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SOME FEATURES OF THE SURFACE LAYER OF THE GULF OF ST. LAWRENCE.

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Introduction

The Gulf of St. Lawrence is a marginal sea of triangular shape, comprising an area of approximately 57,000 sq. mi. (148,000 sq. km), with two main openings to the ocean, Cabot and Belle Isle Straits. From the St. Lawrence River System, which extends inland approximately 2000 miles, the Gulf of St. Lawrence receives the drainage of half a continent.

The main feature of the submarine physiography (figure I) is the Laurentian Channel, a deep trench, with a maximum depth of 500 m. extending from the continental shelf almost to the mouth of the Saguenay River. To the west of the Laurentian Channel is the shallower area known as the Magdalen Shallows. One-quarter of the area of the Gulf is shallower than 50 m., while less than one-fifth is deeper than 300 m.

The first detailed oceanographical observations in the Gulf of St. Lawrence were carried out in 1914-15 by the Canadian Fisheries Expeditions (Hjort, 1919). This expedition introduced modern methods of oceanography into Canadian waters, and through a detailed analysis of observations made during a spring and summer cruise, the main features and oceanographical problems of the waters of the Gulf of St. Lawrence were outlined. This expedition was followed by the Cheticamp Expedition in 1917 under the Biological Board of Canada (Huntsman, M.S.S. Report), and the Belle Isle Strait Expedition under the joint auspices of the Biological Board of Canada and the Canadian Hydrographic Service (Huntsman, unpublished M.S.S.), and the various cruises between 1931 and 1935 of the "Cape Agulhas" under the auspices of the Newfoundland Fisheries Research Laboratory (Thompson, 1936). These latter expeditions dealt with specific sectional problems of the Gulf of St. Lawrence. For several years previous to 1938, the staff of the Biological Station of Laval University gave particular attention to the estuarial waters of the St. Lawrence River (Gaudry, 1938; Nadeau, 1938; and Tremblay and Lauzier, 1940). Throughout a period of years, the Canadian Hydrographic Service collected information on the general water conditions, recording temperatures, salinities and densities at a number of points in the Gulf of St. Lawrence (Dawson, 1922). The outstanding tidal and current work of Dr. Dawson in this area is of course well known (Dawson 1913, 1920 etc.).

It was not until 1945 however, that a full scale study of Gulf of St. Lawrence waters was initiated by the Atlantic Herring Investigation Committee. This study was augmented later by the activities of the Atlantic Oceanographic Group of the Canadian Joint Committee on Oceanography and the Naval Research Establishment of the Defence Research Board of Canada, which organizations co-operated with the Atlantic Herring Investigation Committee, to make seasonal cruises over the area for a period of four years. Since 1949, the seasonal surveys have been continued under the auspices of the Canadian Joint Committee on Oceanography.

Data

Comprehensive files of oceanographic data as compiled by the Atlantic Oceanographic Group of St. Andrews, N. B. were available to the authors for analysis. The data, pertaining to the Gulf of St. Lawrence are filed on cards and indexed according to cruise, location, time, date and depth. Specific temperature records illustrative of the monthly development of the surface layers throughout the period of May to November, were chosen from those pertaining to the Southwestern Gulf, Cabot Strait, and the Anticosti Area. These are plotted in figure 2.

All available temperature records were used to determine, for each degree square of latitude and longitude, for each month of the period May to November:

(a) the average thickness of the surface water layer as determined by the thermocline (figure 3), and,

(b) the average distribution of surface water temperatures (figure 4).

Data from specific seasonal cruises in May, August, and November were used to illustrate the seasonal distribution of temperature and salinity at depths of 0 m. and 50 m. (figures 5, 6, 7, 8, 9 and 10).

The Surface Layer and Its Development

The surface layer of the Gulf of St. Lawrence is one of its most interesting oceanographical features. Defining it as the layer delineated by the surface and the top of the thermocline, the layer is a body of almost homogeneous water, both as to temperature and salinity. Following a winter season, as shown by the bathythermograph records of figure 2, a delineation of a surface layer becomes noticeable at depths varying between 35 and 60 m. for the Cabot Strait and Anticosti areas respectively. At this time the stability of the waters is very low, and the heat absorbed at the surface is readily carried to greater depths by the process of mixing, chiefly the result of wind action. As the season progresses we therefore find this surface layer increasing in temperature. During the period of vernal warming, the efficiency of the processes of vertical mixing is decreased due to the development of an exceptionally strong thermocline which brings about increased stability in the waters of the thermocline layer. We therefore find the thickness of the surface layer decreasing progressively towards the height of Summer, at which time the surface layer is approximately 5 to 10 metres in thickness. Another factor which enters to determine the stability is the salinity, but suffice to mention here that the layer of thermocline in the Gulf of St. Lawrence coincides with the layer of the more intense salinity gradient.

After the height of Summer, when the resultant transfer of heat is from the surface layer to the surrounding atmosphere, the decreasing surface temperatures, and therefore increasing surface densities, enhance the vertical mixing processes and the surface layer gradually thickens. The stability of the upper layers reaches a very low value in the late autumn months and in November we find the surface layer is 40 metres or more in thickness.

The surface layer, as referred to in this paper, is therefore considered as a mixed layer, as indicated by its vertical temperature distribution, whose thickness is primarily controlled by external factors such as land drainage, radiation, precipitation, evaporation, and wind action, which are operative at the surface.

The Thickness of the Surface Layer

The average thickness of the surface layer in the Gulf of St. Lawrence as determined from the thermocline is illustrated in figure 3, for the months of May to November inclusive.

In May, the greatest average thickness (as much as 25 metres) of the surface layer is found between Anticosti Island and Cabot Strait, corresponding with the waters of minimum surface temperatures (figure 4). The least average thickness is found in the southwestern Gulf (less than 10 metres), along the north coast of Prince Edward Island, where the surface water was relatively warm. Towards the St. Lawrence estuary, the surface layer was comparatively thin (as low as 10 metres).

In June, the range of average thickness of the surface layer has increased with a maximum thickness of more than 30 metres near Anticosti Island and a minimum of less than 5 in the centre of the Gulf and North of Anticosti Island.

In July, the uniformity of the average thickness from less than 5 metres to greater than 10 metres, is in contrast to that of June, and the decrease in thickness, since June is prominent.

In the July-August interval an increase in thickness to greater than 15 metres has taken place, and the layer thickness of 10 metres is generally uniform throughout the Gulf.

By September the average thickness of the layer has increased to more than 20 metres, with considerable variation throughout the Gulf, and with a thickness of greater than 15 metres prevailing.

In October, the average thickness of layer has increased to 30 metres, with the greatest values pertaining to the main Gulf area.

In November average values greater than 60 metres are to be observed, the minimum value of the average thickness of the surface layer being less than 10 metres.

The minimum thickness of the surface layer attained in the months of July and August is an outstanding feature, and, referring to figure 2, it will be obvious that this feature is associated with the development of a strong thermocline. Associated with the development of a thermocline is also a general tendency towards uniformity in the thickness of the surface layer throughout the Gulf area. Throughout the months of September, October, and November, the cooling processes, and the vertical mixing enhanced by wind action are seemingly activated with varying efficiency in different parts of the Gulf, with the result that the thickness of the surface layer varies considerably over the area during the Autumn months.

The Temperature of the Surface Layer

The average distribution of surface water temperatures is illustrated in figure 4 for the months of May to November inclusive. As the surface layer is, for all purposes, a mixed layer, as indicated in figure 2, these surface temperatures are illustrative of the temperatures of the surface layer.

In May, the average surface temperature ranged from 1.0°C to 8.0°C with the minimum in the Cabot Strait area and the maximum in the St. Lawrence Estuary and Northumberland Strait. Such a range of temperature is to some extent related to ice movements, the warmer temperatures indicating the areas which were first clear of ice. The estuarial waters too, at this time of the year are generally warmed at a greater rate than those of the open Gulf due to the greater absorption of heat by the land masses.

In June, the minimum temperature was, on the average, recorded along the North Shore of the Gulf between Anticosti and Belle Isle Strait, the maximum in the southwestern sector. In the interval between May and June, the maximum warming is recorded for the southern Gulf where the temperatures attained a range between 7 and 12°C. In the northern portion of the Gulf, and particularly where upwelling of the colder sub surface waters is a feature, average temperatures in June were still as low as 2°C.

In July, Belle Isle Strait and the Estuary of the St. Lawrence were the areas of minimum average temperature, with values less than 12°C. Along the north shore of the Gulf, temperatures were still relatively low, ranging between 13 and 15°C. Average temperatures were as high as 19°C in the southern portion of the Gulf.

In comparison with July, there is very little change in the general surface temperature situation in the Gulf in August, although it is quite evident that a large portion of the Gulf waters had reached its summer maximum in July and that the cooling process was underway.

In September, continued cooling on a small scale since August is in evidence. The average temperatures of the main body of water range from approximately 10° to 16°C with temperatures as high as 18°C in southwestern Gulf and as low as 5°C to the north of Anticosti Island.

In October, the waters of the main portion of the Gulf have reached an average temperature of less than 10°C. The average temperatures range from 7°C in the Estuary to 13°C in the southern and easterly areas. On the whole the cooling process was responsible for a general decrease in temperatures of 3-4°C in the September-October interval.

In November, the general cooling over the main Gulf area brought the temperatures down to the average level of 4°C. Along the Gaspe Coast, the average temperatures were as low as 2°C, while along the Cape Breton Coast temperatures were as high as 9°C.

Temperature Trends in the Gulf of St. Lawrence

Since 1930, surface water temperatures have been taken twice daily at Entry Island of the Magdalen Islands. The data of the first six years were analysed by Hachey (1939) to indicate the annual cycle of temperatures as illustrated by these waters. In general the minimum temperatures were in the neighbourhood of $-1.8^{\circ}C$ during the Winter months, while the maximum temperatures were to be observed in August. It has been shown (Hachey and McLellan, 1948) that the trends of water temperatures at Entry Island throughout the period 1930-1947 were similar to those for the Atlantic Coast generally.

In Table I, the highest monthly mean temperatures are recorded for each year of the period 1930-1950 and the variations from the normal noted. In all cases these monthly means were for the month of August. The average monthly means for July, August and September are also recorded, and the variations from the normal are noted. The mean Summer temperatures vary from 16.8 and $16.7^{\circ}C$ in 1930 and 1947 respectively, more than one degree above normal, to $13.5^{\circ}C$ in 1941 which was more than two degrees below normal. While the low August mean of $14.4^{\circ}C$ was recorded in 1941, there are several years in which the August mean was higher than those of 1930 and 1947.

The Seasonal Distribution of Surface Temperatures and Salinities

The seasonal distribution of temperature and salinity at the surface in Spring, Summer and late Autumn is shown in figure 5, 6 and 7 respectively.

In Spring, waters of less than 30.0 $^{\circ}/oo$ were found mostly in the western sector of the Gulf in a relatively narrow strip along the coast, with temperatures generally greater than 6.0°C and as high as 11.0°C. Generally, the surface waters of the main Gulf were of a salinity between 31.0 °/oo and 32.0 °/oo and of a temperature of 4.0°C to 6.0°C. Patches of water of a salinity between 30.0 and 31.0 °/oo with temperatures of less than 3.0°C are to be noted to the north near Belle Isle Strait and to the south of the Magdalen Island.

TABLE I

Highest monthly mean (August) and summer mean (July, August, September) surface water temperatures at Entry Island in the Gulf of St. Lawrence.

Year	August		Summer	
	Mean	Diff. from Normal	Mean	Diff. from Normal
1930	18.0	0.6	16.8	1.2
1931	17.5	0.1	15.6	0.0
1932	17.7	0.3	15.8	0.2
1933	17.5	0.1	15.3	-0.3
1934	17.0	-0.4	16.1	0.5
1935	18.4	1.0	15.8	0.2
1936	17.0	-0.4	15.0	-0.6
1937	18.3	0.9	16.4	0.8
1938	18.2	0.8	15.9	0.3
1939	17.4	0.0	15.3	-0.3
1940	17.8	0.4	15.6	-0.6
1941	14.4	-3.0	13.4	-2.2
1942	17.4	0.0	16.3	0.7
1943	16.2	-1.2	15.1	-0.5
1944	17.0	0.6	15.6	0.0
1945	18.7	1.3	16.4	0.8
1946	17.2	-0.2	15.8	0.2
1947	18.3	0.9	16.7	1.1
1948	17.0	-0.4	15.0	-0.6
1949	16.8	-0.6	15.5	-0.1
1950	17.3	-0.1	15.5	-0.1

In Summer the salinity of the surface waters has generally decreased over the whole Southwestern Gulf, the waters of a salinity less than 30.0 ‰ occupying the southwestern portion of the Gulf and the isohaline of 30.0 ‰ extending from the Estuary of the St. Lawrence southeasterly to Newfoundland. Minimum surface salinities of less than 26.0 ‰ are found on the north side of Prince Edward Island and in the Bay of Chaleur. Little change is to be noted in the salinity of the waters in the northeastern area.

The surface temperature distribution in the Summer was such that the warmer water, higher than 15.0°C, was located in the southwestern Gulf from the Bay of Chaleur to the Laurentian Channel, in the Cabot Strait area, and along part of the west coast of Newfoundland. The temperatures ranged from less than 4.0°C to greater than 18.0°C. In particular the surface temperatures ranged from approximately 10.0°C in the Estuary of the St. Lawrence to 18.0°C in the Cape Breton area. The surface drainage waters from the land masses to the east are probably well contained within the isohalines of less than 30.0 ‰, and the warmer waters, reflecting the influence of land heating and localized warming, are therefore generally contained within the same boundaries.

By October, the surface salinities have generally increased over the whole area of the Gulf, the outflowing waters from the Estuary of the St. Lawrence generally contained within isohalines of less than 30.5 ‰. The general direction of the horizontal temperature gradient is similar to that of Summer, but with temperatures ranging from 7.0°C in the Estuary to 12.0°C off

Cape Breton.

The main characteristic of the surface salinity distribution during the foregoing seasonal observations was the northwest-southeast tendency of the isohalines with the lower surface salinities confined to the southwestern area. The intensity of the surface salinity gradient varies with the season, being greatest in the Spring and least in the late Autumn. Most of the water of low salinity (less than 30.0 °/oo) is produced in the northwestern sector of the Gulf and is, or becomes, associated with the Gaspe current. The stronger the Gaspe current, the greater is the Coriolis force and hence the greater the horizontal salinity gradient. The Gaspe current, on this basis, has a greater surface velocity in the Spring months with the velocity decreasing with the progress of the seasons. This surface velocity should not be confused with the volume transport of the Gaspe current, the details of which have not been thoroughly investigated to date.

That upwelling is an important feature in controlling surface water temperatures is indicated by the minimum surface water temperatures of 3.4 °C observed along the North Shore of the Gulf in August (figure 6) and associated with waters of maximum salinity (31.9 °/oo). This upwelling is, no doubt, associated with northwest winds which tend to remove the surface waters from the north coast of the Gulf.

The Seasonal Distribution of Temperatures and Salinities at 50 Metres.

The distribution of temperature and salinity at a depth of 50 metres is shown in figures 8, 9, and 10 for Spring, Summer and late Autumn respectively.

In Spring (figure 8) the lower temperatures with a minimum of -1.3°C are associated with the lower salinities in the southwestern part of the Gulf (31.4 - 32.0 °/oo) and the higher salinities in the northeastern area (32.0 - 32.5 °/oo). Temperatures greater than 2.0°C at 50 metres generally occupy the central part of the Gulf in Spring. The waters at this level are those of the "upper layer" ($<$ 32.0 °/oo) as defined for the Scotian Shelf (Hachey, 1942).

In Summer (figure 9), the temperature of the waters at 50 metres ranged from -0.5 to 2.0°C, with the area generally covered by waters of temperatures between 0.0°C and 1.0°C and associated with salinities less than 32.0 °/oo. Colder water is thus evident at this depth of 50 metres in August, 1947, as compared with that observed in the May of 1948. While these observations were made in different years it is pertinent to appreciate the differences indicated here, as well as the suggestion that colder waters penetrate the Gulf area in the interval between May and August. This sub surface penetration, if real, takes place both through Belle Isle Strait and Cabot Strait, and possibly on a considerable scale.

In late Autumn (figure 10), a substantial increase in the temperatures at 50 metres is to be noted over the marginal area of the Gulf. The main area at this depth is still covered by waters of temperatures less than 1.0°C and even less than 0.0°C. Salinities similar to those of Summer prevail.

Discussion

There are many features of the surface layer in the Gulf of St. Lawrence which require further elucidation. In this layer we find that salinities in the Southwestern portion of the Gulf decrease with the progress towards the height of Summer. Generally decreasing salinities in coastal waters are associated with increasing land drainage, and in areas of the Canadian Atlantic, land drainage is greatest in the Spring months. Associated with this feature of decreasing salinities, is a thinning of the surface layer which occurs with the establishment of stronger vertical temperature gradients in the thermocline. To some extent therefore, in that the increasing vertical temperature gradient is accompanied by increasing stability, vertical mixing is confined to an ever thinning surface layer with the progress from Spring to Summer. Hence the drainage waters, even though lessening in volume after the Spring maximum, are seemingly more effective in lowering the salinity in Summer when confined to a thinner surface layer.

The Gaspe Current plays a very important role in determining the hydrographic conditions in the Gulf of St. Lawrence. According to Dawson (1913), "the water of the Gulf may be roughly divided by a line running from the South-West Point of Anticosti, to the middle of Cabot Strait. Along the south-western side of this line, the water has a lower density; as it is apparently made a little fresher by the outflow of the St. Lawrence River."

"The general drift of this water of lower density is outwards, towards the Atlantic", and this general drift stems from, and is a continuation of the Gaspe current which has its origin in the St. Lawrence Estuary. It has long been known that there is a downward current in the middle of the St. Lawrence Estuary which continues along the south shore for the whole length of the Gaspe coast. The mechanism whereby outflowing river water is mixed with ocean waters, within the St. Lawrence Estuary, to produce the Gaspe current has been considered by various authors (Gaudry, 1938; Nadeau, 1938; Tremblay and Lauzier, 1940).

The Gaspe current in the offing of the Gaspe coast runs constantly southeastward or outward from the St. Lawrence to the Gulf. In general, it occupies a belt lying between two and fourteen miles (3.6 and 27. km) off shore, and the depth of the current may extend to 90 fathoms (165 m.) (Dawson, 1913). Velocities as high as 3.92 knots (5.4 km per hour) have been observed, although the average velocity is probably about 1.5 knots (2.8 km per hour). In a consideration of the horizontal salinity gradient in the surface layer in the vicinity of the Gaspe coast (figures 5, 6 and 7) it was suggested that the Gaspe current has a greater velocity in the Spring months, with the velocity decreasing with progress of Summer. It can be reasoned on a physical basis that decreasing velocities in the strength of the Gaspe current could involve a widening of the stream and a decrease in the thickness of the layer of flow. On this basis, the thinning surface layer in the western section of the Gulf of St. Lawrence is associated in part, with decreasing velocities of the Gaspe current. It is obvious that there are many fundamental problems to be considered in a detailed study of the Gaspe current.

It might be noted that the temperatures and salinities of the surface layer of the Gulf of St. Lawrence are associated directly with the mechanism of the Gaspe current, and show very little direct connection with the water movements through the Belle Isle or Cabot Straits, except when consideration is given to sub surface depths.

Summary

1. The surface layer of the Gulf of St. Lawrence, which is defined as the layer delineated by the surface and the top of the thermocline, is a body of almost homogeneous water both as to temperature and salinity.

2. The thickness of this surface layer varies with the season, from a value of 35 to 60 metres in Spring to a minimum of 5 to 10 metres at the height of Summer, and to a late Autumn maximum of greater than 60 metres.

3. The progressive thinning of the surface layer, as Summer is approached, is associated with an increasing vertical temperature gradient in the thermocline, and a tendency towards uniformity in the thickness of the surface layer throughout the Gulf area.

4. Upwelling of colder waters along the north shore of the Gulf is a factor in depressing surface water temperatures in this region. The St. Lawrence Estuary is another area where surface temperatures are depressed through the mechanism of mixing which is associated with the production of the Gaspe current.

5. Mean summer surface water temperatures over a twenty year period indicate considerable variation from year to year, with the highest mean summer temperatures experienced in 1930 and 1947, and the lowest mean summer temperatures in 1941.

6. Surface salinities in the open Gulf decrease from a high in early Spring to a minimum in summer, increasing again in late Autumn.

7. At 50 metres in mid summer, water colder than that found either in early spring or late autumn extends over the general area of the Gulf. A proposed analysis of the water body below the surface layer will determine whether these lowered summer temperatures at the 50 metre-level are the result of:

(a) the progressive inward movement of Labrador water,

(b) the thinning of the surface layer, bringing deeper and colder waters to the 50 metre-level, or,

(c) a variation in the deeper water temperatures as between the years 1947 and 1948.

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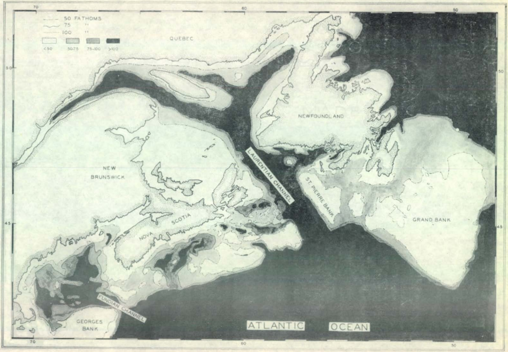

Figure 1 The Submarine Physiography of the Gulf of St. Lawrence and Neighboring Areas.

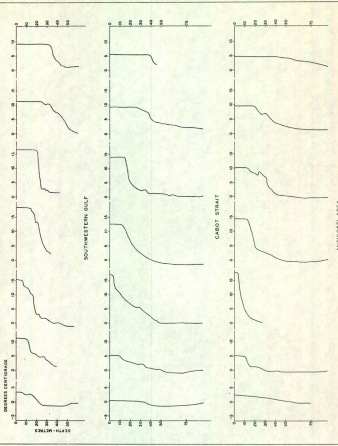

Figure 2 Monthly Progress in the Development of the Surface Layer in the Gulf of St. Lawrence.

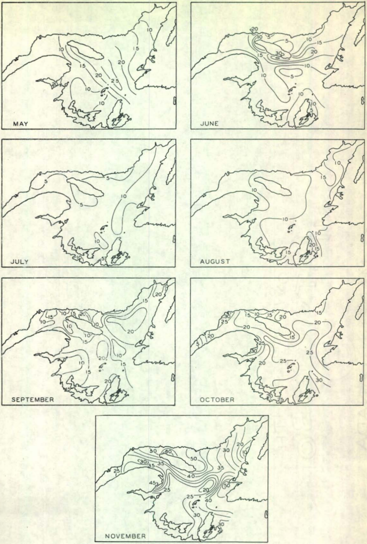

Figure 3 The Average Thickness of the Surface Layer in metres in the Gulf of St. Lawrence.

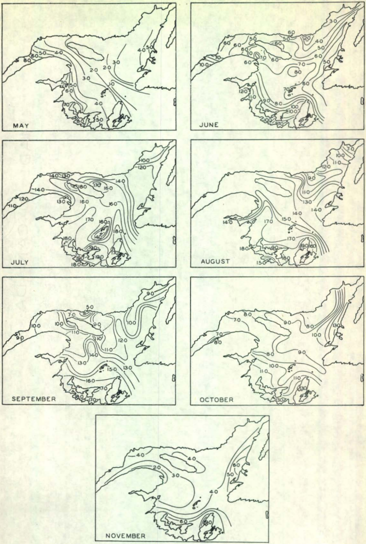

Figure 4 The Average Distribution of Surface Water Temperatures in the Gulf of St. Lawrence. (Degrees Centigrade)

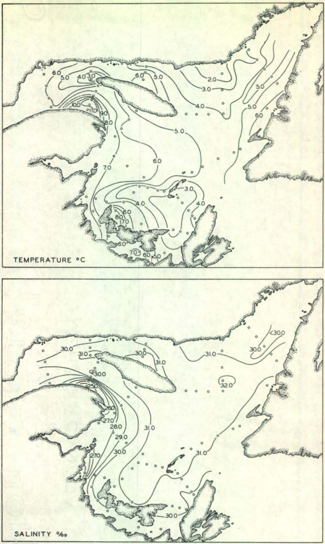

Figure 5 Surface Distribution of Temperature and Salinity in May, 1948.

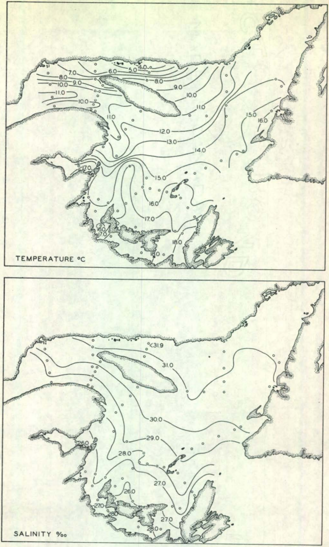

Figure 6 Surface Distribution of Temperature and Salinity in August, 1947.

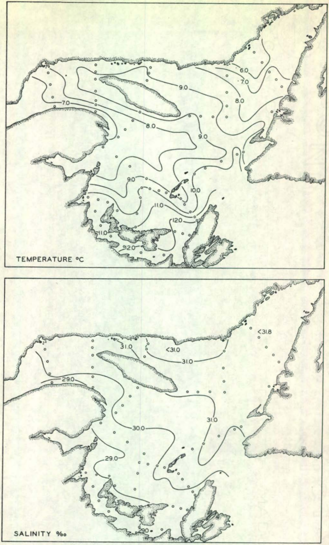

Figure 7 Surface Distribution of Temperature and Salinity in October, 1948.

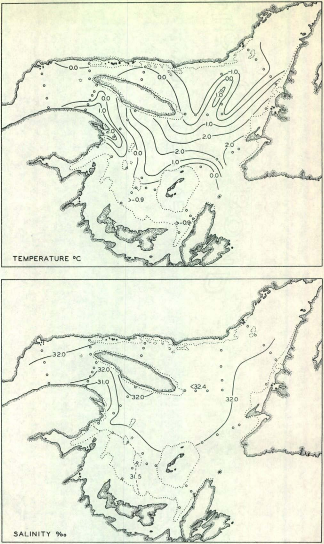

Figure 8 Distribution of Temperature and Salinity at 50 metres in May, 1948.

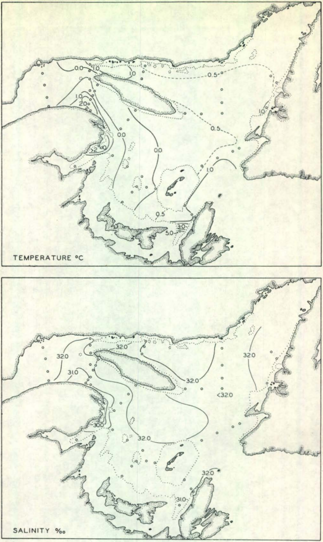

Figure 9 Distribution of Temperature and Salinity at 50 Metres in August, 1947.

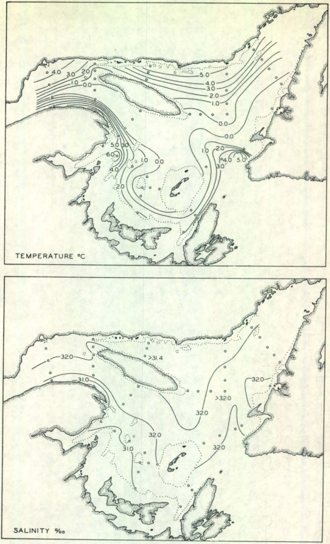

Figure 10 Distribution of Temperature and Salinity at 50 Metres in October, 1948.