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A STUDY ON MIXING AND CIRCULATION IN THE ST. LAWRENCE ESTUARY UP TO 1964

by

H. J. A. NEU

DECEMBER 1970

AOL REPORT 1970-9

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SUMMARY

The salinity and temperature distributions in the St. Lawrence Estuary during fresh water inflows of approximately 11,000 m^3/sec in February and 17,000 m^3/sec in May of 1963 are reported and analyzed.

The mixing character of the Estuary varied from being well mixed at the head to moderately mixed in the section below the head to Tadoussac. In the deep section below the mouth of the Saguenay River, stratified conditions prevailed.

The water was appreciably fresher on the south side of the channel than on the north side except off the mouth of the Saguenay River. Progressing seaward, the depth of the fresh upper layer decreased along the north shore and increased along the south shore. Temperatures in the surface layer during February were higher on the north side than on the south. In May this trend was reversed.

It was concluded that the primary motion in the system is a longitudinal two-layer circulation in which the surface layer deviates toward the south shore and the deep layer toward the north shore. There is a net seaward flow of lower-salinity water on the south side and a compensatory flow of higher-salinity water on the north side. The Gaspé Current is a high-velocity surface stream which forms below Tadoussac and grows seaward with the entrainment of the water from the rivers of the north shore.

Upwelling of the deep warmer water to the surface maintains a nearly ice-free channel along the north shore through most of the ice season.

It is demonstrated that the intensity of the estuarine circulation in the St. Lawrence Estuary is determined primarily by the quantity of fresh water entering the system. Velocity estimates indicate that for a fresh water inflow of 17,000 m^3/sec the resulting flow of the surface layer is approximately twice that for 11,000 m^3/sec.

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1.0 INTRODUCTION

An estuary, as defined by Cameron and Pritchard 1963, is a semi-enclosed body of coastal water within which the sea water mixes with the fresh water from the land drainage.

In the St. Lawrence River, the point farthest upstream where salt water of oceanic origin was measured was near Orleans Island, 27 km below Quebec City. The estuary, therefore, is considered to begin here and to extend below Pointe-des-Monts, where it joins the Gaspé area, an embayment of the St. Lawrence Gulf system.

The estuarine channel, as shown in Fig. 1 and 2, is a funnel-shaped bay, varying in width from 20 km above the mouth of the Saguenay River to about 48 km near Baie Comeau. The depth increases from about 10 m in the shoal area off Orleans Island to 60 m above the Saguenay. Off the mouth of this river, the bed drops abruptly to 300 m, and remains approximately at this depth through the rest of the defined system.

The main sources of fresh water are: the St. Lawrence River, the Saguenay River and a group of rivers consisting of the Bersimis, the Outardes and the Manicouagan. The St. Lawrence enters the system at Orleans Island, the Saguenay at Tadoussac, while the group of rivers joins the estuary above Baie Comeau. The inflows from this 'group' have been considered as a single river, since they are in close proximity to each other.

The original aim of the investigation was to determine the reason why more ice accumulates along the south side of the estuary. Aerial observations reveal that this ice is mostly packed and snow-covered, while along the north shore it is more translucent and therefore probably younger.

This feature seems to indicate that surface water deviates toward the south shore, while the warmer water of the underlying layers deviates toward the north shore.

It should be noted that this report is an abbreviated version of an unpublished manuscript prepared in early 1964 which has only now become available for publication.

2.0 HYDROLOGIC AND METEOROLOGIC DATA

The survey periods in February and May were chosen primarily to permit an evalution of the differences which occur in the estuary due to a large variation in the fresh water inflow. Meteorological effects on the results are also reviewed.

2.1 Fresh Water Inflow

All major fresh water inflows, except that of the St. Lawrence River itself, enter the system from the north shore, the inflow from the south shore being insignificant. This is an important feature which should be noted.

During the periods of the surveys, the inflows were found to be fairly uniform, as shown in Fig. 3. In February, the inflow from the St. Lawrence varied from 8,500 m^3/sec to 7,900 m^3/sec and in May from 10,400 m^3/sec to 9,050 m^3/sec. The Saguenay inflow, which is artificially

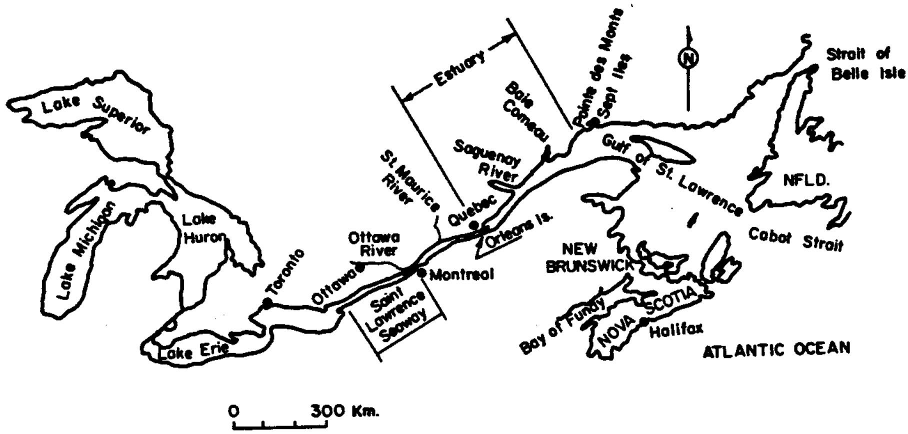

Fig. 1. Great Lakes and St. Lawrence system.

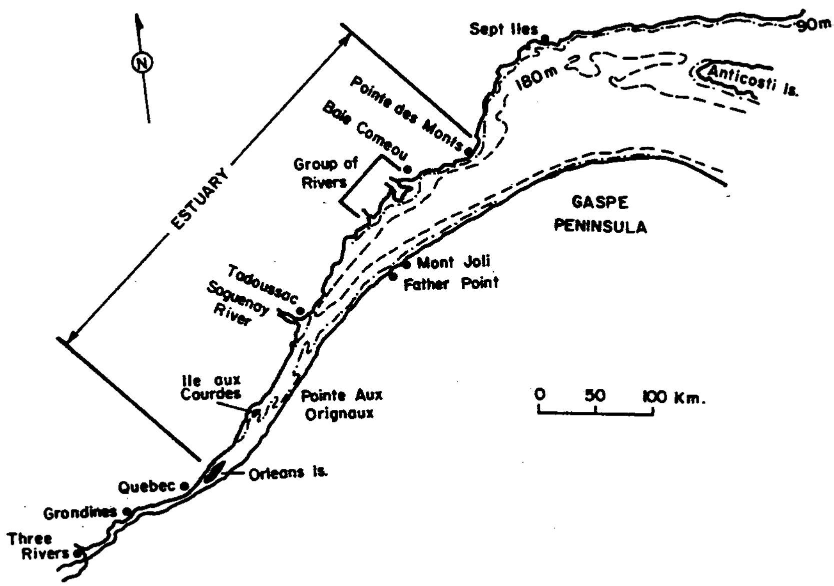

Fig. 2. Lower St. Lawrence River and estuary.

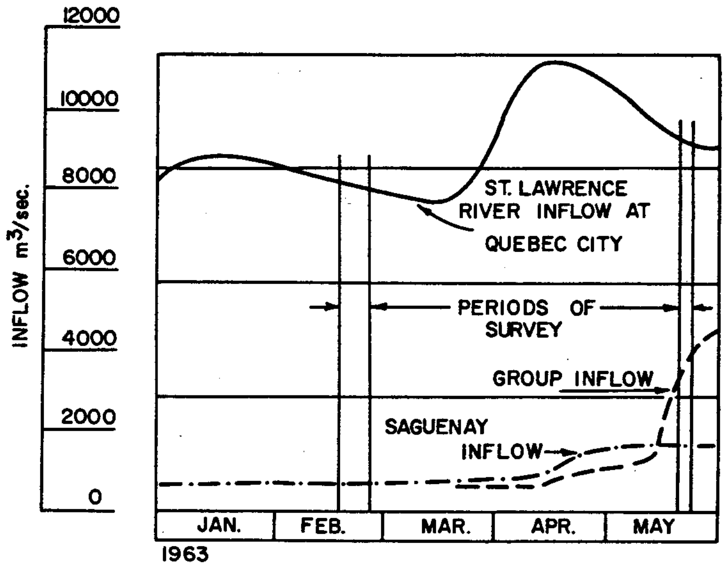

Fig. 3. Fresh water flow into the estuary.

controlled, changed very little during each survey and was 710 m^3/sec in February and 1,840 m^3/sec in May. The combined inflow from the group of rivers varied little, except during the survey in May. Their discharge was 710 m^3/sec in February and 1,410 m^3/sec during the first half of May, increasing to 3,950 m^3/sec during the survey. The total inflow, including smaller streams, was about 11,000 m^3/sec in February and 17,000 m^3/sec in May.

The river discharges were obtained from the Water Resources Branch, Department of Northern Affairs and National Resources.

2.2 Tide

The maximum range of the tides entering the St. Lawrence Estuary is about 4 m, but they are augmented within the system so that their ranges are nearly doubled when they reach the upper end. (See Fig. 4 showing tide wave profiles of data recorded 11 February 1959.)

In the lower part of the estuary, the increase is moderate and the surface profile of the wave is regular with the slopes small. Above Father Point where the bay narrows, and then farther upstream where the channel becomes shallow, the tide range increases more and more rapidly and the water surfaces attain slopes of exceptional steepness. An outstanding example of this is shown in the profile at 1700 hours when the water level at Quebec was near Low Water, and at Point-aux-Orignaux near High Water, resulting in a difference in water elevations of 3.7 m over a distance of 100 km.

It is evident that these tides play an important role in the mixing of the waters of the estuary. Their currents exert a profound influence by the turbulence they produce. This tends to break down the separation between the river water and the ocean water, thus initiating a vertical mixing of the two. In an extreme case, the vertical mixing may be so thorough that there is only a little variation of salinity from the surface to the bottom.

Using the tidal streams derived from the tide ranges, it can be assumed that the mixing is appreciably stronger in the upstream part of the system than in the lower.

2.3 Air Temperature

During the surveys, seasonal air temperatures prevailed. As shown in Fig. 5, they were, at Quebec City, -13°C in February preceded by a period of one month of similar temperatures. In May, the average temperature had risen to +12°C, with the transition through zero at the beginning of April.

2.4 Wind

It is apparent that the wind can have an important influence on estuarine circulation and mixing. Through the stress exerted on the surface it can produce a net transport of water and the resulting generation of waves will increase the intensity of vertical mixing. In the surface layer the water transport will be mainly in the direction of the wind.

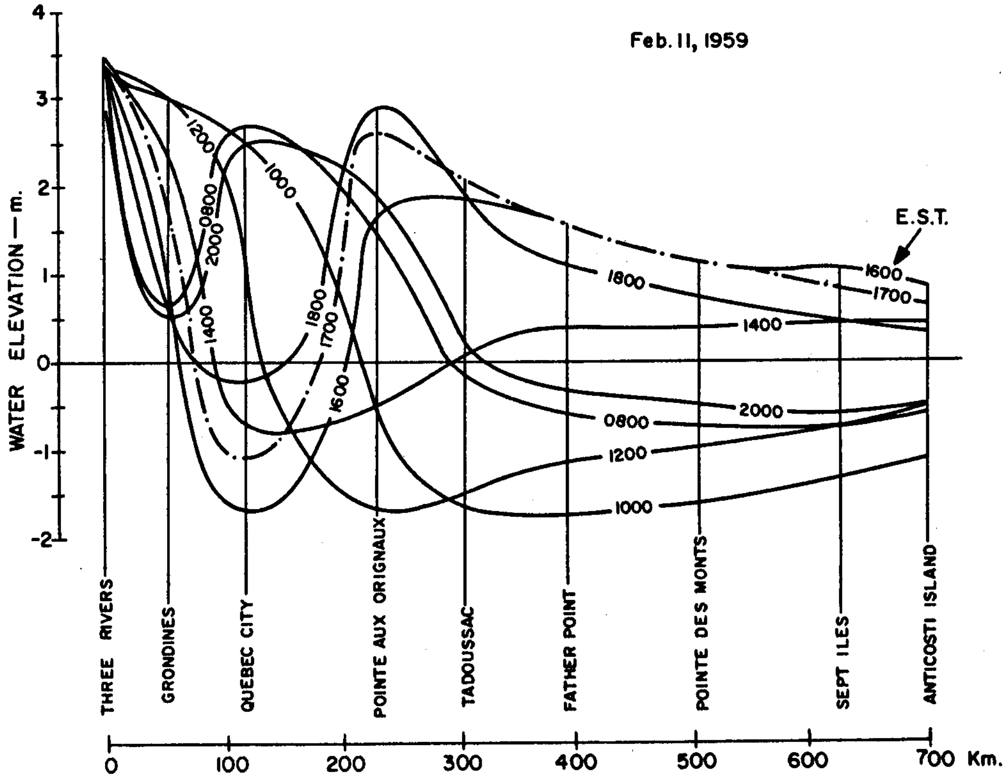

Fig. 4. Two-hour profiles of tide wave.

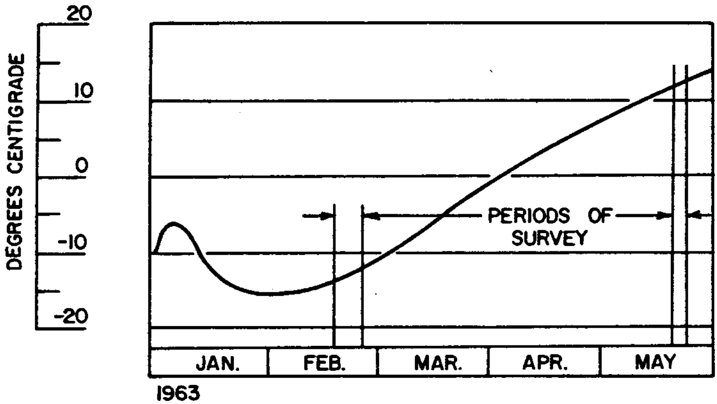

Fig. 5. Mean air temperature at Quebec City.

Direct wind data were available from several observation stations along the shore of the estuary. In addition, geostrophic winds were obtained from barometric pressure distribution charts.

Wind data from ground stations, particularly relating to directions, are often affected by local topographic features. From comparisons with geostrophic winds, it was found that the wind observations at Mont Joli were acceptably representative of the winds over the waters of the St. Lawrence Estuary.

As shown in Fig. 6, prior to and during the surveys, the wind in February was from the northwest for half the time and from the east, south and west for the remainder, while in May the significant direction was the south and southwest. The average wind velocity was 8 m/sec with a maximum of 15 m/sec.

Winds from the northwest and from the southeast sectors cause a drift of the surface water across the channel. The thickness of this layer depends on the strength and the duration of the wind, but, according to Wiegel, 1964, it can be in the order of 1 m. Assuming the wind-induced current to be three percent of the wind speed, the transport across the surface of the deep section of the estuary is calculated to be as much as the fresh water inflow. This appears to be large, but, as shown later (6.5), it is only of the order of 3-5 percent of the total volume of water circulating and can, therefore, be considered as a negligible factor in the dynamics of the system.

3.0 SURVEY AND EQUIPMENT

The surveys were conducted from 18-25 February and from 21-24 May 1963. The ships used were the CCGS "TUPPER", a buoy ship capable of navigating in the ice of the St. Lawrence during the winter, and the CCGS "PUFFIN", a shallow draft, northern supply vessel.

Seven survey sections along the estuary were established for both the February and May surveys. Ice in February restricted entry to certain areas of the estuary and hence minor variations in location occurred and some stations were omitted. In May an additional section was added between Ile-aux-Coudres and the Saguenay River.

In each survey section three or four stations were occupied across the channel and water samples were taken from the surface to the bed, using Knudsen reversing bottles. The temperature was measured at each sampling depth with deep-sea reversing thermometers, and the density was measured onboard the ship with stem hydrometers. Since the differences in density were large and consistent, this method was considered sufficiently accurate for the assessment of the general dynamic characteristics. From the densities and the temperatures measured, the salt content of the water was estimated.

4.0 OCEANOGRAPHIC PROPERTIES

The data of the survey are graphically reported, showing the variation in the properties of the water body along longitudinal, horizontal and transverse sections.

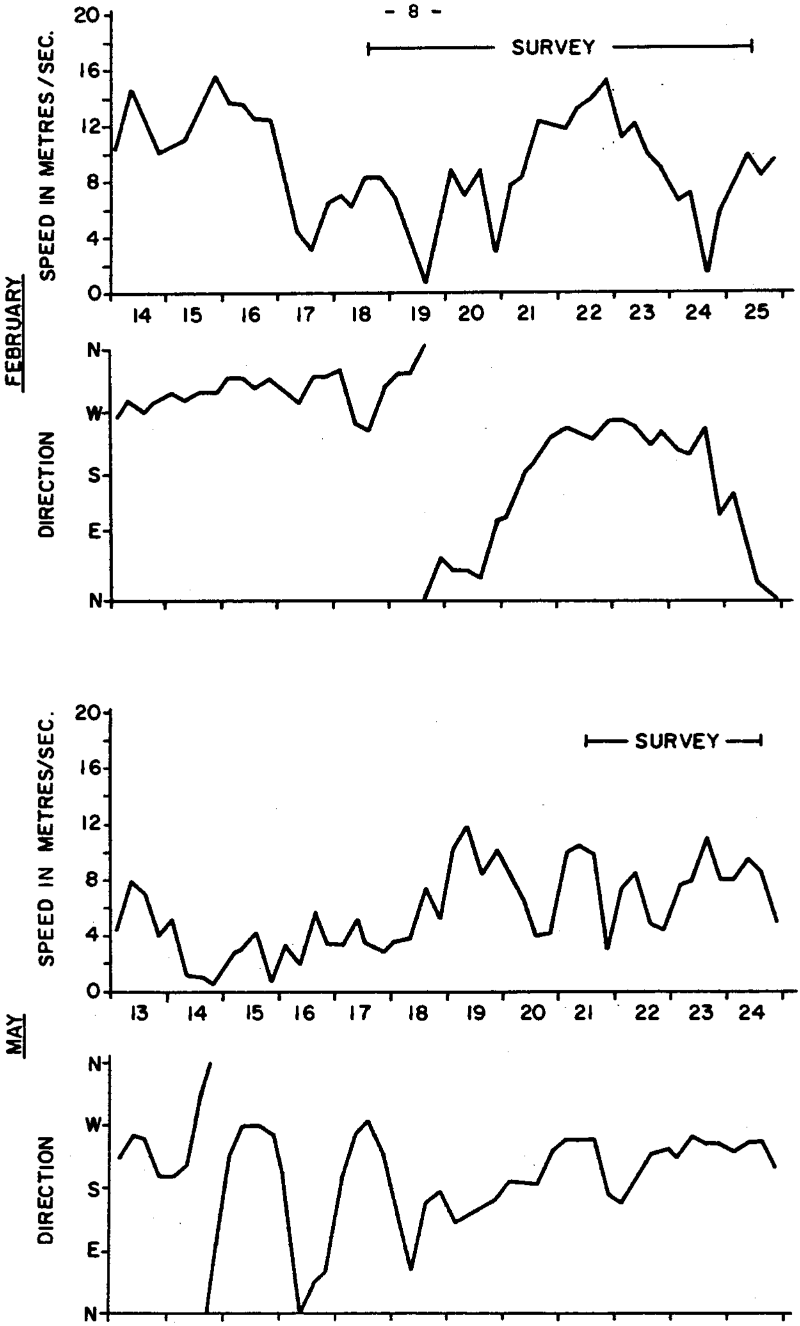

Fig. 6. Wind data at Mont-Joli, Quebec.

4.1 Distribution of Salinity

As demonstrated in Fig. 7 and 8, the salinity distribution in the deep section of the estuary differs greatly from that in the shallower section above Tadoussac. The two sections will be discussed separately.

4.1.1 Salinity distribution below Tadoussac

In the deep, central part of the channel (see profiles 2 and 3 of Fig. 7 and 8) the isohalines are almost horizontal or tilt slightly upward in the seaward direction. The increase in salinity seaward is therefore small, implying that mixing is slight. Vertically, the body of water is divided into two layers (Fig. 15), an upper layer (including the halocline) approximately 70 m thick and a deeper layer which fills the rest of the channel.

The salinity of the deep layer was the same in both surveys, i.e., 33 to 35°/₀₀. This salinity is also found over and beyond the Continental Shelf, suggesting that this ocean water penetrates 800 km upstream without being noticeably changed by the fresh water in the system.

Conditions in the upper layer, however, differed appreciably from those in the deeper layer. Its depth appears to be influenced by the height of the sill at the upstream end of the deep section, though the layer is deeper in February than in May. The salinity content, particularly at the surface, differed greatly between the two surveys. In February it increased seaward from 30.5 to 32°/₀₀, while in May it remained at approximately 28.5°/₀₀ throughout the section. In May the halocline is more prominent because of the presence of more fresh water.

The salinity distributions along the sides of the estuary differ from that along the centre. Along the north side, the isohalines slope more upward (Fig. 7) than in the centre, implying that either mixing is stronger or, more probably, that fresher water is drawn off and replaced by more saline water from the deeper zone. On the south side, the isohalines slope downward, indicating that fresher water accumulates at a faster rate than the system is mixing to maintain constant salinity.

As shown on the horizontal salinity chart of Fig. 10, there is a wedge of water in the southern half of the channel whose salinity decreases at an exceptional rate in the seaward direction. The layer, several kilometres wide, is inclined toward the south shore and in May starts halfway between Tadoussac and Father Point and has the appearance of a stream in which most of the fresh water of the lower estuary accumulates. It is inferred that this body of water, which is more clearly defined in May than in February (Fig. 9), is the upstream part of the Gaspé Current or its major tributary. The dynamics of the current will be discussed later.

As mentioned, no appreciable quantity of fresh water enters the system from the south shore where the stream is located. The 25 percent of fresh water which entered the estuary in May from the 'group' of rivers must have crossed the channel immediately to join the flow on the south side. In Section G (Fig. 8), which is the survey section next to the 'group' of rivers, a large decrease in salinity at 9-m depth (Fig.10)

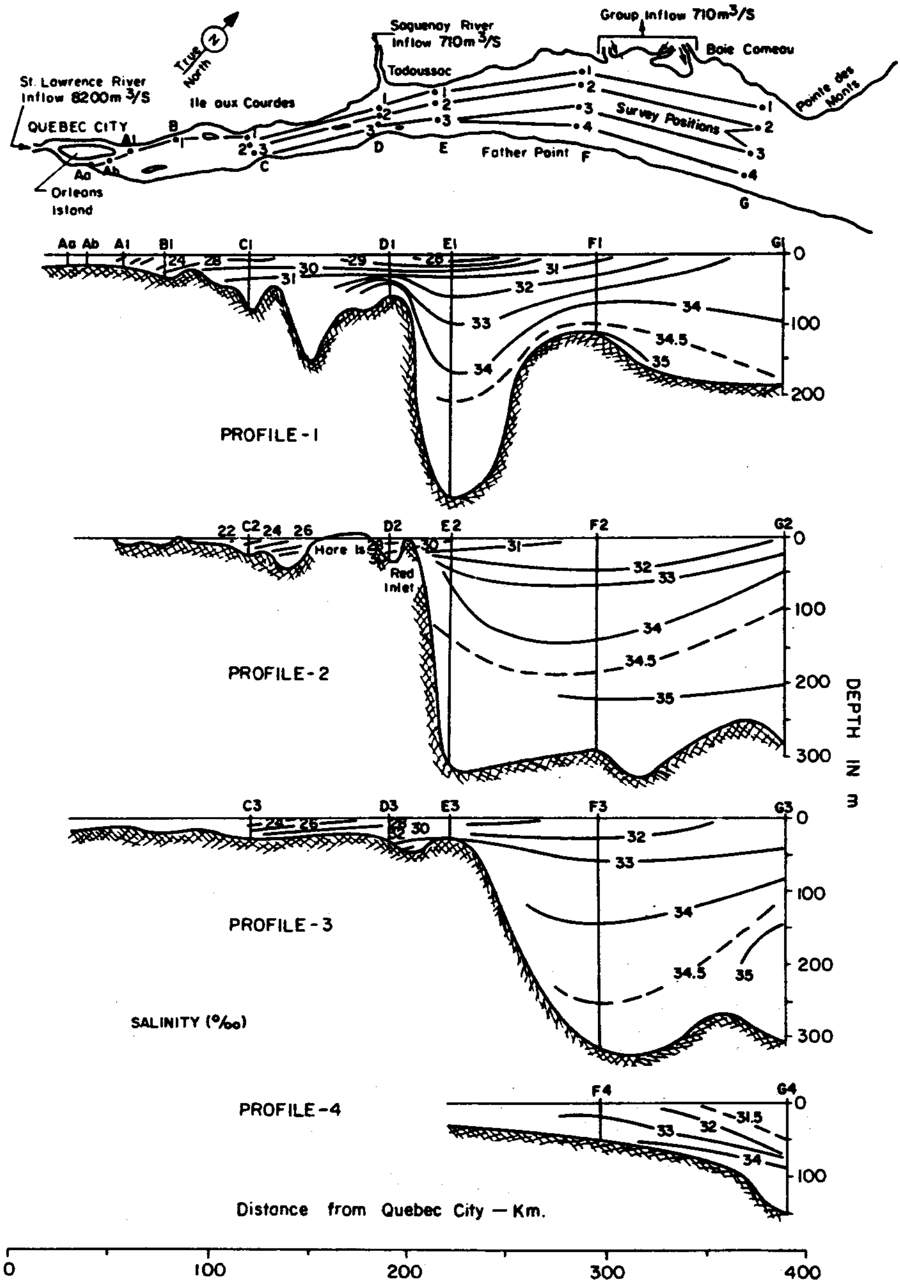

Fig. 7. Longitudinal salinity profiles, 18-25 February 1963.

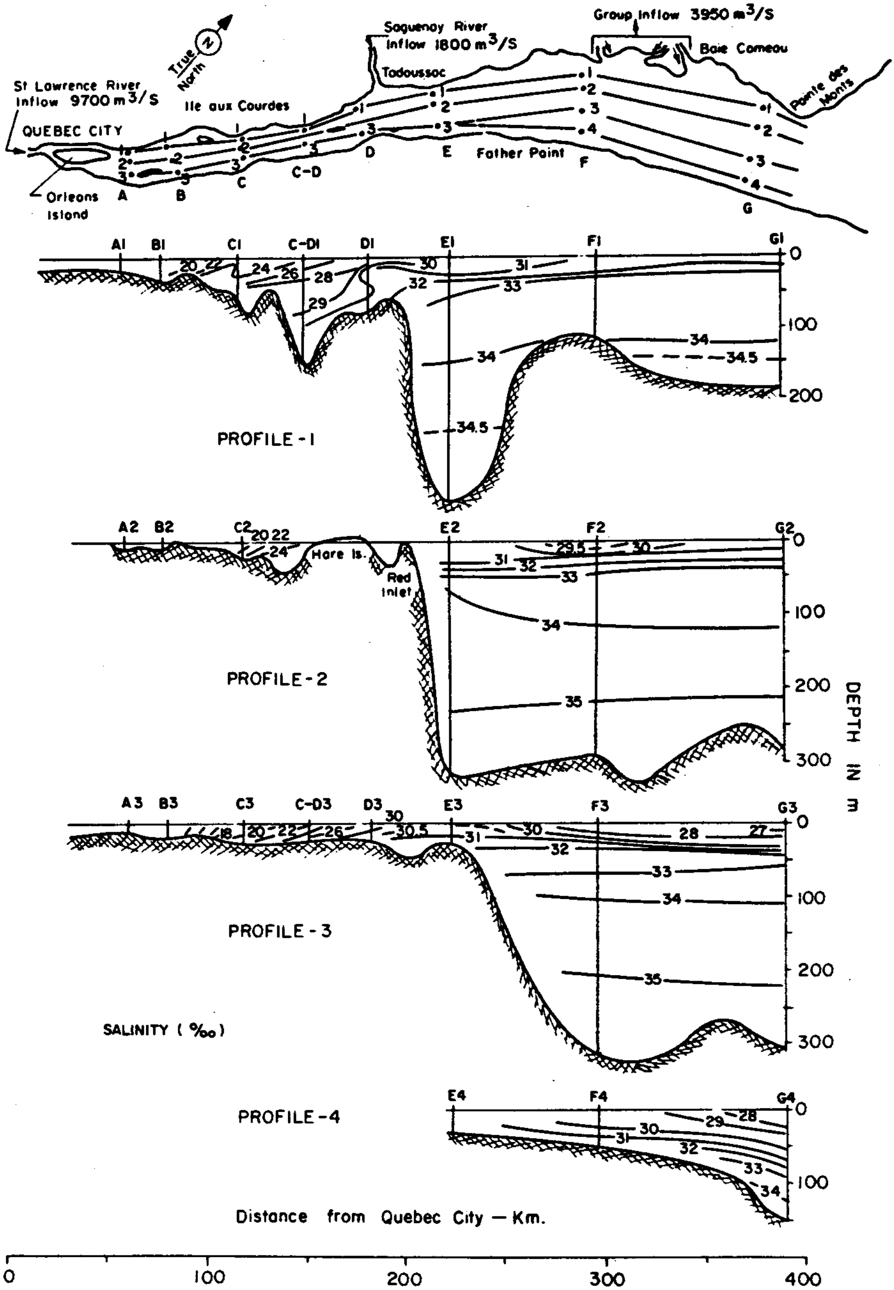

Fig. 8. Longitudinal salinity profiles, 21-24 May 1963.

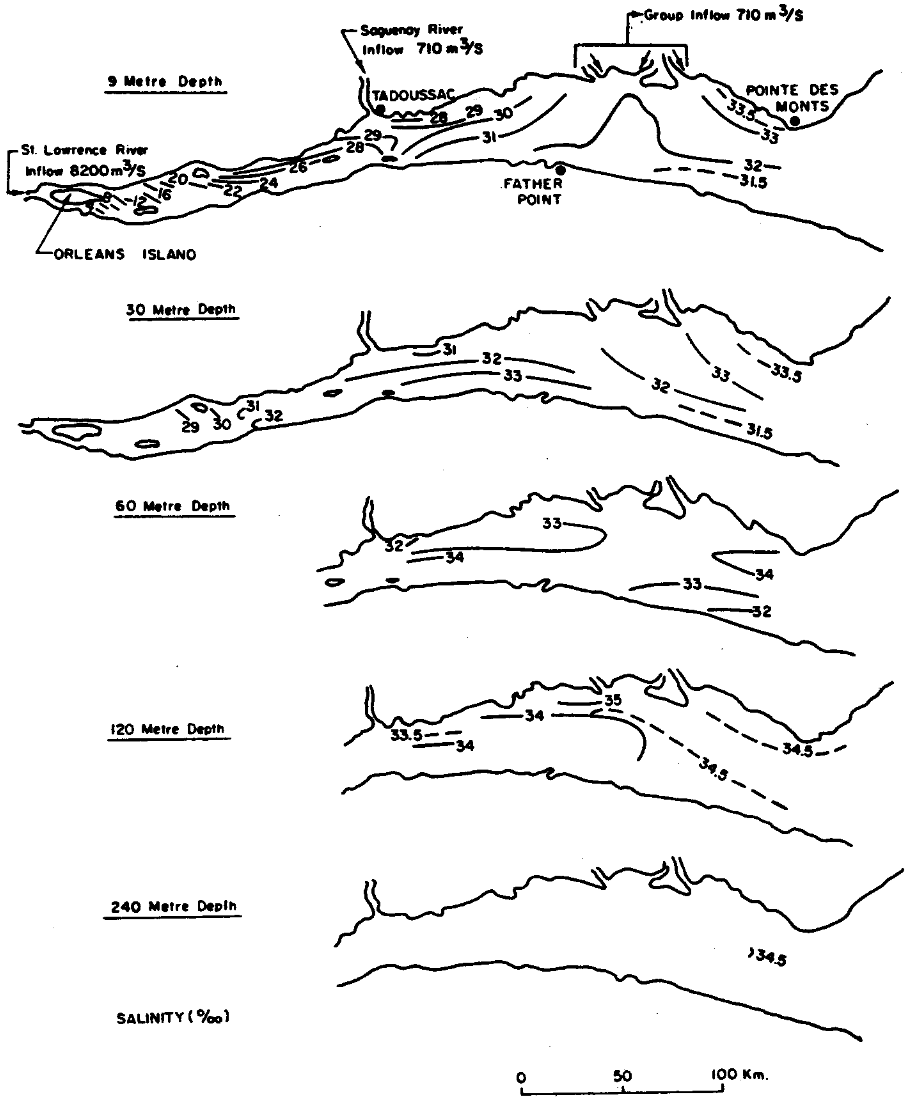

Fig. 9. Horizontal salinity charts, 18-25 February 1963.

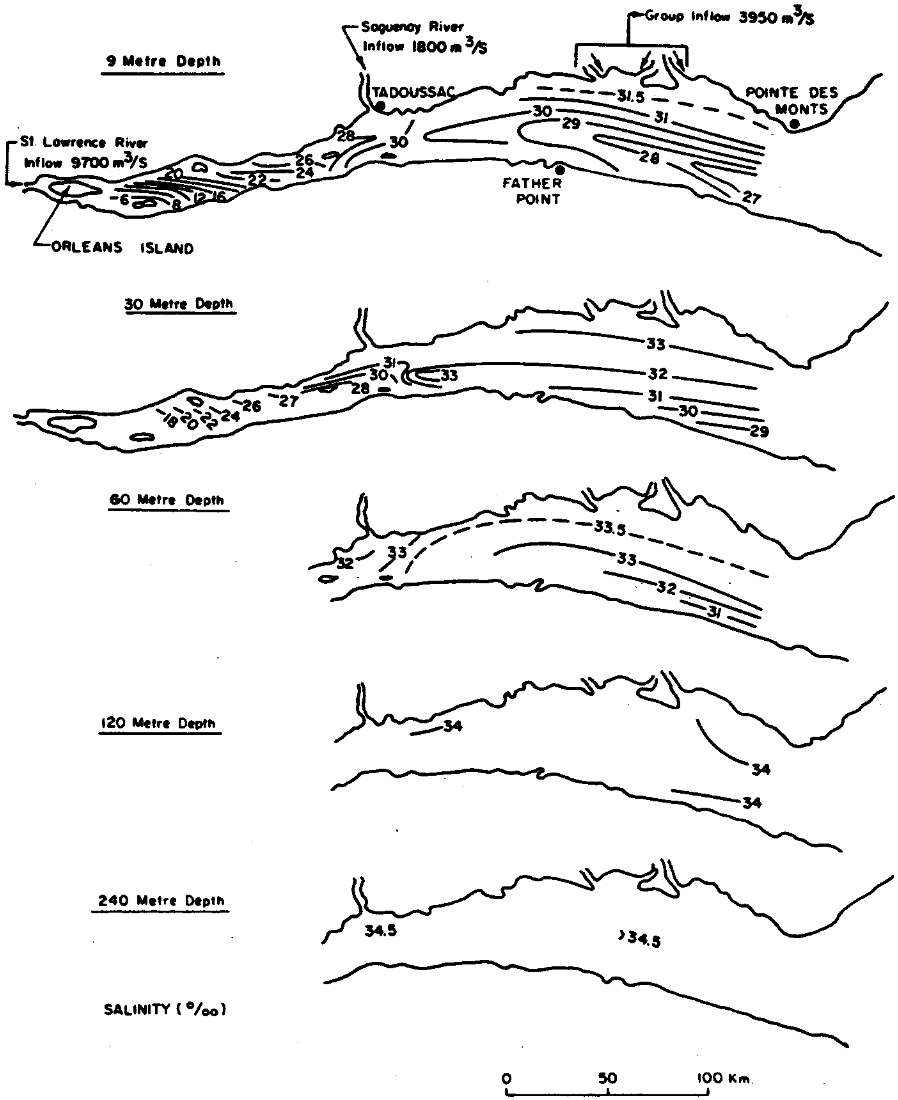

Fig. 10. Horizontal salinity charts, 21-24 May 1963.

was measured only at positions 3 and 4, i.e., at the south side of the estuary. The transfer of the fresh water across the northern half of the channel occurred in a thin top layer where measurements were not performed. However, the existence of this water was observed by eye as a brown colour, distinctively different from the rest.

4.1.2 Salinity distribution above Tadoussac

The upper section of the estuary is 20 to 70 m deep with a central group of shoals and islands dividing the channel in many places into two arms of which the north arm is generally deeper than the south.

As seen on the longitudinal profiles of Fig. 7 and 8, the isohalines, which were almost horizontal in the deep section of the estuary, slope upward in the shallow section (Fig. 8). Their gradient increases steadily upstream until they are very steep (in the order of 1:100) at Orleans Island.

In this comparatively shallow section of estuary the vertical mixing extends throughout the depth, mixing the fresher water downwards and the more saline water upwards. The main factor in the mixing intensity is the ratio of the amplitude of tidal currents to the river flow of the St. Lawrence. As the amplitude of the tidal current increases in the upstream direction, there is a wide range in the degree of stratification occurring. While halfway along the channel the total increase in salinity from surface to bottom is about 7°/₀₀, it is less further upstream. At the head of the estuary tidal currents are very strong, thus mixing is so intense that there is little variation in salinity from surface to bottom, in May less than 1°/₀₀.

Due to the Coriolis effect, there is still a lateral variation of salinity, the lower-salinity water occurring on the south side, the average difference being more than 5 and 8°/₀₀ in February and May, respectively. Apparently, associated with this there is a net seaward flow of lower-salinity water on the south side and a compensating flow of higher-salinity water on the north side. This circulation is further intensified by an eddy which forms below Orleans Island in response to the river flow into the estuary and the alternating tidal flow. The combination of these currents promotes this type of mixing.

The fresh water inflow from the St. Lawrence River of 9,700 m^3/sec in May shifted the zones of equal salinity approximately 20 km seaward, compared with those for the inflow of 8,200 m^3/sec in February. Water having a salinity in excess of 32°/₀₀ (May) and 34°/₀₀ (February) was prevented from entering the system by the sill at Tadoussac.

4.2 Temperature Distribution

Water temperatures differed greatly between the two surveys, as shown by the temperature distribution curves of Fig. 11, but the same two-layer system generally prevailed in the deep part of the estuary. The upper layer is colder in February and warmer in May than the underlying water. The thermocline is more prominently defined in May than in February and its position coincides with that of the halocline.

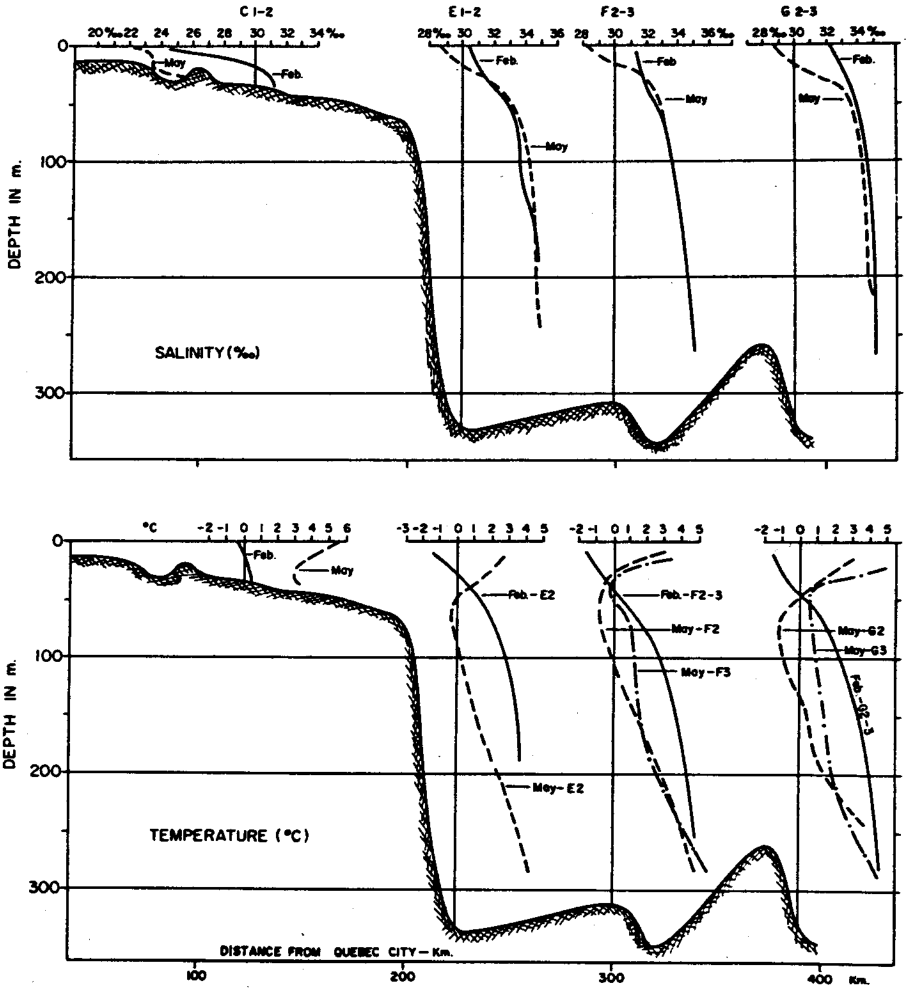

Fig. 11. Vertical salinity and temperature distribution in central section.

4.2.1 Temperature distribution in February

Prior to and during the survey the water was subjected to intense cooling and the temperature of the surface layer approached or had already reached the freezing point (Fig. 12 and 14). This was evident from the ice which covered 30 to 40 percent of the water surface.

This seasonal cooling created a temperature field in the deep section of the estuary which was remarkably well stratified, as illustrated in the longitudinal temperature profiles of Fig. 12. The temperature increased from nearly freezing at the surface to approximately 4°C at mid-depth, below which it was quite uniform. This arrangement implies that the heat was transferred vertically upward to the surface by thermal and dynamic convection.

The isotherms slope in a way similar to the isohalines, indicating that the temperature in the surface layer increased along the north shore toward the sea, while on the south shore cold water with a temperature of -1.5 to -2°C formed an increasingly thick layer toward the Gulf. From this it may again be inferred that water having a greater heat content is brought up from deeper zones along the north shore, whereas cold water from the upper layer is transferred to the south side, where it accumulates.

In the section above Tadoussac, heat from the deep channel penetrates over the sill into the downstream part of the shallow section where a temperature gradient of 1° was observed between the surface and the bed.

At the mouth of the Saguenay River conditions differ and the temperature pattern is reversed, as shown in Fig. 16.

4.2.2 Temperature distribution in May

In May the heat distribution was changed completely; the temperature of the air had risen to an average of +12°C and the surface of the estuary was therefore warming instead of cooling. This is reflected in the temperature distribution which was again stratified but divided into zones (Fig. 13).

At the bottom of the deep channel water at 4 to 4.5°C was still to be found. Vertically, the temperature of the water decreased quickly until an intermediate depth was reached, where a layer of cold water at a temperature of less than -0.5°C was found across the entire channel. A similar layer was observed by Lauzier *et al* in the Gulf of St. Lawrence farther downstream. The thickness of this layer increased from south to north and the temperature in its centre was colder on the north side than on the south. Spread over this body of cold water was a thin layer of warmer water in which the temperature increased toward the surface.

The intermediate cold water layer was part of a cold water zone which previously extended to the surface. When the atmospheric temperature exceeded that of the water at the beginning of April, a warmer surface layer began to form, trapping the cold water between two warmer layers.

In February the surface layer was warmer on the north side than on

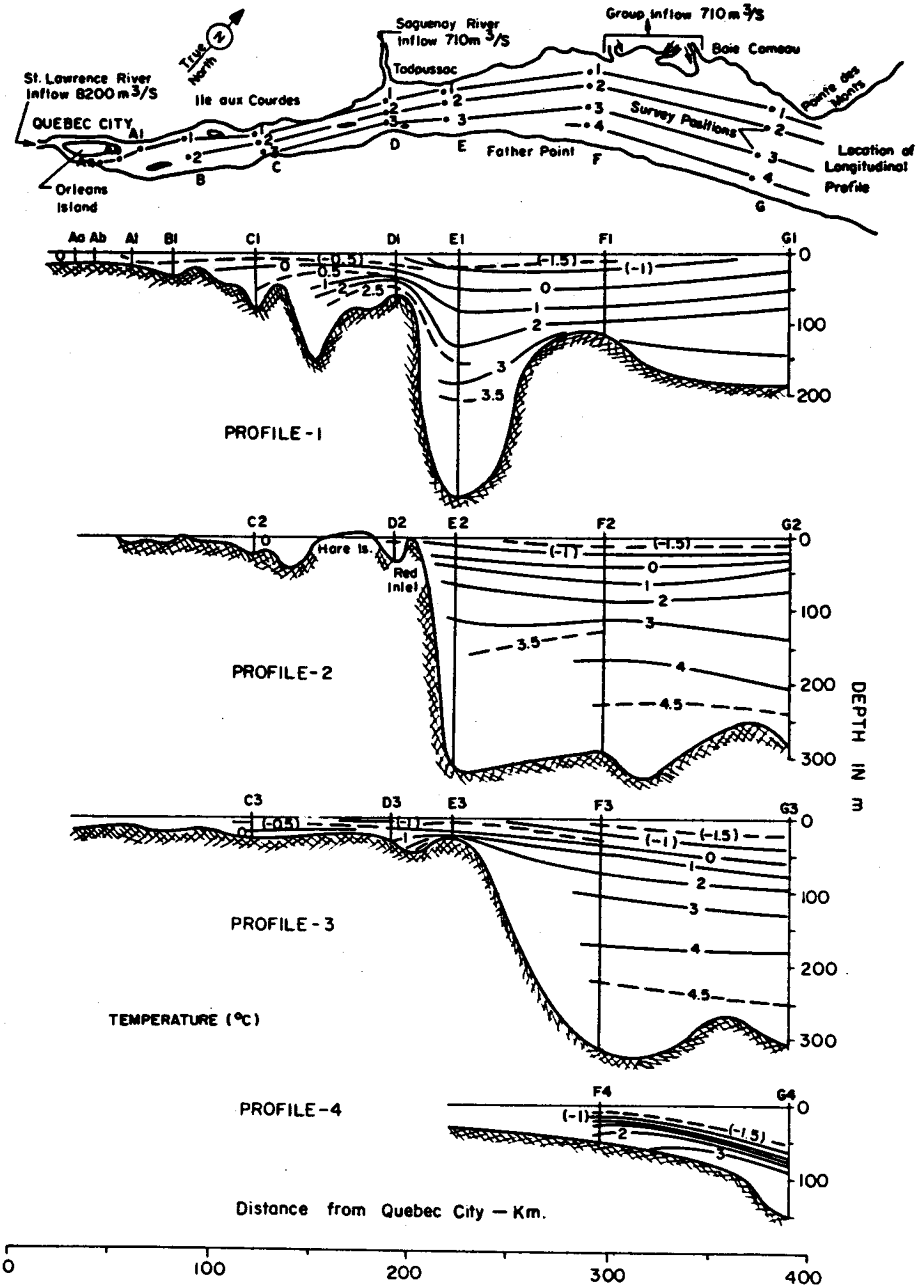

Fig. 12. Longitudinal temperature profiles, 18-25 February 1963.

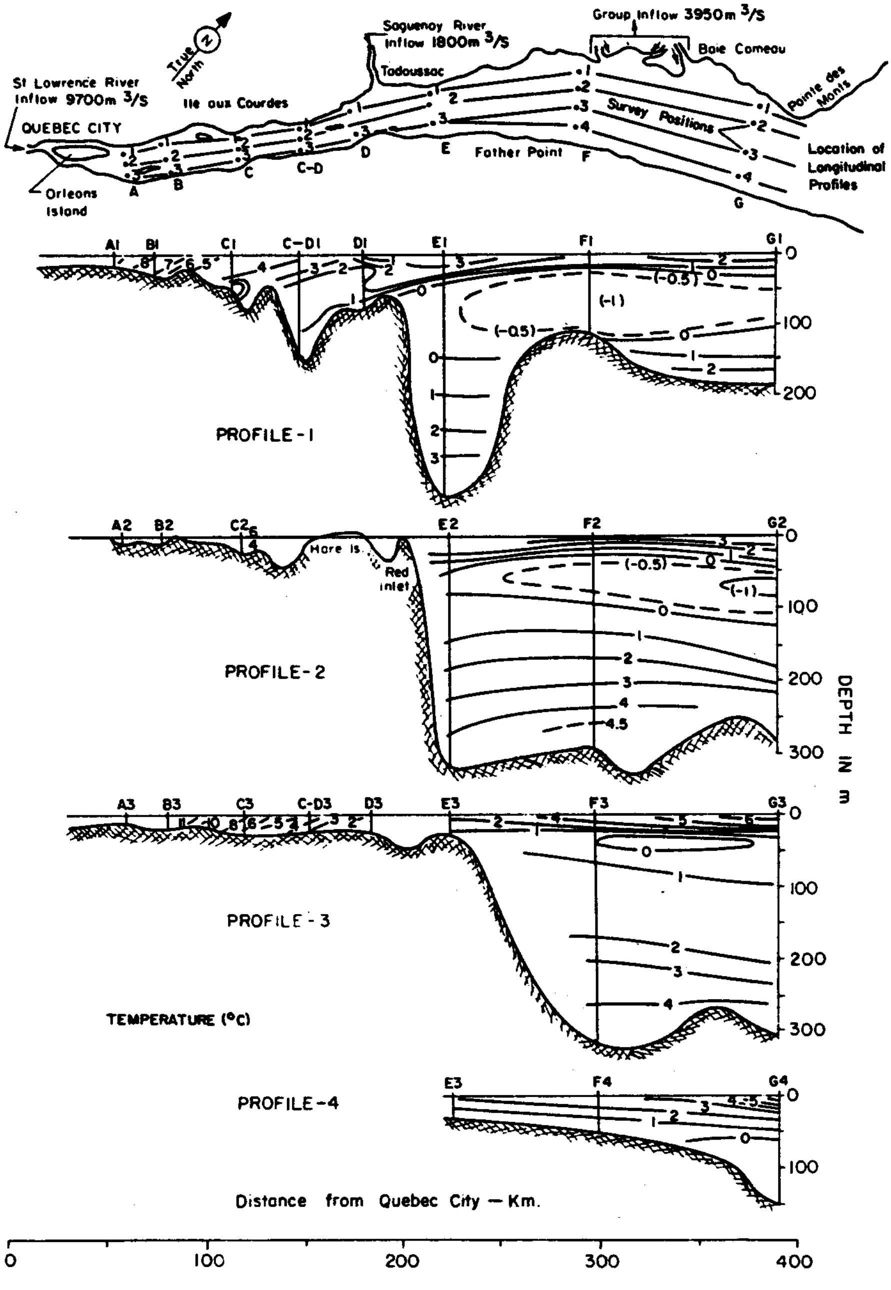

Fig. 13. Longitudinal temperature profiles, 21-24 May 1963.

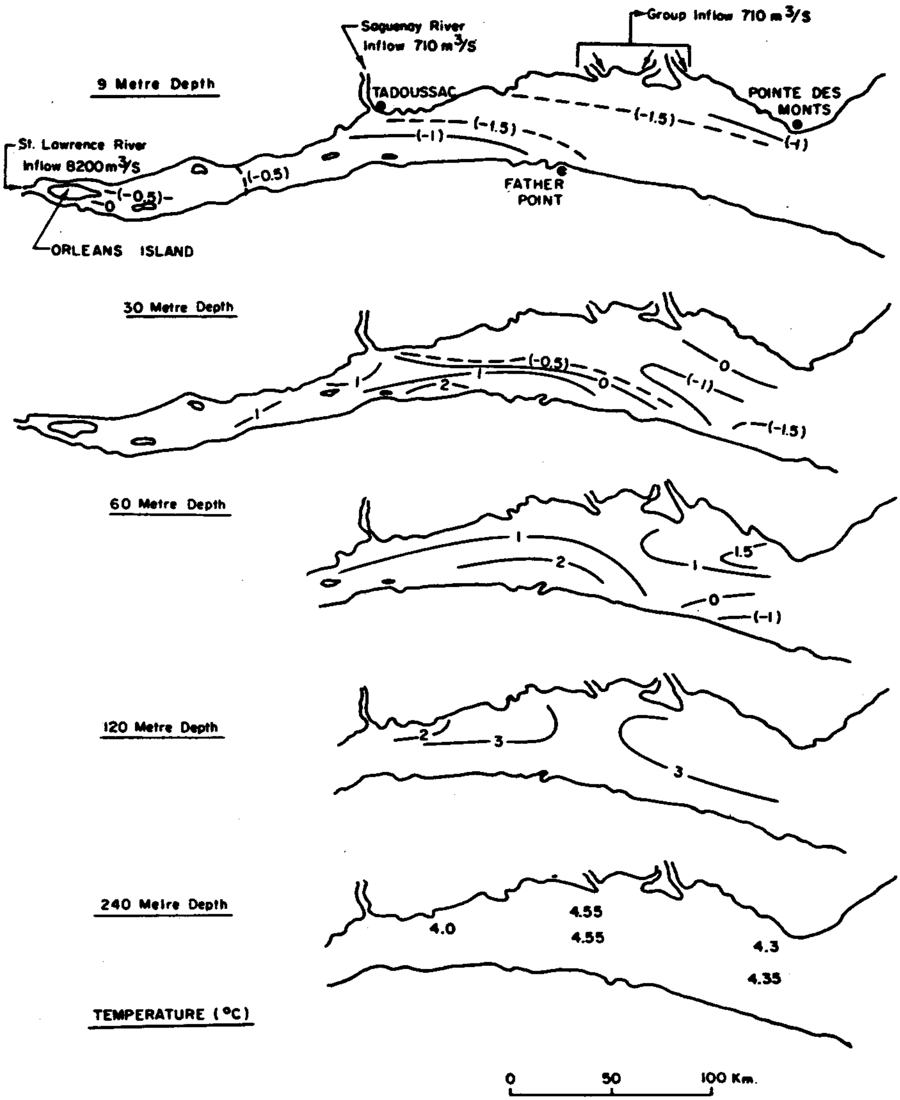

Fig. 14. Horizontal temperature charts, 18-25 February 1963.

the south side. This was reversed in May, but for the same reason, i.e., the lateral transport. This surface motion, which diverted the cold surface layer toward the south shore in February, carried water of appreciably higher temperature than that of the underlying zone in May. The water upwelling from deeper layers along the north shore was warmer in February and colder in May than the surface water.

In the upper section of the estuary the heat structure, in May, was greatly affected by the inflow of warmer water from the river which had already reached a temperature of +10°C. The isotherms, as shown in Fig. 13, sloped upward, suggesting a mixing with colder water approaching from below. The horizontal temperature charts, Fig. 15, illustrate that here also the north side was appreciably colder than the south.

On the south side of the channel there is a temperature anomaly (see 10-m depth in Fig. 15), which supports the existence of the Gaspé Current, in the same way as inferred from the salinity data. In this case the stream is identified by a band of warm water whose temperature increased seaward.

4.3 Discussion of Oceanographic Properties

In the deep section of the St. Lawrence Estuary, the water is divided into two layers, an upper and a deep layer, while in the shallow section the upper layer extends throughout the depth. The salinity of the deep layer was the same in May as in February, suggesting that its content remains constant throughout the year although the salinity of the upper layer changes with the fresh water inflow.

Obviously, the lighter water of the upper layer is flowing seawards over the deep layer which, for continuity, is flowing upstream with a smaller velocity. As described by Pickard 1964, mixing occurs within the halocline of the upper layer. In the deep section below Tadoussac, entrainment into this halocline occurs by the upward movement of deep water across the interface. There is no downward movement of the lighter water. In the section upstream of Tadoussac mixing extends through the entire depth with no deep layer of almost undiluted sea water as a source of water for entrainment. The salinity therefore decreases upstream at all depths.

The upper layer is triangular in cross section with the deeper side along the south shore where the water is principally fresher, but colder in February and warmer in May (Fig. 16) than on the north side, except where the Saguenay River enters the system. The depth of this layer increases seaward along the south shore while decreasing along the north shore.

Clearly, there is a displacement of water in the upper layer toward the south shore and a compensating flow of the deeper water toward the north shore. This is caused primarily through interaction between the two-layer flow and the effect of the earth's rotation represented by the Coriolis force.

The depth of the upper layer was less in May than in February despite the larger fresh water inflow. The salinity distribution charts in Fig. 17 indicate a large concentration of fresh water in the surface

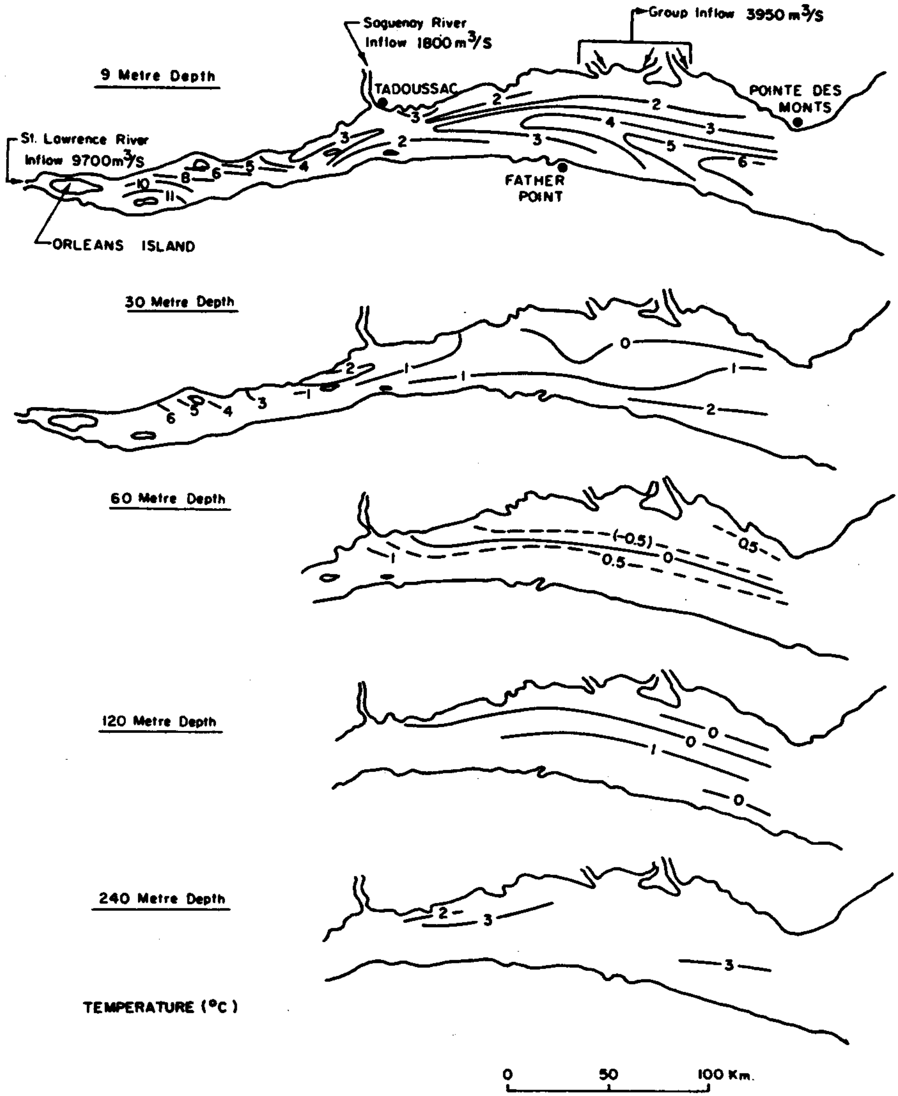

Fig. 15. Horizontal temperature charts, 21-24 May 1963.

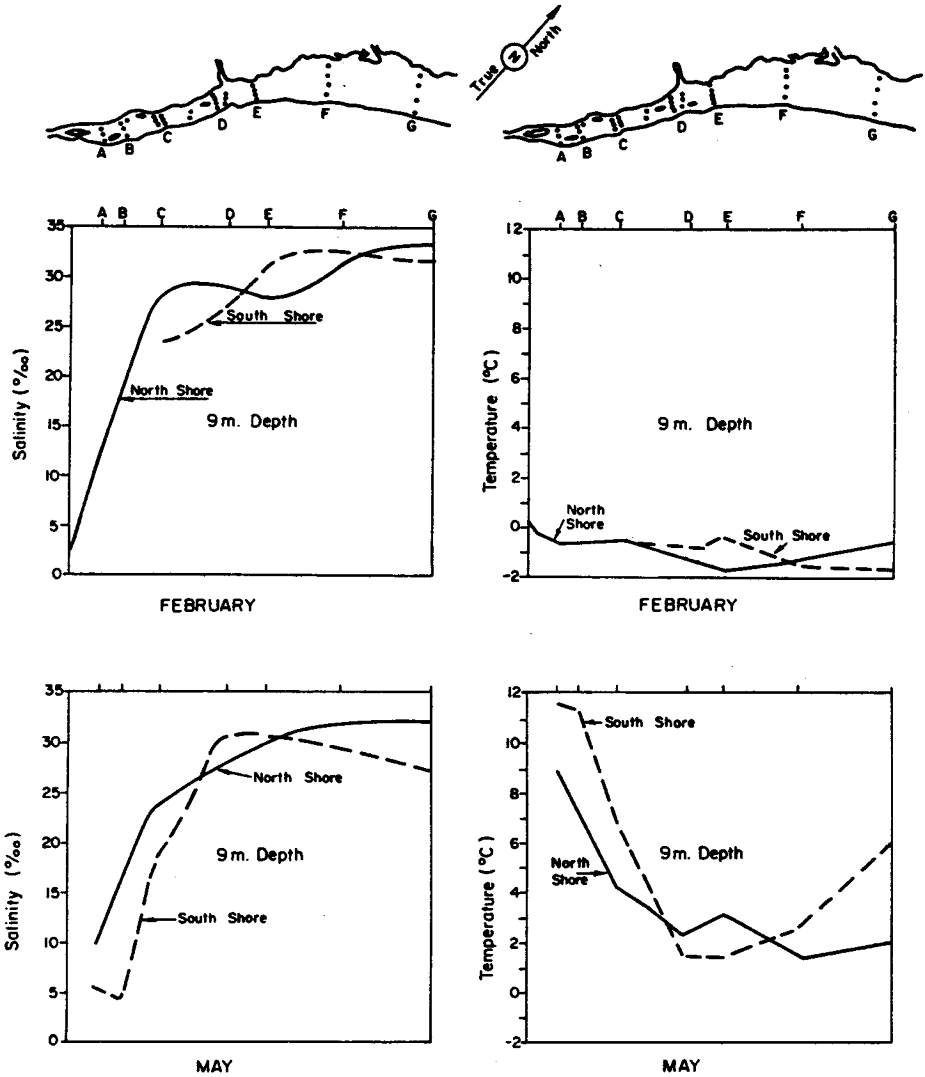

Fig. 16. Salinity and temperature on north and south sides of channel.

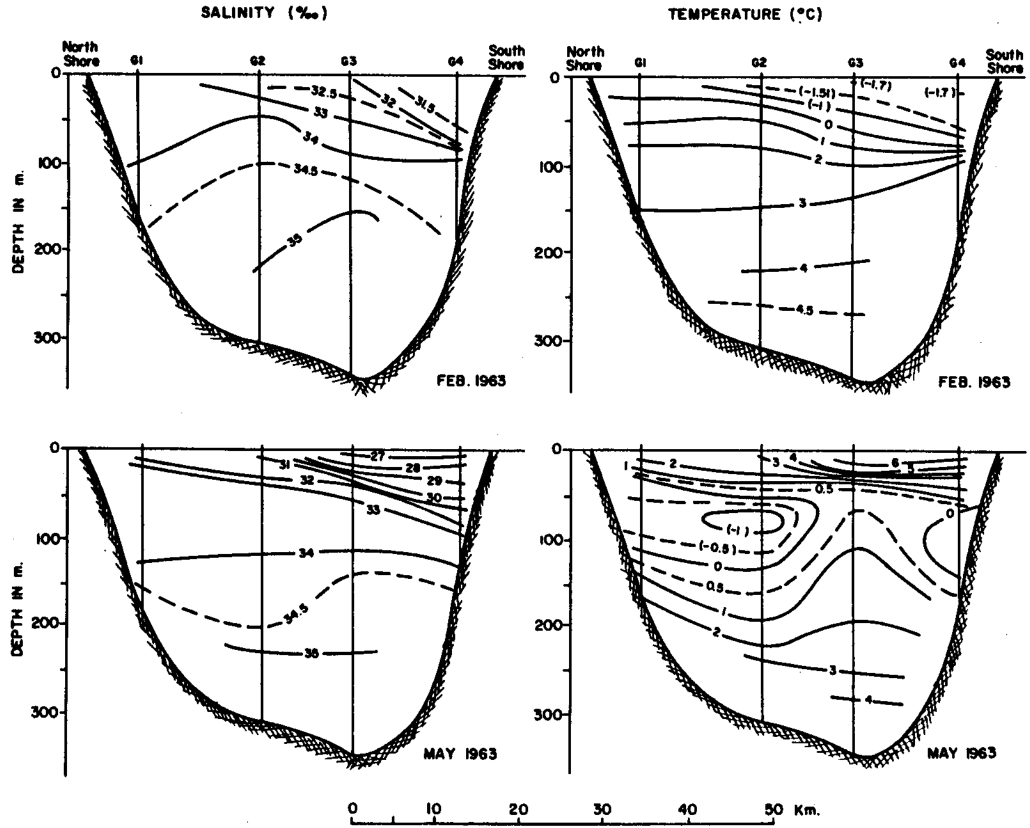

Fig. 17. Salinity and temperature across channel at Pointe-des-Monts.

layer. Tully, 1950, who had observed the same phenomena in the Alberni Inlet, British Columbia, concluded that the freshet, having a shorter duration than is required by the system to establish a new displacement equilibrium for the temporarily increased discharge, overruns the surface layer of the upper zone.

The water in the deep layer, where the salinity exceeds 33°/₀₀, is prevented by the sill at Tadoussac from entering the shallow section of the estuary, except for a short distance along the north side of the channel in February.

5.0 HYDRODYNAMICS

The Coriolis force gives rise to a slope of the surfaces of equal densities across the estuary (Fig. 18) and if all acceleration and frictional terms are negligible in comparison with the Coriolis term, observation of this slope may be used to compute the longitudinal velocity of flow. This is the method widely used for ocean current studies.

The longitudinal velocity derives from the equation of motion:

$$u = - \alpha \frac{\partial p}{\partial y} \cdot \frac{1}{f}$$

where p is the pressure, α is the specific volume ($\alpha = \frac{1}{\rho}$, where ρ is the density) and $f = 2\omega \sin\phi$ is the Coriolis parameter. $\frac{\partial p}{\partial y}$ can be determined from the density distribution.

The results of such a computation, using Sverdrup's tables (Sverdrup *et al*, 1942) for the anomalies of the specific volume, are shown in Fig. 20. From the salinity and temperature distribution (Fig. 19) and from the application of continuity of volume transport, the plane of zero motion at cross section G was assumed to extend from a point on the surface between survey positions G_1 and G_2 and drop to 125-m depth in February and 80-m depth in May at the south shore.

Toward the north shore and in the deeper layer, the velocities were small and directed inward, varying from zero to 15 cm/sec, while in the upper layer they were directed outward and reached 50 and 100 cm/sec in February and May, respectively.

The 1959 Atlantic Coast Tide and Current Tables reported that high velocity currents are concentrated along the south shore in an area known as the Gaspé Current. This current runs constantly outward from the St. Lawrence Estuary into the Gulf at 70 to 100 cm/sec during tides. These observations are consistent with the calculations based on the internal pressure field including the location of the highest velocities.

The Gaspé Current, according to this concept, is the high velocity region of the outflowing surface layer. It is a density phenomenon created by the fresh water inflow from the St. Lawrence River and the rivers from the north shore.

The transport through the triangular-shaped upper layer is estimated to be 300,000 m^3/sec in February and 500,000 m^3/sec in May. The respective

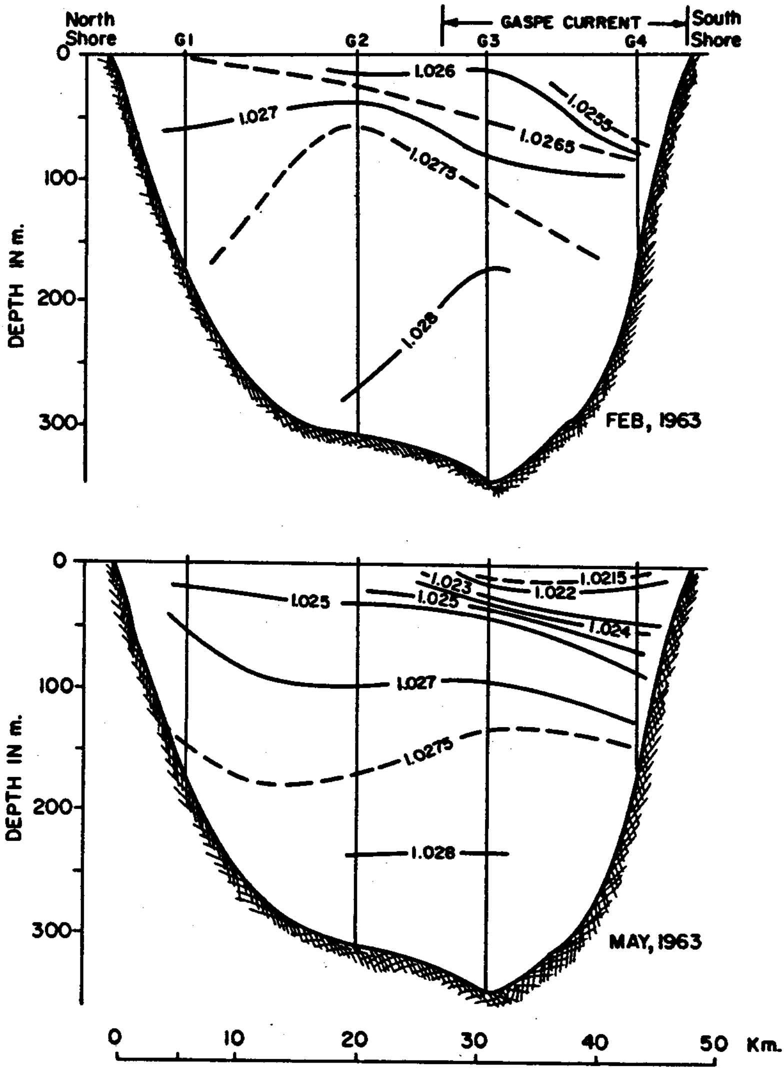

Fig. 18. Density across channel at Pointe-des-Monts.

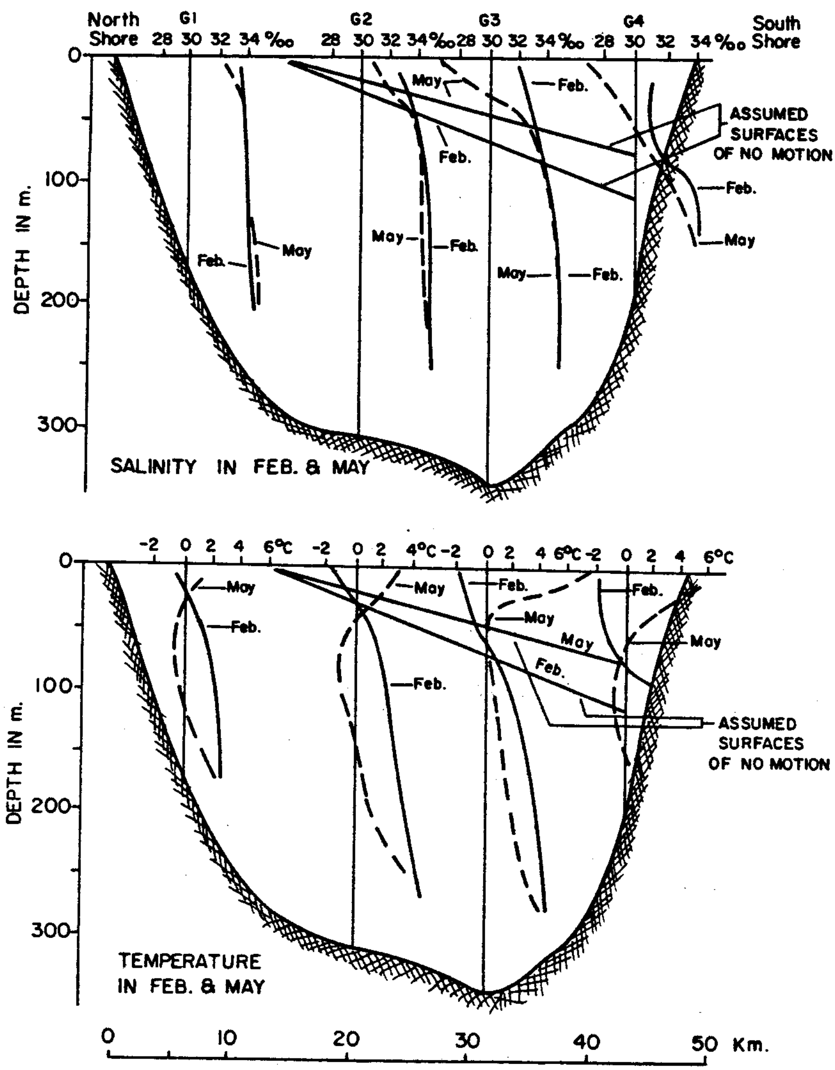

Fig. 19. Vertical salinity and temperature distribution at Pointe-des-Monts.

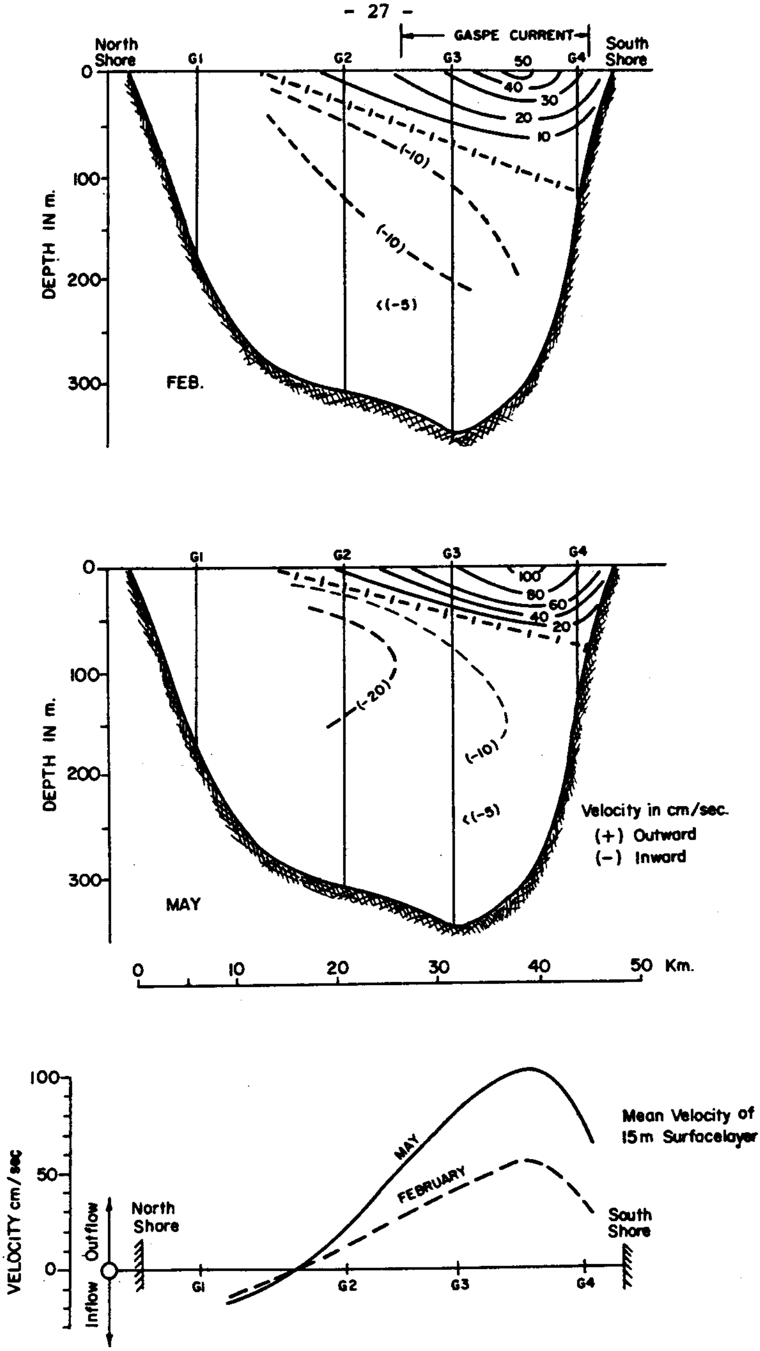

Fig. 20. Estimated current velocities at Pointe-des-Monts.

flushing times for the estuary above Pointe-des-Monts are two months and one month.

6.0 CONCLUSIONS

6.1 All three basic types of estuarine mixing are found in the St. Lawrence Estuary: the well-mixed, at the head of the estuary; the moderately-mixed, in the section below the head; and the stratified, in the deep section below Tadoussac.

6.2 The water is divided into two layers, a deep layer containing ocean water and an upper layer comprised of a mixture of ocean and fresh water. Mixing occurs in the upper layer by advective and exchange processes. In the section above Tadoussac the upper layer fills most of the channel.

6.3 The lighter water of the triangular-shaped upper layer flows seaward, while part of the mixed water and the undiluted sea water of the deeper layer flows landward. In addition to this two-layer circulation, there is a transverse motion, which deviates the upper flow toward the south shore and the deeper flow toward the north shore. Thus, the water moves out of the estuary primarily on the south side and inward on both its northern side and in the deeper layer. The Gaspé Current is the high velocity region of the upper layer.

6.4 The water is generally fresher on the south side than on the north. During the winter, when the atmosphere is colder than the water surface, the estuary is warmer on the north than on the south side, while during the rest of the year, when the air is warmer, conditions are reversed, the transition occurring during the beginning of April.

In winter the heat brought to the surface along the north shore maintains a reasonably open channel, while the ice is carried toward the south shore where it accumulates (Fig. 21).

6.5 The outward flow in the upper layer is computed (5.0) to be 300,000 m^3/sec in February and 500,000 m^3/sec in May with fresh water inflows to the estuary of 11,000 and 17,000 m^3/sec.

The flushing times for the estuary are two months and one month, respectively.

6.6 The Saguenay River, in conjunction with the sill at Tadoussac, disturbs the regular circulation pattern of the system. This phenomenon warrants a more detailed investigation. For example, its effect on the dispersal of the intermediate cold water layer. It would appear that large quantities of this layer from the Gulf is transported upriver and dispersed in this area.

6.7 The most important conclusion is that the intensity of the estuarine circulation in the St. Lawrence Estuary can be characterized solely by the fresh water inflow. The volume of sea water brought into circulation is controlled by the amount of fresh water being discharged into the system.

6.8 From this it follows that modifications to the fresh water run-off (e.g. hydro-power developments and water diversions) alter the flow

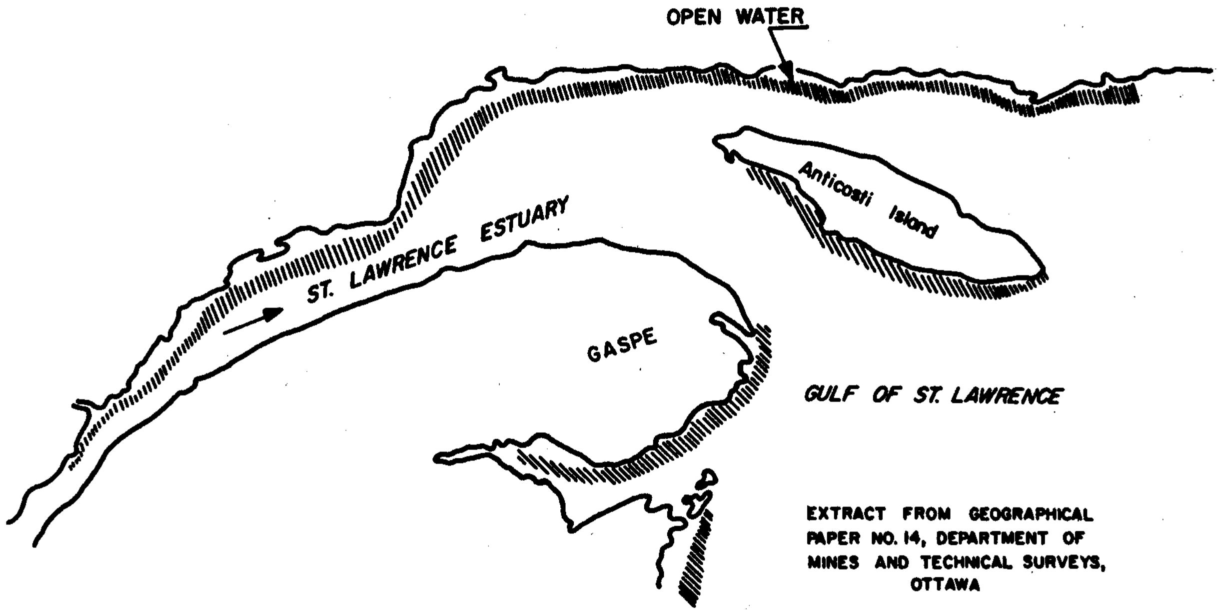

Fig. 21. General areas of open water during winter 1957.

regime and with it the salinity and temperature structure of the system.

The regulation of the fresh water discharge of the St. Lawrence system since the turn of the century should have decreased the circulation during the summer and increased the water temperature in the surface layer. This could have affected the climate of the adjacent region.

Furthermore, the installation of the Manicouagan power scheme, which changes the natural run-off of the 'group' of rivers, will alter the Gaspé Current, modifying the seasonal salt and temperature balance not only of the estuary but probably also of the Gulf of St. Lawrence.

6.9 Whether these changes were or are beneficial is undecided, though the possibility exists that their consequences may be likened to large-scale heat pollution with ecological implications. Thus, to avoid such consequences, future modification of this type should be carefully studied.

7.0 ACKNOWLEDGEMENTS

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8.0 REFERENCES

1. CAMERON, W. M., and D. W. PRITCHARD. The Sea. Ideas and Observations on Progress in the Study of the Seas. H. N. Hill, General Editor, Interscience Publishers, Chap. 15, p. 306-324.

2. LAUZIER, L. M., R. W. TRITES, H. B. HACHEY, and W. B. BAILEY. 1957. Report of the Atlantic Herring Investigation Committee. Fish. Res. Bd. Canada, Bull. No. 111, Sections 10 to 16.

3. PICKARD, G. L. 1964. Descriptive Physical Oceanography. Pergamon Press.

4. SVERDRUP, H. U., M. W. JOHNSON, and R. H. FLEMING. 1942. The Oceans. Prentice-Hall Inc., New York, p. 1053-1059.

5. TULLY, J. P. 1950. Notes on the Behaviour of Fresh Water Entering the Sea. Proc. 7th Pac. Sci. Cong., New Zealand, p. 267-289.

6. WIEGEL, R. L. 1964. Oceanographical Engineering. Prentice-Hall, Intl. Series in Theoretical and Applied Mechanics, Fluid Mechanics Series, p. 317-321.

7. 1959. Atlantic Coast Tide and Current Tables. Cdn. Hydrog. Service, Surveys and Mapping Branch, Dept. of Mines and Technical Surveys, Ottawa, p. 135-136.