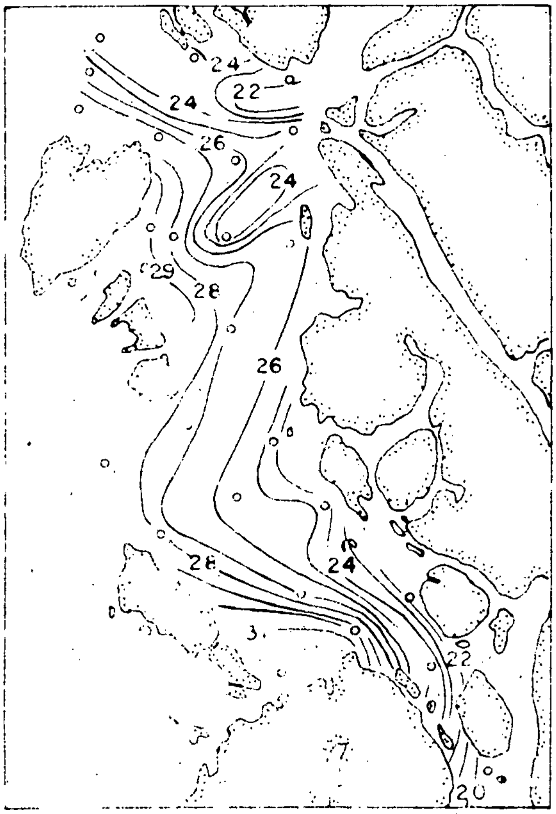
SURFACE SALINITY, AUG. 3, AND FRESH WATER CONC. AUG. 3-5, 1948

FIG. 13

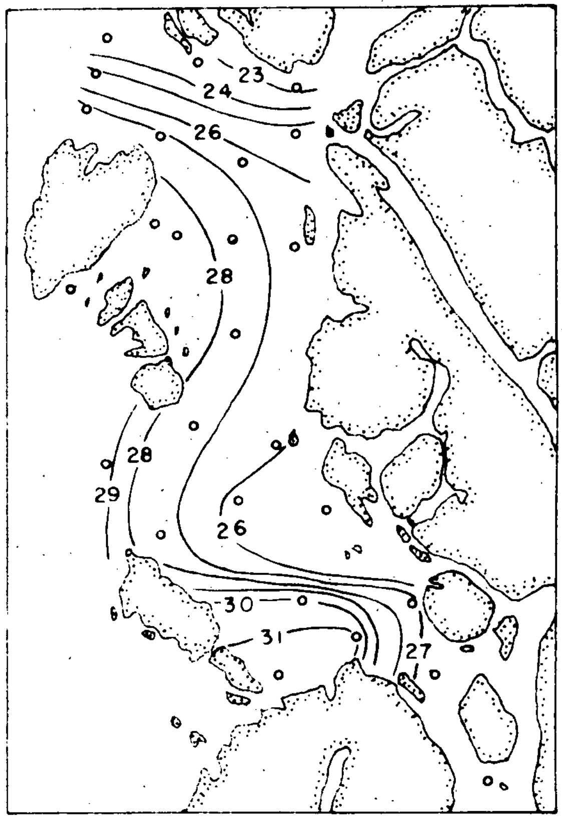


FRESH WATER CONC., AUGUST 16, 17, 18, 19, 1948

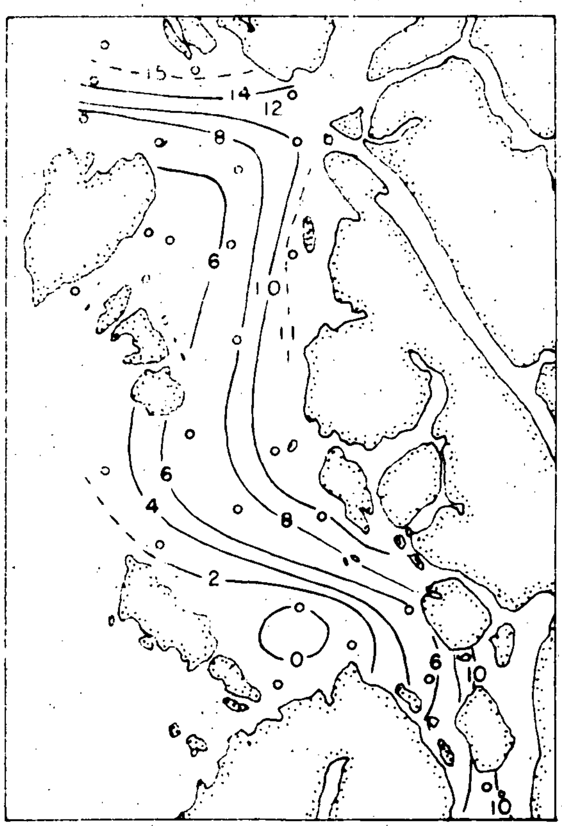
FIG. 14



(a) SURFACE SAL., SEPT 8-10



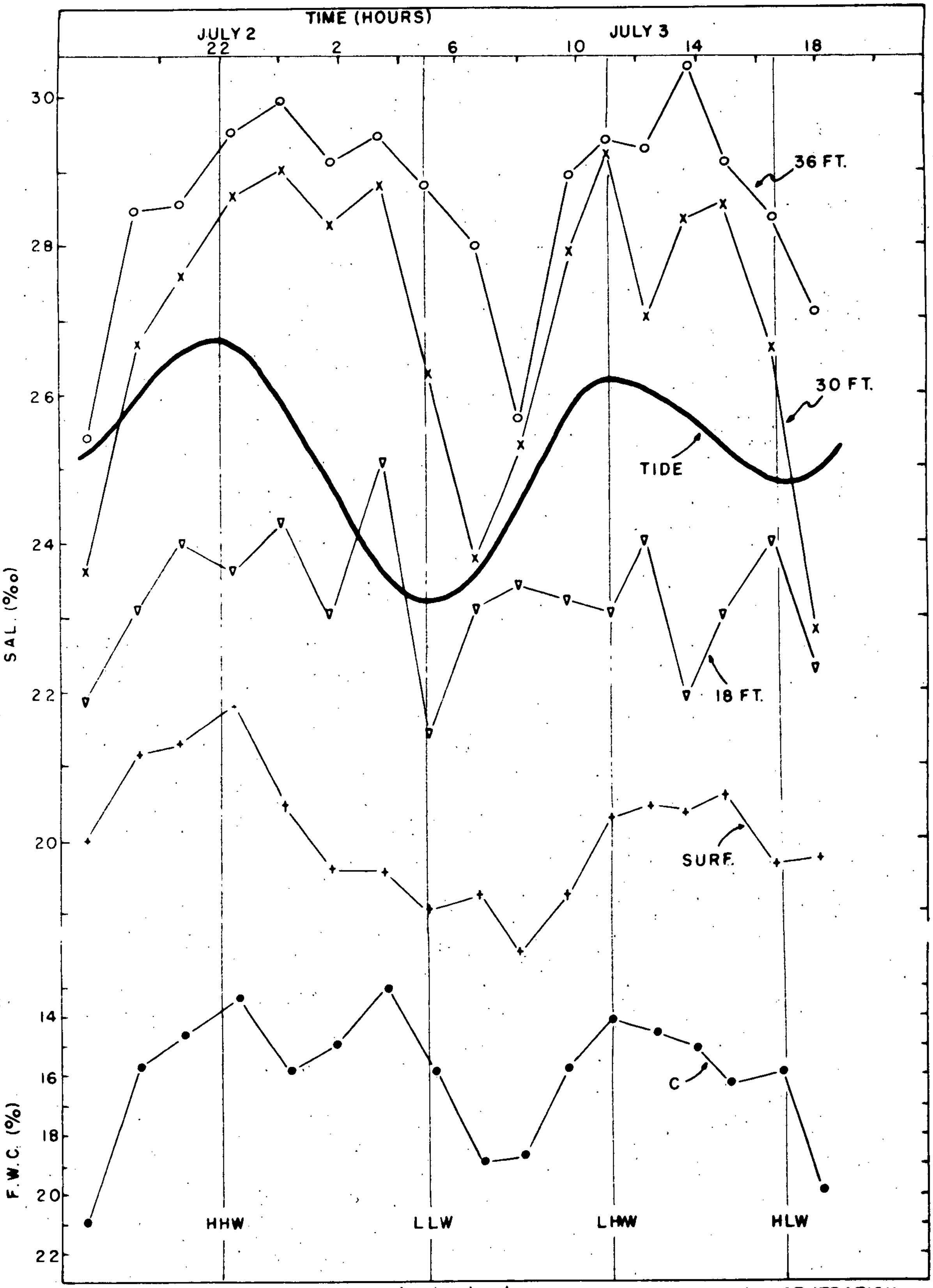
(b) SAL. AT 6 FT., SEPT. 8-10



(c) F.W.C., SEPT. 8-10

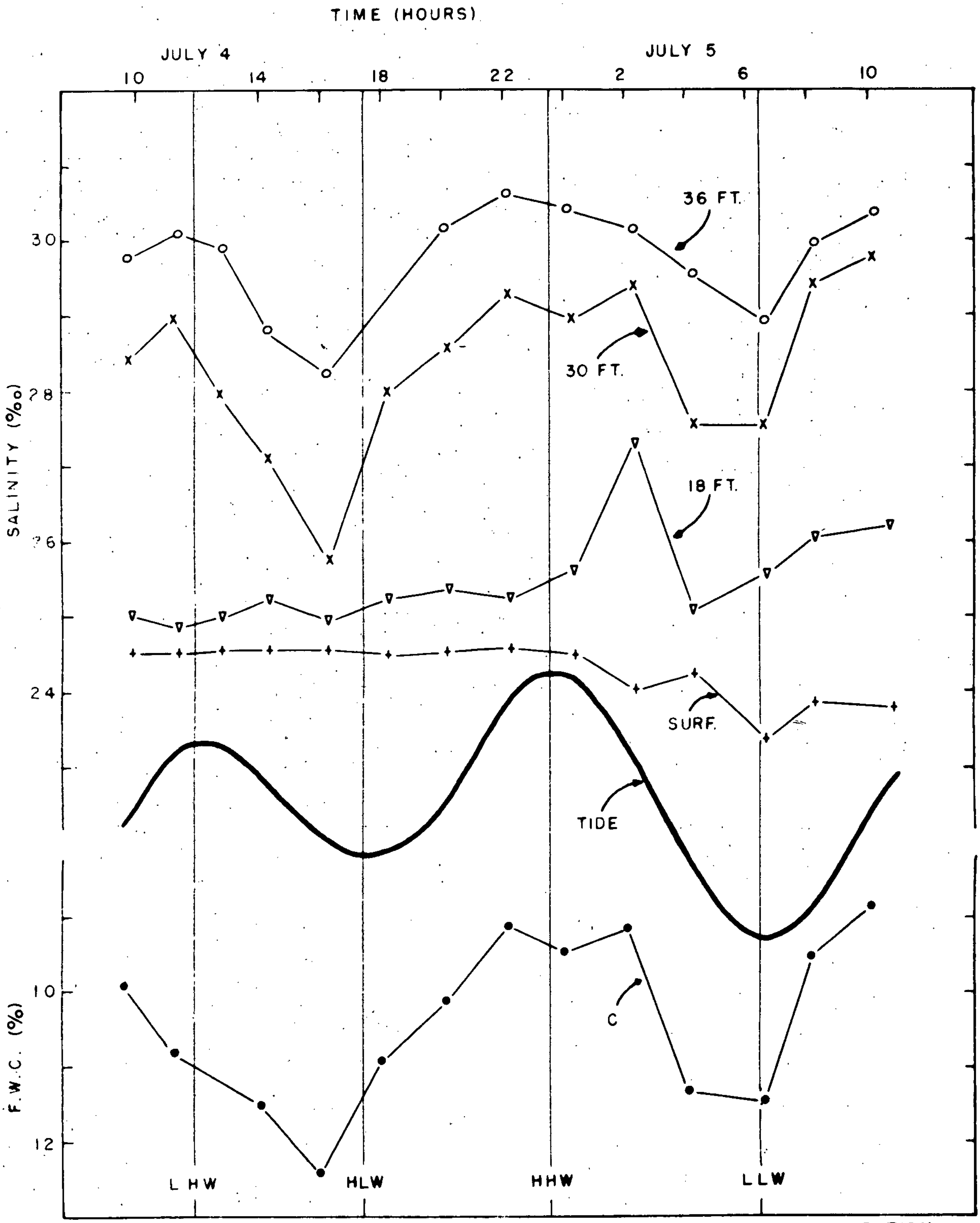
SURFACE SAL., SAL. AT 6 FT., AND FRESH WATER CONC., SEPT. 8-10, 1948

FIG. 15



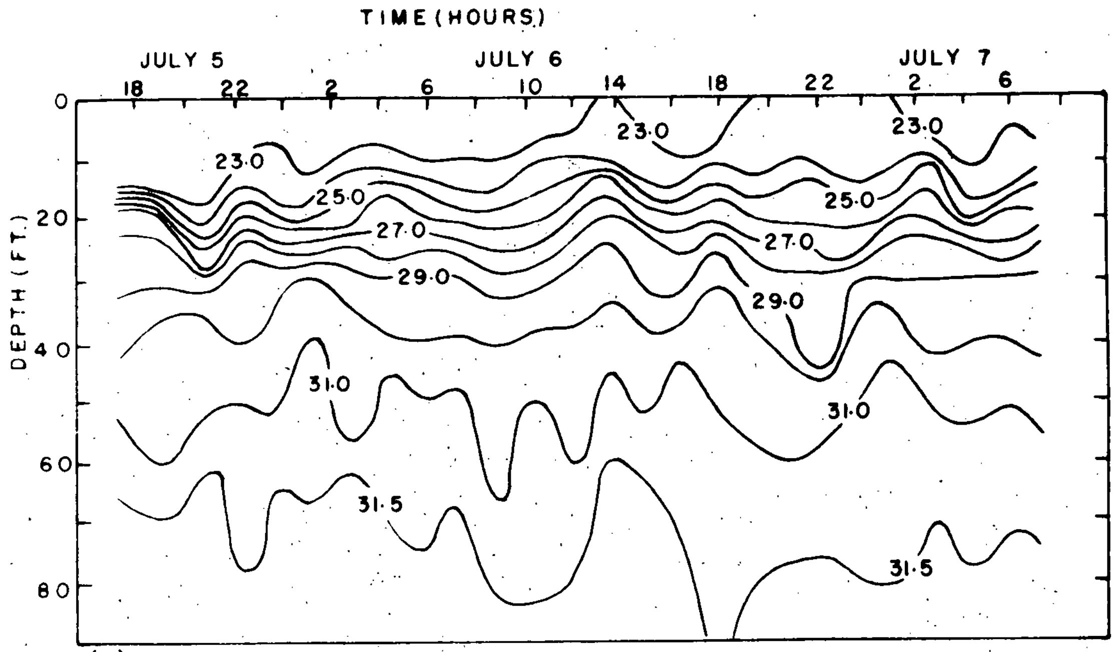
VARIATION IN SALINITY AT 0', 18', 30', 36', AND FRESH WATER CONCENTRATION
AT ANCHOR STATION 80,
JULY 2-3, 1948.

FIG. 16

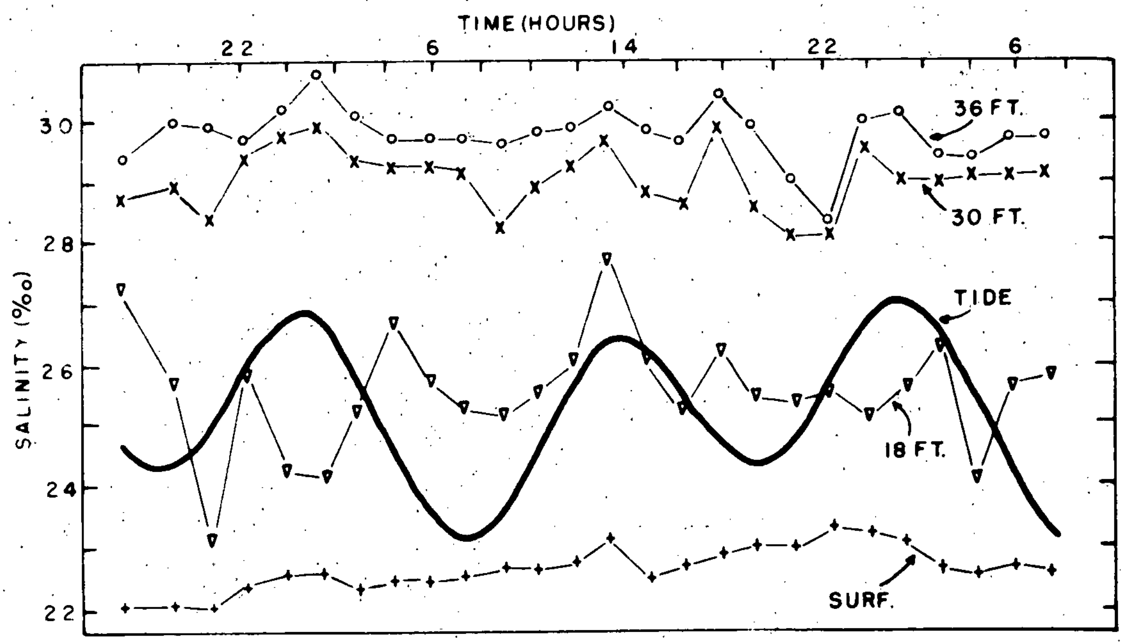


VARIATION IN SALINITY AT 0, 18, 30, 36 FT., AND FRESH WATER CONCENTRATION, AT ANCHOR STATION 81, JULY 4-5, 1948

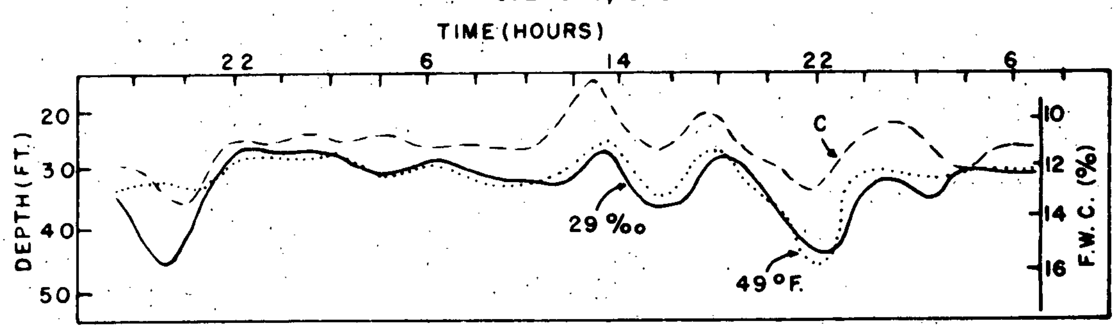
FIG. 17



(a) SALINITY SECTION AT ANCHOR 82, JULY 5- 7, 1948

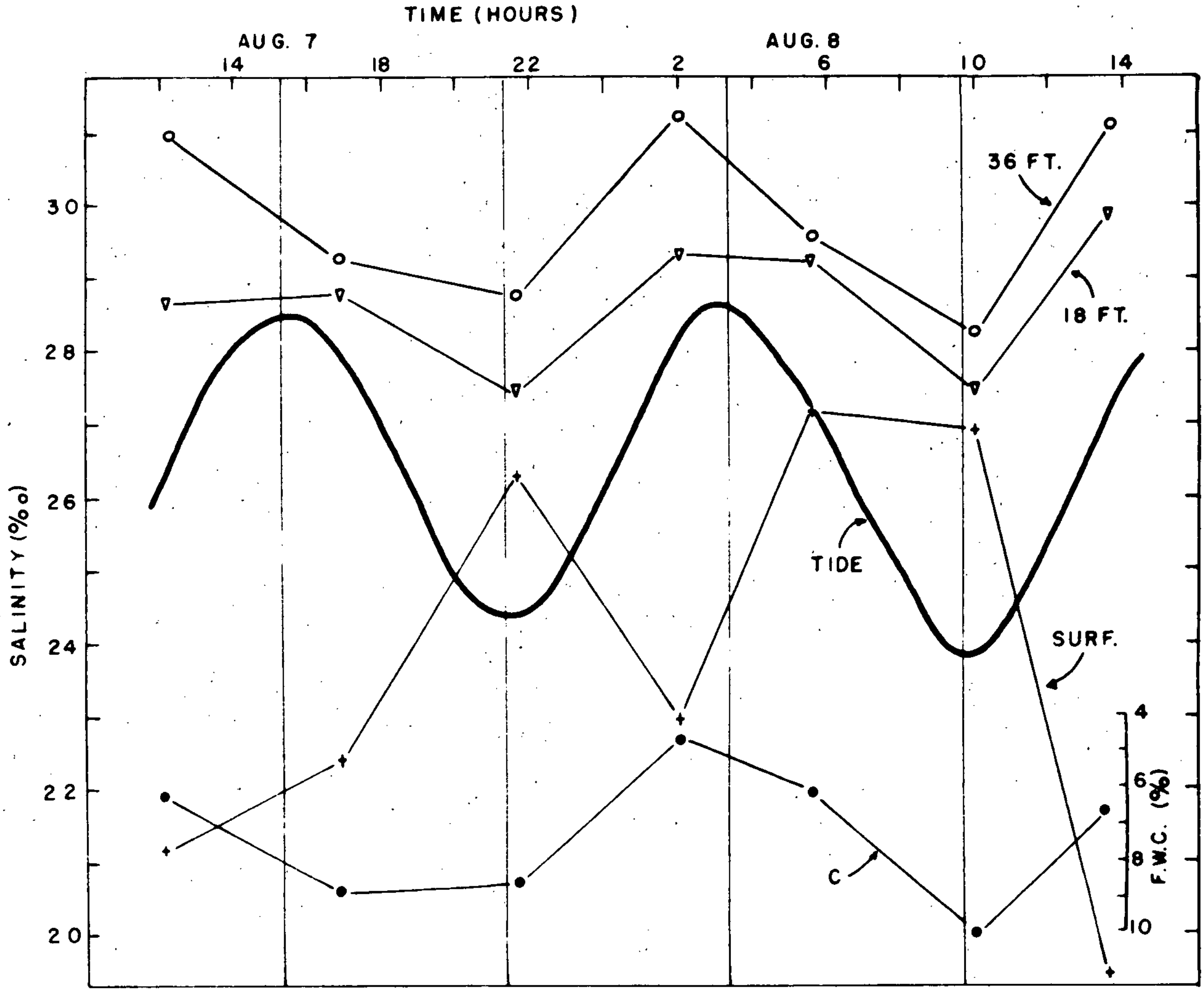


(b) VARIATION IN SALINITY AT 0, 18, 30, 36 FT., AT ANCHOR STATION 82, JULY 5- 7, 1948

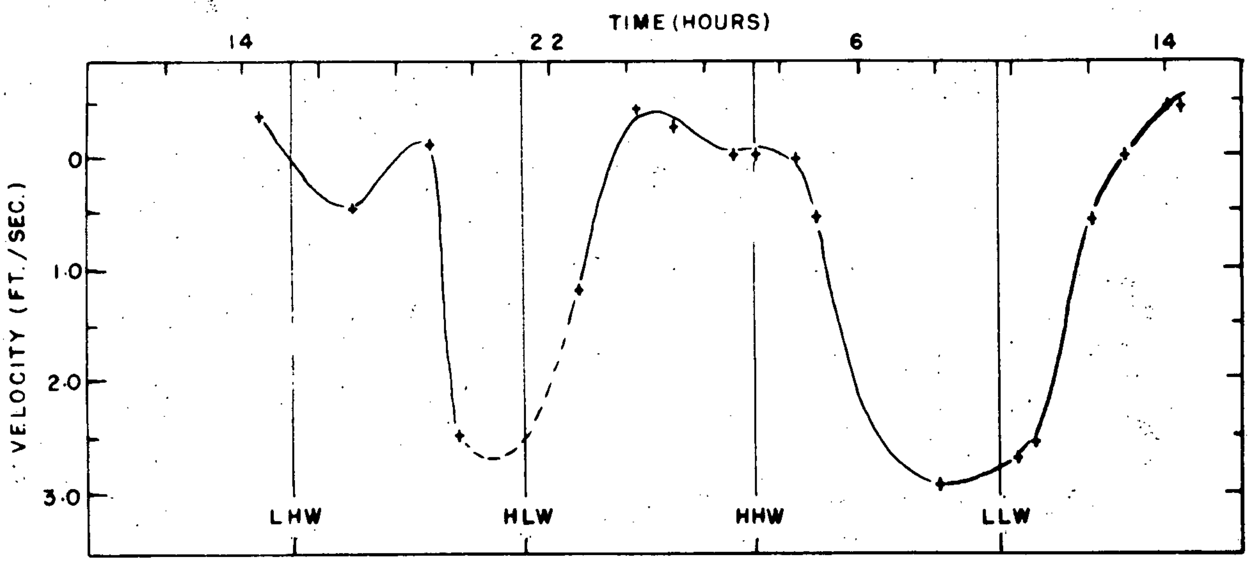


(c) VARIATION IN FRESH WATER CONC., DEPTH OF 49 °F ISOTHERM AND 29 ‰ SALINITY LINE, AT ANCHOR STATION 82, JULY 5- 7, 1948

FIG. 18

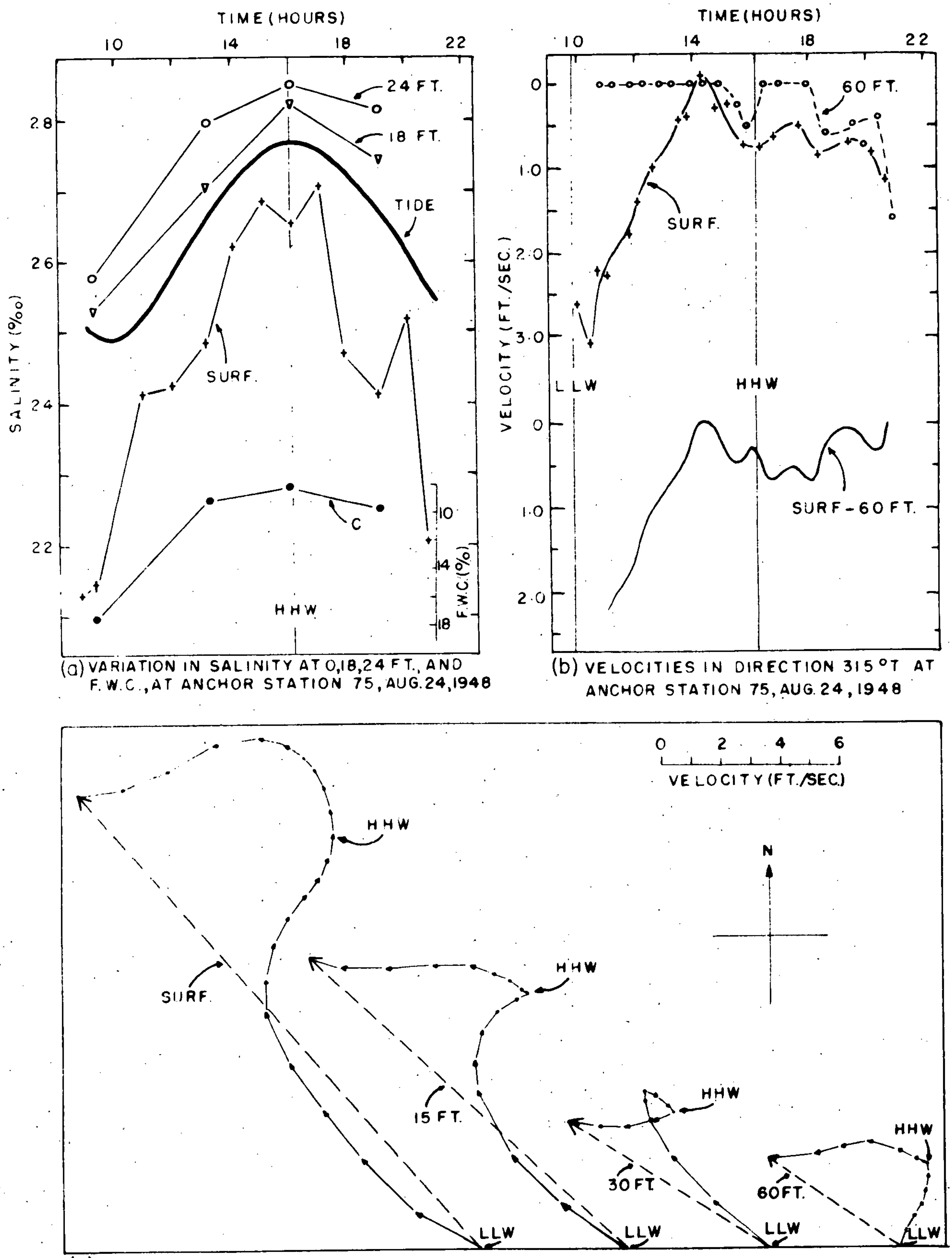


(a) VARIATION IN SALINITY AT 0, 18, 36 FT., AND FRESH WATER CONCENTRATION AT ANCHOR STATION 113, AUG. 7 - 8, 1948



(b) SURFACE VELOCITY IN DIRECTION 315°T, AT ANCHOR STATION 113, AUG. 7 - 8, 1948

FIG. 19

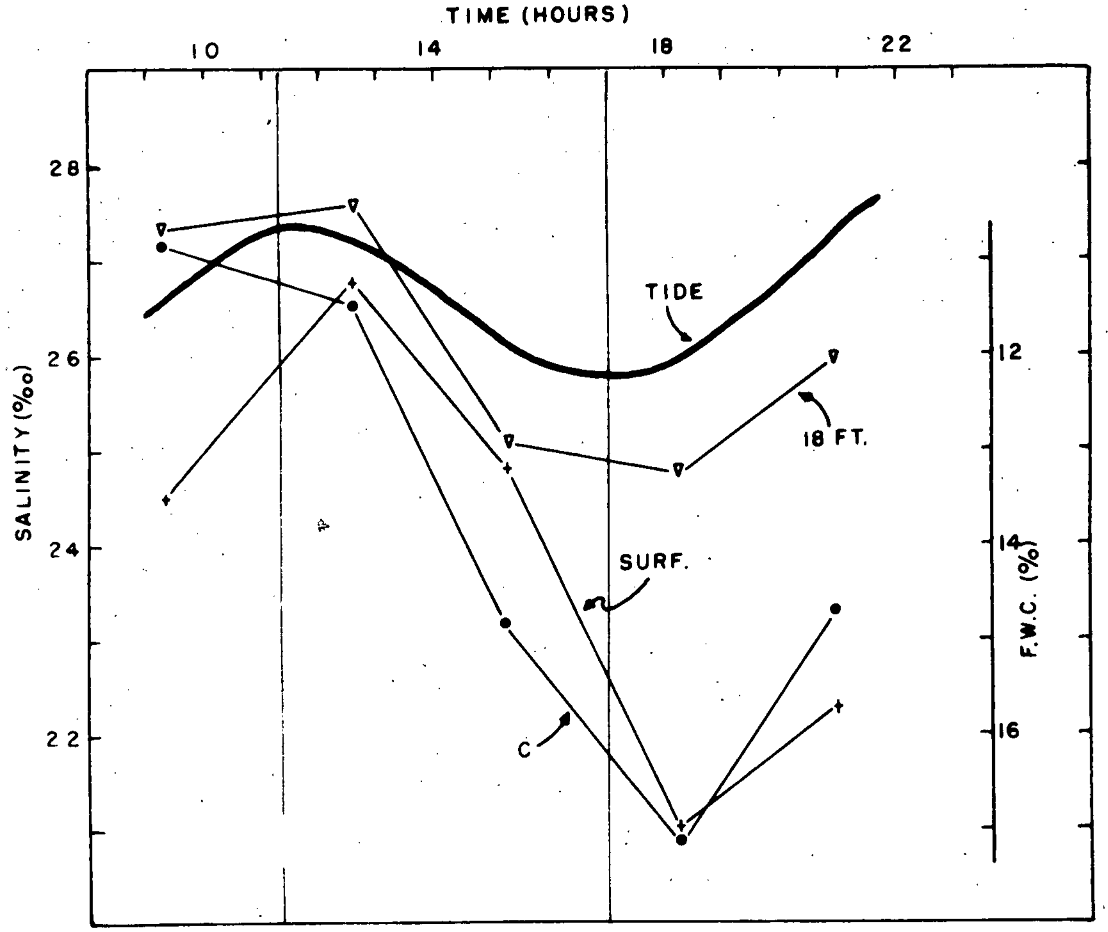


(a) VARIATION IN SALINITY AT 0, 18, 24 FT., AND F.W.C., AT ANCHOR STATION 75, AUG. 24, 1948

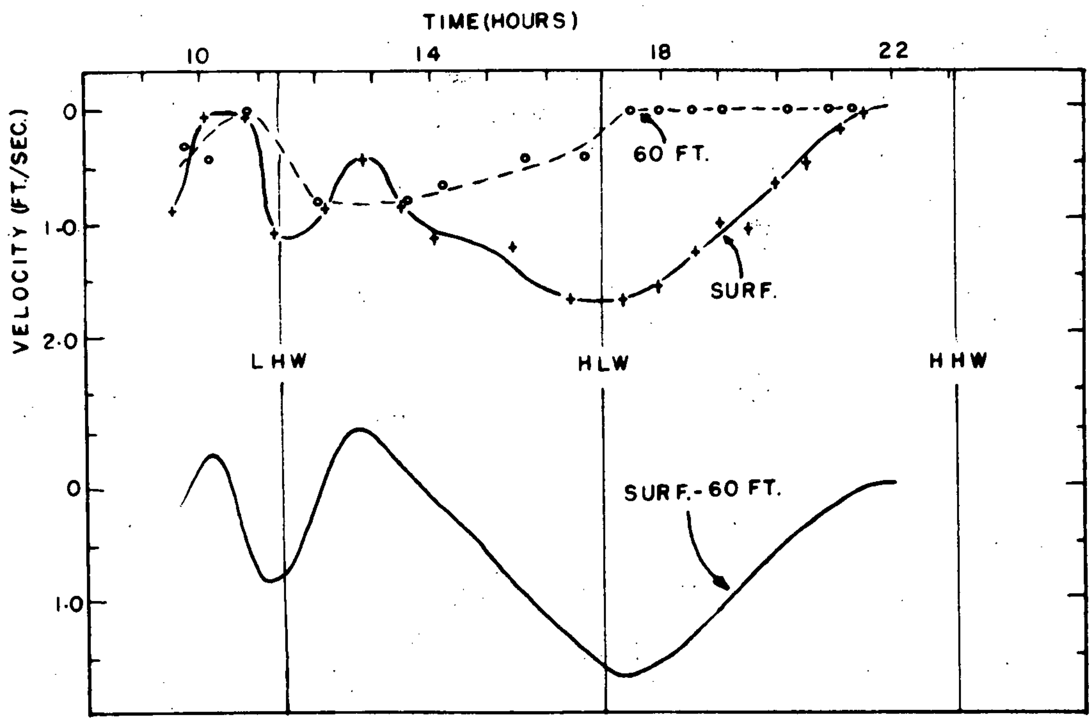
(b) VELOCITIES IN DIRECTION 315°T AT ANCHOR STATION 75, AUG. 24, 1948

(c) HODOGRAPH OF VELOCITIES AT ONE-HALF HOUR INTERVALS, AT ANCHOR STATION 75, AUG. 24, 1948

FIG. 20

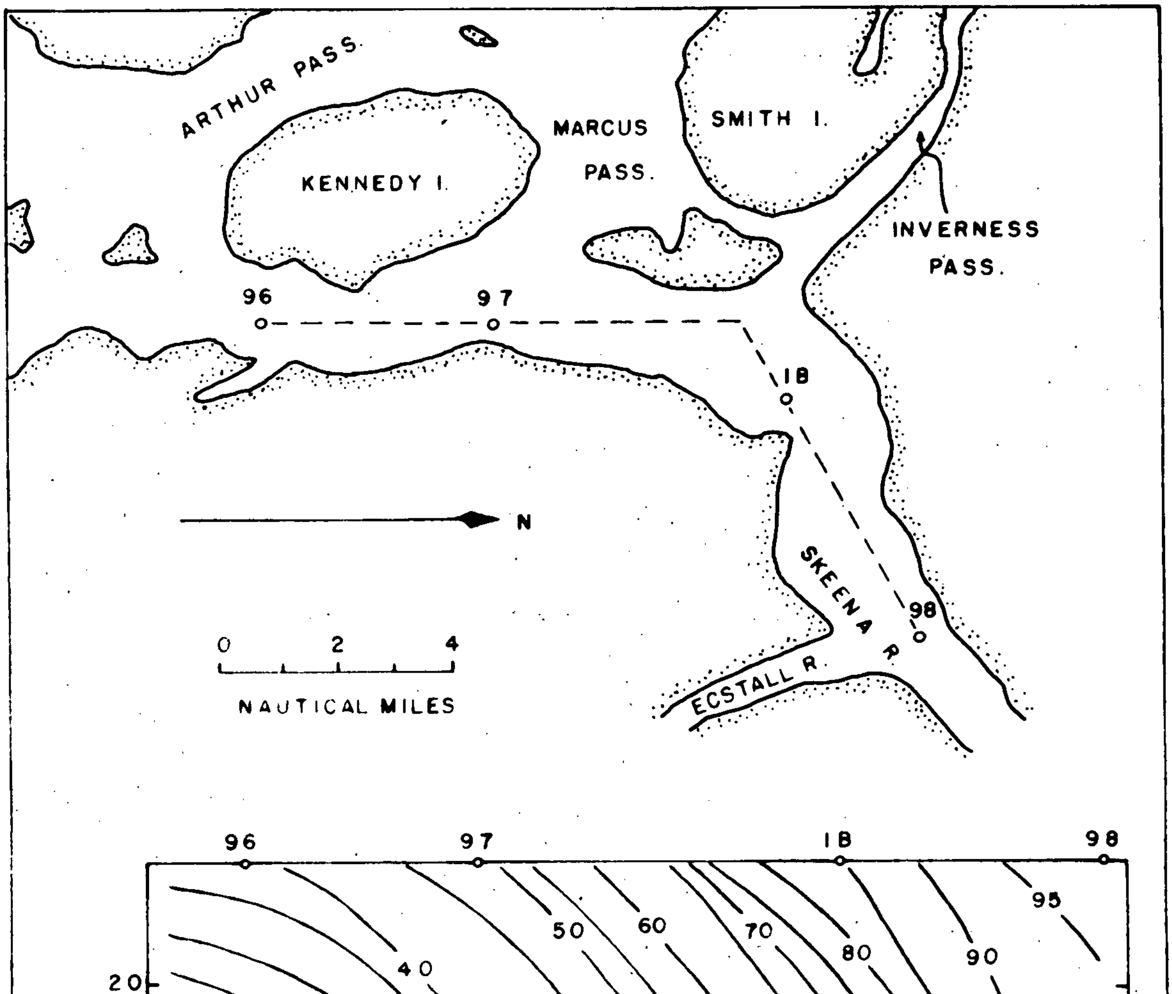


(a) VARIATION IN SALINITY AT 0, 18 FT., AND FRESH WATER CONCENTRATION, AT ANCHOR STATION 76, AUG. 31, 1948



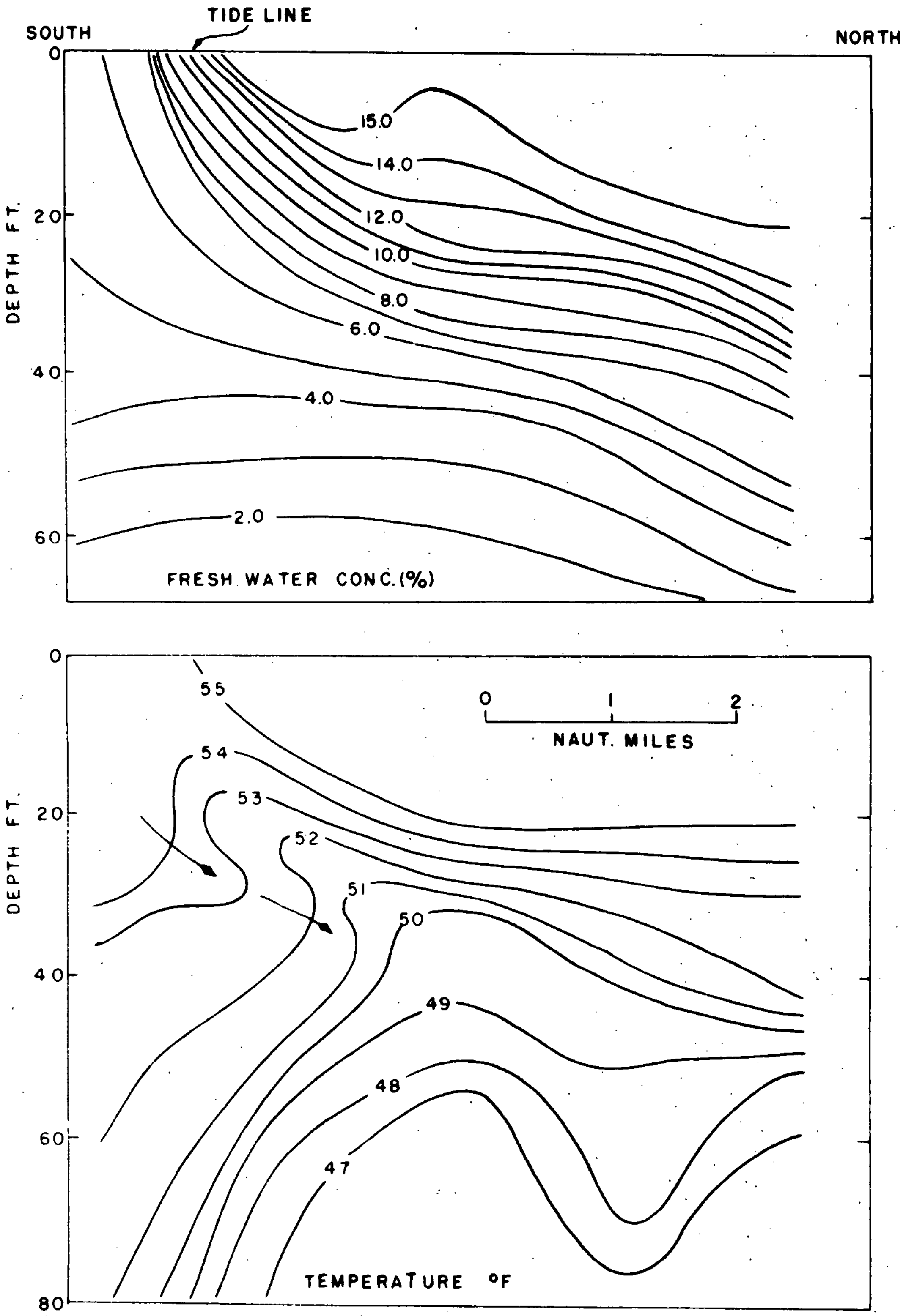
(b) SEAWARD VELOCITIES AT ANCHOR STATION 76, AUG. 31, 1948 (FROM CAMERON, 1951)

FIG. 21



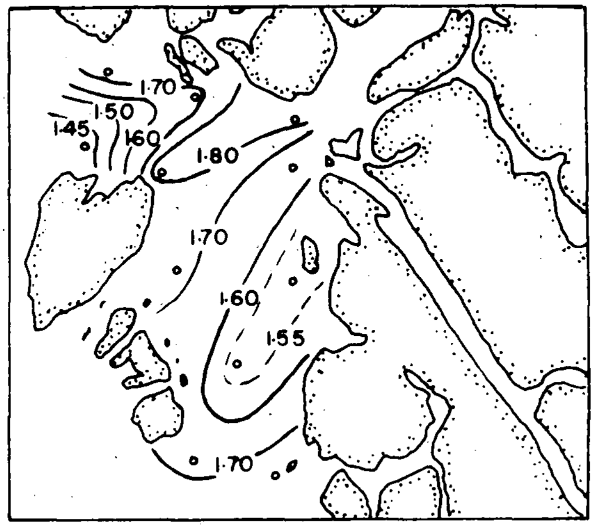
FRESH WATER CONCENTRATION (%) IN SECTION THROUGH MAIN CHANNEL OF SKEENA RIVER, SEPT. 7, 1948

FIG. 22

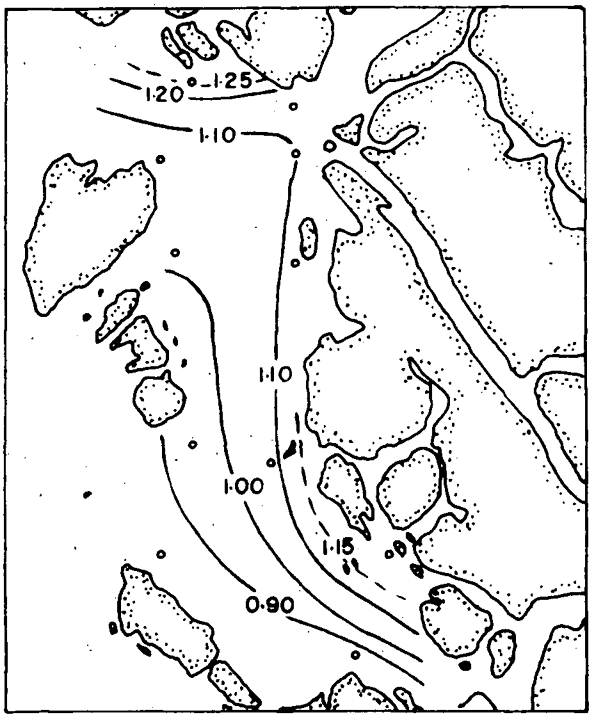


SECTION FROM NORTH TO SOUTH IN DUNDAS PASSAGE,
JULY 21, 1948.

FIG. 23



(a) AVERAGE DYNAMIC HEIGHT ANOMALY (FT.), REL. 90 FT., JUNE 8-11, 1948



(b) AVERAGE DYNAMIC HEIGHT ANOMALY (FT.), REL. 60 FT., AUG. 10-19, 1948

GEOPOTENTIAL TOPOGRAPHIES OF THE SEA SURFACE

FIG. 24