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A Canadian Coastal Sea —
The Gulf of St. Lawrence

R. W. Trites and A. Walton

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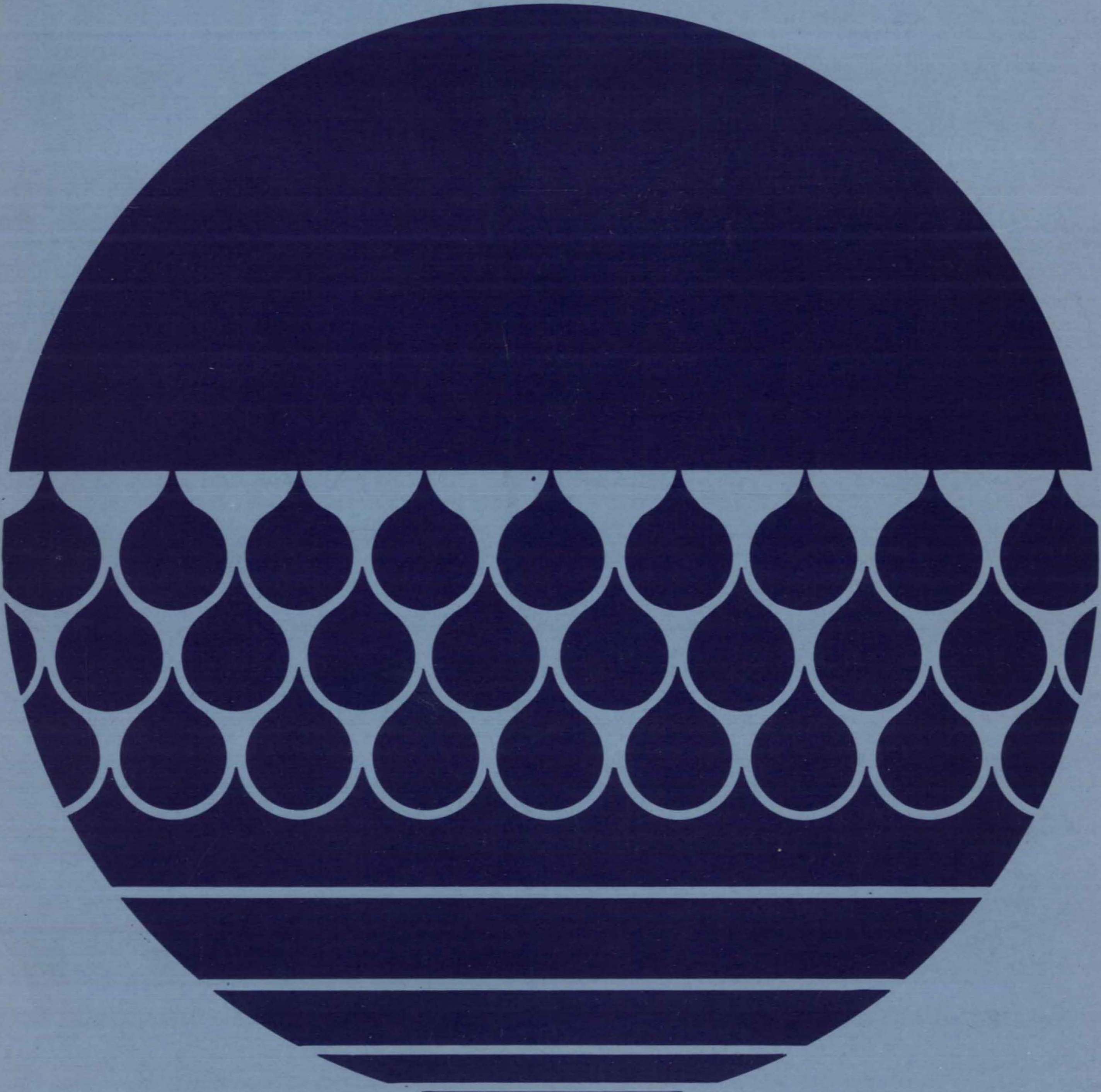

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A CANADIAN COASTAL SEA - THE GULF OF ST. LAWRENCE

by

R.W. Trites and A. Walton

Atlantic Oceanographic Laboratory
Ocean and Aquatic Sciences
Department of the Environment

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ABSTRACT

A synthesis of our current oceanographic understanding of the Gulf of St. Lawrence is presented. The review embraces physical, chemical and biological oceanography together with a brief discussion of man-made changes which have occurred in the area.

SOMMAIRE

Il s'agit d'une synthèse de nos connaissances actuelles sur l'océanographie physique, chimique et biologique du Golfe Saint-Laurent. On y traite aussi brièvement des changements apportés par l'homme à cette région.

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1. INTRODUCTION

The Gulf of St. Lawrence plays an important role either directly or indirectly in the livelihood and recreation of a large number of people. About one-quarter of all Canadian fishermen catch nearly 25% of the total Canadian commercial fish production there; it is an important avenue of transportation even though the service is impeded or interrupted in winter months by ice; in summer months it is used extensively for recreational activities; it is the site for active oil exploration; predictably, it also constitutes a waste receptacle, which in the past has proven to be detrimental to some of the estuarine and near-shore areas.

Recently the Government of Canada has agreed to support a number of coordinated programs of interdisciplinary research directed towards the comprehensive understanding of certain marine regimes in Canada. These regimes include the Strait of Georgia and the Gulf of St. Lawrence, on the western and eastern seaboards of Canada respectively. With regard to the Gulf of St. Lawrence the priority problems are seen to be the fisheries, environmental integrity, the impact of major industrial developments such as gas and oil, and climate. The ultimate goal of the project is to identify and examine the interactions between these four problem areas. In short, the long range objective must be to move in the direction of managing the Gulf as a system rather than on a piece-meal basis, if we are to achieve maximum overall benefits on a national basis.

These programs do not, of course, mark the commencement of research in the various regions. On the contrary, oceanographic activities, particularly in fisheries and physical oceanography have been pursued for the past 75 years. Rather, they represent a serious attempt to dovetail these activities with the more obvious social needs of the country.

In this paper we have attempted to summarize what is known, in a physical, chemical and biological sense, about the Gulf of St. Lawrence in the hope that it will serve as a useful background resource document.

2. PHYSICAL FEATURES

2.1 Physiography and Bathymetry

The Gulf of St. Lawrence has an area of approximately 250 x 10^3 km^2 (Figure 1). The principal connection with the Atlantic Ocean is through Cabot Strait with a width of 104 km, a maximum depth of 480 m and a cross-sectional area of 35 km^2. A dominant bathymetric feature of the Gulf is the Laurentian Trough, a deep trench with a maximum depth of 500 m, extending from the Continental Shelf to the mouth of the Saguenay fjord (Figure 1). The Esquiman Trough ajoins the Laurentian Trough and extends from the central part of the Gulf northeastwards towards the Strait of Belle Isle. Extending northeastwards between Anticosti Island and the north shore of the Gulf is the Anticosti Trough. Adjacent to the Laurentian, Esquiman and Anticosti Troughs are shelves where the water depths are much less than 200 m. Of principal importance are the Magdalen Shelf extending southwestward from the Laurentian Channel to the shores of Prince Edward Island, Nova Scotia, New Brunswick, and the southeastern Gaspé Peninsula. Depths are mostly less than 50-75 m. One-quarter of the Gulf is shallower than 50 m, while less than one-fifth is deeper than 300 m (Lauzier *et al.*, (1957). The topography of the St. Lawrence River estuary is of particular interest. The Laurentian

Trough ends abruptly near the mouth of the Saguenay, with maximum depths decreasing from >320 m to <40 m over a distance of <20 km. The Saguenay system, which branches off the main estuary, has depths in excess of 250 m but is isolated from the Laurentian Trough by two major sills. From a 20 m sill at its mouth the floor of the east basin plunges to 250 m and 18 km upstream it rises to a second sill, 70 m deep. The second basin reaches depths of up to 275 m over much of its 80 km length.

2.2 Fresh Water Discharge

The St. Lawrence system includes the Great Lakes, the St. Lawrence River, and the Gulf of St. Lawrence (Figure 2). The St. Lawrence River, which has a drainage basin extending inland approximately 3200 m, constitutes the largest single source of fresh water. Due to their vast area, the Great Lakes have a large storage capacity and thus reduce the effect of seasonal variations in the discharge of their tributaries. On the other hand, the watershed of the St. Lawrence River proper, the estuary and the Gulf, have relatively few natural storage basins. Their discharges, therefore, exhibit marked seasonal variations, being low in winter and high in spring. The impact of fresh water to the Gulf of St. Lawrence is very asymmetrical, since the drainage basin on the southern and eastern sides of the Gulf are minor by comparison to those of the St. Lawrence River Basin and the basins of the rivers feeding the north shore region of the Gulf.

A number of attempts have been made recently to estimate the total fresh water discharge into the Gulf of St. Lawrence. Trites (1972) has done this for the period 1957-1965 and estimated a mean annual value of 13.44 x 10^3 m^3/s. Estimates of precipitation less evaporation were also made for the Gulf of St. Lawrence to enable a net total fresh water budget to be derived. These computations indicated that net fresh water input varied from a minimum of 9 x 10^3 m^3/s in March to a maximum of 28 x 10^3 m^3/s in May, and a mean annual input of 16 x 10^3 m^3/s. Subsequently Jordan (1973) estimated the total runoff for the period 1960-1970 and El-Sabh (1975) has extended the study to cover the two decades 1950-1970. River discharge was calculated to vary from a minimum of 13.8 x 10^3 m^3/s in February to a maximum of 30.8 x 10^3 m^3/s in May with a mean annual value of 19.1 x 10^3 m^3/s. Year to year fluctuations on the mean were also found to vary widely (Figure 3) from a maximum of 23.0 x 10^3 m^3/s in 1952 to a minimum of 16.3 x 10^3 m^3/s in 1959.

2.3 Water Masses

In terms of the vertical temperature distribution, the Gulf in summer can be considered as a three-layer system. At this time, a warm surface layer, 10-20 m thick, overlays an intermediate cold layer that is usually less than 1°C, and a deep warm layer (4-6°C) with a temperature maximum at 200-300 m (Figure 4B). The two upper layers undergo seasonal variations and become one, thermally, during the winter months. The origin of the intermediate cold layer has been the subject of considerable speculation (Tremblay and Lauzier, 1940; Forrester, 1964; Banks, 1966). Earlier it was thought that this cold water was formed outside the Gulf as its T-S characteristics are very similar to Labrador Current water, but it is now thought to be formed almost entirely locally during the winter.

Forrester (1964) has summarized concisely and quantitatively the T-S composition of the Gulf. His analysis permits one to see readily what are the major water masses, what proportion of the total volume of the Gulf they occupy, and how they vary from summer to winter. He also determined the total volume of water falling inside T-S boxes of size 1°C by 0.2‰. Figure 4C shows an extract from his analysis. The envelopes that are shown encompass most of the points on the T-S scatter diagram. Figures 4A and 4D also show the volume of water by salinity and temperature class respectively for 0.2‰ and 1°C intervals (the points have been joined for visual convenience). On the T-S diagram, the most striking change from summer to winter is the shrinkage in area representing the water in the upper 75 m. This prominent part of the envelope, however, represents less than half the volume of the Gulf. Examination of Figures 4A and 4D indicates a very strong T-S mode centered at 5°C and 34.6‰ both in summer and winter. About 17% of the Gulf water falls within ±0.5°C and ±0.3‰ of this point. In winter, a strong mode centered at -1.5°C and 32.2‰ is evident and about 26% of the water in the Gulf lies within ±0.5°C and ±0.3‰ of this point. The residue of this mode is still present in summer at 0.0°C and 32.4‰, slightly shifted from its winter position and about 8% of the water in the Gulf falls within ±0.5°C and ±0.3‰ of this point. On the basis of the T-S diagrams, the summer-winter differences in water with salinity >33‰ appear insignificant. This indicates that approximately 45% of the volume of water in the Gulf is little affected by local seasonal changes in heat budget and fresh water inflow.

The temperature maximum of the deep layer may vary seasonally from about 4°C to 6°C, and the salinity at the temperature maximum seldom departs from 34.6‰ by more than 0.2‰. The source of this water is outside the Gulf (Lauzier and Bailey, 1957) and its volume correlates with its maximum temperature which in turn can be correlated with the temperature of Labrador Water (Lauzier and Trites, 1958). Observations indicate that the maximum temperature varied from a low of about 4°C in the 1920s to a high of nearly 6°C in the 1950s, accompanied by an increase in volume of the deep layer.

Recently El Sabh (1975) has carried out an extensive examination of all available temperature and salinity data between 1950 and 1970 for the Cabot Strait and estuarine areas and has provided refinement in defining the spatial and seasonal variations for these regions. These areas will be discussed in more detail in a later section.

2.4 Ice

For several months each year, ice in varying concentrations is present in the Gulf. It arises from three sources (El-Sabh 1969): (a) Labrador ice that enters through the Strait of Belle Isle; (b) ice from the St. Lawrence River and estuary; (c) ice fields which are locally formed in the Gulf. Based on five years of ice cover data from 1961 to 1965 published by the Meteorological Branch, Matheson (1967) has compiled mean ice concentration maps at fortnightly intervals during the ice season. Five of these have been selected to show the general features (Figure 5). Ice starts to form in December in sheltered areas. During January, the ice concentration increases rapidly, although the region west of Newfoundland remains unfrozen due to influx of warmer surface water through Cabot Strait. By the last week of January, the southwestern and central parts of the Gulf are covered by heavy ice originating in the St. Lawrence River and estuary. As winter progresses, ice is moved seaward through Cabot Strait. Ice concentrations along the north shore of the Gulf and south shore of Anticosti Island tend to be generally lower as a result of the prevailing offshore northwesterly winds of the winter period. Major ice concentrations usually persist until April when a rapid break-up commences due to vernal warming. Ice is retained longest in the southern part of the Gulf and Strait of Belle Isle areas.

2.5 Tides and Tidal Currents

The semidiurnal and diurnal tides from the North Atlantic Ocean are both propagated through Cabot Strait (Farquharson, 1962) and are illustrated in Figures 6A and 6B, which show the semidiurnal lunar tidal constituent M_2 and the diurnal constituent K_1 respectively. There are two amphidromic points for the M_2 constituent - one near the Magdalen Islands and a second near the western end of Northumberland Strait. In most areas of the Gulf, the semidiurnal constituent dominates. Tidal range increases rapidly towards the St. Lawrence River with a mean range of about 4 m near Quebec City.

Except in the St. Lawrence estuary, Cabot, Belle Isle and Northumberland Straits, and other locally confined regions, tidal currents seldom exceed 1 km/hr. In Cabot Strait, tidal streams are typically of the order of 2 km/hr. In some areas, the phase of the tidal stream varies significantly with depth. Forrester (1970, 1974) has found evidence of internal tides in the St. Lawrence estuary seaward of the Saguenay River entrance. From his studies he has concluded that the tidal streams observed in the estuary result not only from the well known surface or barotropic tide but also from a pronounced internal or baroclinic tide generated by the interaction of the surface tide with the rapidly shoaling bottom topography at the river end of the Laurentian Channel. The semidiurnal internal tide appears to be mainly a progressive Poincaré type wave propagating seaward along the axis of the channel with a wavelength that is dependent on the density stratification. Under conditions observed in 1965, 1968, and 1969 the wavelength was found to be about 60 km, but should be expected to shorten with less intense density stratification and lengthen with more intense stratification. Forrester also drew attention to the likelihood of the presence of a diurnal internal tide of the Kelvin type propagating seaward, but his data were insufficient to draw firm conclusions. Subsequent measurements (Forrester 1975, personal communication) under different stratification conditions have confirmed these earlier conclusions.

The very short wavelength of the internal tides, combined with its dependence on density stratifications makes predictions of tidal stream difficult unless both intensive and extensive measurements of both the velocity and mass fields have been taken.

It is possible that internal tides occur more widely throughout the Gulf. If so, then, because of their short wavelengths they would produce regions of relatively strong convergence and divergence between the trough and crests of the progressive internal tides. The unexplained build-up and relaxation of ice pressure frequently reported by ships operating in heavy ice in the estuary and at times in other parts of the Gulf, could conceivably be caused by an internal tide.

2.6 Circulation

Knowledge about the circulation in the Gulf has been gradually accrued from a variety of studies that have employed direct current measurements (both Eulerian and Lagrangian), indirect methods such as geostrophic computations, and modelling using analytical, electrical analogue, and numerical techniques.

Current measurements have been undertaken across Cabot Strait (1959, 1966), Gaspé Passage (1962), St. Lawrence estuary at Pointe des Monts (1963), Belle Isle Strait (1963), near Rimouski (1965), and at selected sites between Baie-Comeau and the mouth of the Saguenay (1968, 1969, 1973, 1974). Self-recording current meters were moored commonly at three depths at each site and operated for periods of usually not less than one month (Farquharson, 1962, 1966; Farquharson and Bailey, 1966; Forrester, 1970, 1974). In addition, extensive current measurements were taken in Northumberland Strait in connection with a study of a proposed causeway (Farquharson, 1959), and single-station moorings have been placed at other selected sites in the Gulf from time to time over the past 10 years. The bulk of these measurements have been made during the May-November period. Recently, limited measurements have been attempted during winter months.

Data from four sections are shown in Figure 7. The St. Lawrence estuary and Gaspé Passage sections show clearly the outflow of surface water along the Gaspé coast. This outflow is mostly confined to the upper 25-50 m. An equally prominent feature is the upstream current lying immediately below the seaward moving surface current, with its core at 100 m depth. The flow through Cabot and Belle Isle Straits appears to be somewhat differently structured. The outflow through Cabot Strait is similar to that in the Gaspé section in that the strongest currents are associated with the brackish seaward-moving layer, but the upstream current appears less well defined and occupies a larger proportion of the section. Fluctuations in the daily residual flow occur in all sections and at times it may be unidirectional throughout the entire section, or reversed from the average pattern. These fluctuations appear to be related to meteorological conditions (Farquharson, 1966; Farquharson and Bailey, 1966; Sharaf El Din and Trites, 1971), particularly the pressure patterns and gradients.

Circulation patterns have also been studied in the Gulf using Lagrangian techniques. Drift bottles and sea-bed drifters have been used by Bumpus and Lauzier (1965) and Lauzier (1967), and drogues have been employed by other investigators (Blackford, 1965, 1967; Trites, 1968; Keyte and Trites, 1971; Ingram, 1973). Most of the measurements have been taken during the open water period, although limited tracking of ice flow fields has been attempted.

Trites (1972), utilizing data available up to that time, developed a sketch of a typical summer surface circulation pattern (Figure 8). The general two-way flow in both entrance straits, the counterclockwise circulation in the interior part of the Gulf, and the Gaspé Current, which begins to develop in the Rimouski-Pointe des Monts areas and extends throughout the entire length of the Gaspé coast, are the dominant features. Highest speeds are found in the Gaspé Current and in the outflow through Cabot Strait, reaching values of 15-30 km/day.

In 1965 Forrester (1970) made comparison in a cross-section of the St. Lawrence estuary, between currents measured directly by moored current meters and geostrophic currents calculated from a series of density sections observed with water bottles moored throughout the cross-section and tripped simultaneously. The geostrophic currents calculated from a single density section resembled neither the instantaneous value nor the time-averaged value of the real current. However, the geostrophic currents calculated from the average density field were clearly similar to the average currents as measured by the meters. He concluded that geostrophic currents become meaningful if fluctuations of periods less than about a day can be averaged out.

El Sabh (1975) has undertaken an extensive study of transport in currents in the Gulf employing principally temperature and salinity data. By averaging the temperature and salinity data, and employing Defant's method for calculating the topography of the reference depth, he compiled surface geostrophic current maps on a mean monthly basis for five periods of the year. One of these (August) is shown in Figure 9. Considerably more detail is shown in this figure than that given by Trites (1970), although the gross features are similar. Of particular note is the indication of relatively large gyres. While the geostrophic patterns derived for the other periods of the year all contained gyres, only the one west of Anticosti Island was present at all times.

Data on subsurface currents in the Gulf are sparse and it is not feasible at present to present a picture for the entire Gulf at any season. Sea-bed drifters released by Lauzier (1967 and 1970, personal communication) in the southern and central part of the Gulf show, in general, a well-marked seaward movement along the 100-200 m depth contours in the southwestern border of the Laurentian Trough, that is, along the edge of the Magdalen Shelf. An inward flow usually is present along the 100-200 m depth contours on the northeastern side of the Laurentian Trough. A rather complex pattern emerges for the southwestern Gulf, although a large area ($\sim$18,000 km^2) surrounding the Magdalen Islands shows a general convergence towards the Islands. Residual bottom currents based on sea-bed drifter experiments appear to be mostly in the range 0.5-1.1 km/day.

Although fresh water undoubtedly plays a major role in determining the surface layer features, meteorological forces cannot be neglected. Wind patterns have a seasonal pattern being predominately from the west and southwest in the spring and summer months and from the northwest and west in autumn and winter months.

Theoretical models based on simplified forms of the equations of motion have been used to study the gross features of the circulation in the Gulf (Blackford, 1965 ,1966; Murty and Taylor, 1969). These models considered the wind to be a primary driving force and have in general revealed a pattern rather similar to that depicted in Figure 8. It seems clear, from the success of these models, that the wind, as well as the fresh-water discharge, plays an important role in producing the large-scale surface layer circulation in the Gulf.

2.7 Flushing Times

A knowledge of residence or flushing times is important for a variety of purposes. When detailed current and diffusion measurements are unavailable, it is sometimes helpful to estimate flushing times with very simple models, using parameters more easily estimated. Trites (1972) has taken this approach by calculation of the total amount of fresh water in the Gulf, at a given time, and dividing it by the total input rate. This treatment gave values ranging from 220 to 510 days. He concluded that the residence time of fresh water in the Gulf appears to be less than one year.

An idea as to how quickly a particle remaining at the surface and in the mean flow is likely to move through the Gulf from the Saguenay to Cabot Strait can be gleaned from Figure 8. This is calculated to be approximately three months, and is consistent with the conclusion of El Sabh (1975). However, the internal circulation pattern is such that much of the fresh water does not move swiftly through the Gulf but probably makes one or more 'circuits' before exiting through Cabot or Belle Isle Straits.

While fresh water is a useful tracer for the determination of flushing times, it gives little information about the deeper layer since the bulk of the fresh water is confined to the upper 10-20 m in July and even in March does not penetrate much deeper than 100 m. The deep warm layer, which on average is moving inwards at substantially lower speeds than are found in the surface layer, can be expected to have a markedly longer flushing time. The time required to transit from Cabot Strait is sufficiently long to produce a substantial decrease in the dissolved oxygen concentration (see Section 3.1) and a marked increase in nutrient concentrations in the Laurentian Trough between Cabot Strait and the mouth of the Saguenay (Section 3.2.1).

2.8 Cabot Strait

In terms of cross-sectional areas, Cabot Strait is the principal channel connecting the Gulf of St. Lawrence to the Atlantic Ocean. By comparison, Belle Isle Strait has an unrestricted depth and cross-sectional area of only 12% and 3% respectively of those of Cabot Strait.

The general characteristics of the vertical temperature and salinity structure for summer and winter in the Gulf have been depicted in Figure 4B. A more detailed picture for Cabot Strait is shown in Figure 10 for the month of August, commonly the period during which salinity in the surface layer is at a minimum. Seasonal variations are present in the surface and intermediate layer to a depth of 100-150 m. Maximum seasonal variation for the Newfoundland side and Cape Breton side of the Strait is shown for the surface in Figure 11.

The character of the currents in the strait as determined from current measurements in 1966 is shown in Figure 7. A much more comprehensive picture has been developed by Forrester and El Sabh (1974) and El Sabh (1975), employing geostrophic computations and adjusting the values to satisfy the assumption of zero net salt transport through the section. Using varying time averaged periods between 1950 and 1970, mean monthly transport patterns were developed. The 20-year average picture for August is shown in Figure 12. On average, more than 30% of the seaward transport through Cabot Strait is confined to the upper 25 m on the Cape Breton side while the inward flow occupies the whole depth on the Newfoundland side and the deep layers of the section. The maximum transport rate occurrs at depths of between 50 and 100 m.

The net seaward volume transport through the Strait increases from 11×10^3 m^3/s in July to 25×10^3 m^3/s in August and decreases to 19×10^3 m^3/s in November (El Sabh, 1975). The total seaward transport in August is approximately 20 times the net transport.

2.9 The Estuary-Gaspé Region

Typical circulation in a long estuary such as that of the St. Lawrence consists of a two-layer flow system in which the lower layer flows upstream while the upper layer flows seaward. Brunel (1970) has classified the estuary into three parts: the Maritime estuary extending from Pointe des Monts to the Saguenay Fjord; the Middle estuary extending from the Saguenay to Ile d'Orléans; and the River estuary extending from Ile d'Orléans to Trois Rivières.

Salt water invades the system as far upstream as Ile d'Orléans near Quebec

City. Downstream of this point, the salinity of the surface layer increases rapidly to about 17‰ at the mid-point between Quebec City and the Saguenay. Average salinity in the upper layer just seaward of the Saguenay is approximately 28‰. The general character of the seasonal variation in temperature and salinity of surface water in the Maritime portion of the estuary is depicted in Figure 13. The vertical distribution of salinity, temperature and specific volume anomaly throughout a cross-section in the estuary in November (1955-1969) is shown in Figure 14.

Seaward of the Saguenay, the character of the estuary changes markedly. The presence of the Laurentian Trough permits penetration of the deep saline water. Lateral structure in the surface layer develops with the bulk of the seaward moving fresh water confined to the southern side of the estuary. Seaward from Pointe des Monts, this current intensifies markedly and becomes known as the Gaspé Current (see Figures 7, 8 and 9). El Sabh (1975) reports that the strength of the Gaspé Current reaches a maximum value in the spring, at a time when the fresh-water discharge reaches its maximum value, and decreases as the season progresses, reaching its lowest value in winter. Coupled with the Gaspé Current is an upstream flow along the Anticosti Island side of Gaspé Passage. In the area west of Anticosti, an anticlockwise gyre is apparently present at all times of the year.

3. CHEMICAL AND GEOCHEMICAL FEATURES

From a marine geochemical point of view the Gulf of St. Lawrence must be considered as a dynamic system situated within today's relatively temperate climate. In the past the region has been influenced by periods of both warmer and colder climatic conditions. The system is geochemically dynamic in the sense that many fundamental chemical and geologic processes of additions and losses are continuously at play today. Furthermore, the fact that the St. Lawrence River is draining a major lake system, in the midst of a heavily industrialized region of North America, guarantees at least a temporal instability as long as the pollutants of modern society continue to 'flow'. Geochemical interest in this region stems from our desire to understand sedimentation patterns, chemical interaction between the fresh and marine water environments, possible development of anoxic zones in the various channels and the transport of pollutants and natural substances by a major world river system towards the ocean (Walton, 1970).

3.1 Oxygen

In 1970, Dunbar examined the oxygen data which had been collected in the Gulf to that date. Since 1971, six cruises have been made by the Chemical Oceanography Division, Atlantic Oceanographic Laboratory, to all regions of the Gulf with approximately 100 stations on each cruise sampled for dissolved oxygen. Samples have invariably been taken as close to bottom as feasible and in each identifiable water mass. A preliminary assessment of the first two years data was given in 1972 (Levy and Walton, 1972) and a more comprehensive review of all these results is currently underway.

While in earlier years O_2 values less than 3 ml/l aroused considerable interest, it is now recognized that these low values are characteristic of the deeper waters of the Gulf (e.g., in the Laurentian and Esquiman Troughs). For the most part, the data exhibit the general pattern shown in Figure 15, which presents a section of the O_2 data from Cabot Strait to the mouth of the Saguenay taken in 1973. A general depletion in O_2 is evident in the deep warm water (temperature 4-6°C) as one proceeds from Cabot Strait to the Saguenay fjord along the length of the trough. The magnitude of the depletion does not appear, however, to be linearly related to the distance from Cabot Strait, suggesting that the mechanisms responsible for the depletion are not uniform.

A mechanism usually invoked to account for reduction in O_2 concentration is oxidation of biological materials, assuming that no substantial alternative sources of oxygen exist. Should this be the case, in the deep layers of the Gulf, then accompanying the depletion of O_2 within the water column would be a change in the carbon isotopic composition of the dissolved CO_2 and an increase in the total dissolved CO_2. Thus, measurements of δC^{13} in total dissolved CO_2 along the Laurentian Trough might reveal a δC^{13} change correlated with that of the O_2 concentrations. Recent data obtained by Tan (1975) support this correlation qualitatively for samples collected near the extremes of the channel in the Gulf. Thus in 1973 and 1974 the deep water exhibited a decrease in δC^{13} of $\sim$ 1 per mil from Cabot Strait to the mouth of the Sageunay and an increase in CO_2 concentration of about 5 per cent.

A minimum in dissolved oxygen concentrations, observed by Dunbar (1970) in earlier cruises, is again confirmed in the more extensive data of recent years. Earlier data suggest that the minimum is to be found at depths between 200 and 300 m but for results obtained in 1971, 1972, and 1973 the minimum was found over a greater range of depths, between approximately 200-350 m. The minimum can actually be traced from waters beyond Cabot Strait from the edge of the Continental Shelf along the Laurentian Trough to the mouth of the Saguenay, and along the Esquiman Channel toward the Straits of Belle Isle. Outside the Gulf the minimum concentrations found are approximately 5 ml/l and these decrease gradually as one proceeds along the troughs to values of $\sim$ 2.5 ml/l near the Saguenay.

3.2 Nutrients

The work performed at McGill University as reported by Bulleid and Stevens (1972) and Stevens (1974) has yielded an extensive set of nutrient data, principally from the surface waters of the Gulf of St. Lawrence. Data for deeper waters have been obtained during the past four years by Coote and Yeats (1975) and some of the main features of these latter results are presented here. Three primary nutrients, silicate (as SiO_2), phosphate (HPO_4^{2-}) and nitrate + nitrate (NO_3^- + NO_2^-) have been investigated in these studies at all depths throughout the area.

3.2.1 Variability with Depth, etc.

The concentrations of the nutrients within the Gulf of St. Lawrence are higher than in the oceanic waters outside. This must arise from the combination of nutrient regeneration in the water column and the general inward drift of the deeper water imposed by the estuarine circulation. A sharp increase in all nutrient concentrations as a function of depth is observed at practically every station throughout the Gulf, excluding the Saguenay. In contrast to the behaviour of O_2, nutrients exhibit a general increase in concentration as a function of distance from Cabot Strait to the estuary. The increase is more pronounced for silicate (20 μg-at/l to 40 μg-at/l) than for the other nutrients (e.g. P 1.8 to 2.1 μg-at/l) (Figure 16a). Qualitatively such observations are usually explainable by the decay/decomposition of living matter resulting in nutrient regeneration but it is clear that, in the Gulf, quantitative relationships are not simple. Using an atom ratio of 212:106:16:1 for O:C:N:P it may be demonstrated that approximately one-third of the O_2 depletion along the axis of the Laurentian Trough can be accounted for by the change in phosphate concentrations between Cabot Strait and the estuary. With only a small change in nitrate/nitrite concentrations the fraction is even less. Thus, the mechanism for O_2 removal appears not to be soley accounted for by nutrient regeneration. Silicate regeneration would appear to take place in the deeper, 'quieter' waters, while nitrate and phosphate regeneration probably takes place principally in shallower depths where more rapid exchange processes occur.

The behaviour of the nutrient isopleths at the upper end of the Laurentian Trough supports the widely held notion that the region near the mouth of the Saguenay fjord is an upwelling area, where deeper water, high in nutrients, reaches the surface. Isohalines and isotherms behave similarly.

The differences between summer and winter values for nutrients in the upper layers seem clearly to depend on biological processes. In this regard the Laurentian Trough section for summer 1972 (Figure 16a) can be compared with that for February 1973 (Figure 16b). Crude calculations of nutrient transport through Cabot Strait indicate that the Gulf is a sink for silicate and nitrate in summer, presumably as a result of biological production. In the winter, on the other hand, the transports for the three nutrients through Cabot Strait are in rough balance. It is quite possible that these calculations may be grossly oversimplified but if they turn out to be reasonable, the Gulf, or more probably its sediments, provides a sink for nutrients. An alternative argument is that we are not measuring accurately the total nutrient transports through Cabot Strait. In either event, further data are required.

3.3. Organic Matter in Sediments

In 1971, when these studies were begun, a search of the CODC data for the Gulf of St. Lawrence revealed that out of *ca.* 9000 oceanographic stations listed, not one provided any data on organic matter in the water column. In this respect, the Gulf was less well known than many open ocean areas (e.g., Gordon, 1971). A first objective, therefore, was to obtain quantitative data on organic matter in the water column and in the surficial sediments to provide background information critical to the development of knowledge of the coastal zone. A second objective was to quantify the contribution of land-derived organic matter to the marine environment of the Gulf of St. Lawrence, an area of interaction between land and sea in which organic matter of both marine and terrestrial provenance was expected to be found.

The sediments have been found to be the sink, rather than a significant source, of organic matter in the Gulf. Although there is no simple consistent relationship between the concentration of organic matter in a sediment and its location in the Gulf, there is a significant correlation between the concentration of organic matter and the texture of sediments (see Figure 17): the pelites (clays) have more carbon than the sands and gravels, and as these tend to occur in the deeper portions of the Gulf, more remote from land, there is indirectly a relationship with depth and distance from land (Pocklington, 1973). Comparing the distribution of organic matter in sediments to that of areas of high 'productivity' (Steven, 1974), there is little relationship between the two. Additional information is given by the nitrogen determinations. The regional pattern of C/N ratios (Figure 18) shows high ratios to be limited, of local occurrence (e.g., heads of fjords), and mainly associated with anthropogenic inputs (pulp and paper wastes). A clear progression from sediments of predominantly terrigenous origin to those of entirely marine provenance is shown in the sequence -- Saguenay, estuary - Laurentian Trough (Pocklington, 1975b). This interpretation is supported by the discovery of lignin, a compound of unequivocal terrigenous provenance, in the high carbon, low nitrogen sediments at the heads of fjords, the highest levels being in the vicinity of forest industry (Pocklington and MacGregor, 1973). These data suggest only minimal transport of terrestrial organic matter from the land to the sea, a finding which has social implication as some hazardous materials (e.g., mercury) are closely associated with the terrestrial organic fraction (Loring, 1975).

3.4 Stable Isotope Variations

In an attempt to characterize water masses and to examine the mixing processes in different regions of the Gulf and the estuary, a substantial number of samples was collected during 1973 and 1974 for oxygen and carbon isotope ratio studies. Some of the significant findings in the C^{13}/C^{12} data have been described earlier (3.1) and in this section the highlights of the O^{18}/O^{16} results are presented.

3.4.1 O^{18}/O^{16} Ratios of Water Masses in the St. Lawrence Estuary

The δO^{18} values of surface waters in the St. Lawrence estuary from Ile aux Coudres to Pointe des Monts show a range of -10.0 to -2.0 per mil SMOW and vary linearly with salinity (Figure 19). This suggests conservative mixing of the O^{18}/O^{16} ratios throughout the estuarine regimes and thus demonstrates the applicability of this technique to examination of estuarine mixing. The data further indicate that the regional tributaries do not modify substantially the δO^{18} value for the St. Lawrence River. The δO^{18} value of the St. Lawrence River at Quebec City is estimated on the basis of δO^{18} salinity relations to be -10.1 per mil SMOW. This compares favourably with direct measurements of fresh water from the St. Lawrence River which gives values ranging between -10.1 to -10.6 per mil SMOW.

The δO^{18} values of surface waters in the Saguenay River, a major tributary of the St. Lawrence estuary, also varied linearly with salinity. The fresh water component had an δO^{18} value of -14.2 per mil SMOW, somewhat lower than that of the St. Lawrence River at Quebec. This finding is not unexpected in view of the considerable differences in drainage areas of the two river systems.

3.4.2 O^{18}/O^{16} Ratios of Water Masses in the Gulf

The surface waters (to 1 metre) of the Gulf of St. Lawrence show a narrow δO^{18} range of -1.8 to -1.6 per mil SMOW, but decrease to -4.1 per mil near the mouth of the Saguenay fjord. The deep warm waters (4-6°C) can be characterized by a narrow δO^{18} range of -0.3 to +0.2 per mil SMOW and traceable to the mouth of Saguenay. The δO^{18} values increase progressively with depth at all stations and show linear relations with salinity. The meteoric water contributing to the region is estimated on the basis of δO^{18} salinity relations to have a δO^{18} value of -18.0 per mil SMOW.

3.5 Trace Metals

Concentrations of iron, cobalt, nickel, copper, zinc, cadmium, and lead were measured in both filtered and unfiltered water samples collected in the Gulf of St. Lawrence (Bewers, Macaulay and Sundby, 1974). Only in the case of iron were the concentrations in the filtered and unfiltered samples found to be significantly different. Little can be said regarding the behaviour of cobalt, cadmium, and lead since they were found at concentrations below the detection limits of 0.27, 0.27, and 0.78 μgl^{-1} respectively which are higher than the values reported as typical for marine waters (Turekian, 1969). Nickel, copper, and zinc were predominantly above the detection limits with mean concentrations of 0.38, 0.52, and 1.64 μgl^{-1} and exhibited little variability. The concentrations found for these trace elements are within the ranges found in North Atlantic water (Spencer and Brewer, 1969) and, for copper and zinc in particular, the data agree with those obtained by the GEOSECS investigations in the North Atlantic (Brewer, private communication, 1973). Fresh water run-off or local geological conditions appear, therefore, to exert little influence upon the distribution of these elements in the waters of the Gulf.

3.5.1 Behaviour of Iron

Clear patterns in the distribution of iron can be discerned, which appear to be related to the processes by which iron is transported in the water-suspended matter-sediment system. As pointed out by Lewis and Goldberg (1954) dissolved iron values in sea water are far greater than those that can be accounted for by ionic equilibria with the constituents of sea water at a pH of 8 (5×10^{-8} μgl^{-1}). For 'dissolved' iron the concentrations throughout the Gulf are found to be somewhat less than 3.2 μgl^{-1} except for some higher values (up to 13.5 μgl^{-1}) in low salinity waters. From Figure 20, which indicates the relationship observed between dissolved iron and salinity, it may be concluded that some loss of iron must be occurring during the mixing of fresh and saline waters, otherwise the relationship would be linear.

A similar conclusion for total iron and salinity was reached by Coonley *et al.* (1971) in a study of a lower salinity regime in New Jersey. Here the loss was attributed to precipitation as ferric hydroxide flocs. Although a simple relationship between total, or particulate iron, and salinity is not found in the Gulf of St. Lawrence it is still possible to explain qualitatively the observed three-layer system for particulate iron in the estuarine and Gulf regions. It may be postulated that as iron-rich particles are transported seawards with the surface water, they settle into the underlying water masses giving rise to concentration gradients. These gradients are enhanced by the landward flow of the deep waters and give rise to an increase in the concentration of iron in the nondetrital fraction of the sediments as one proceeds from east to west along the Laurentian Trough (Loring and Nota, 1973).

3.6 Suspended Particulate Matter

A distinct similarity is to be found between the vertical distribution of particulate matter and that of iron, as referred to in the previous discussion (Figures 21 and 22). Sundby (1974) has recently described this three-layer situation for the Laurentian Trough where concentrations in the surface and bottom layers were higher than 0.1 mgl^{-1} while those at intermediate depths were in the range 0.05-0.1 mgl^{-1}. D'Anglejan (1969) described a similar distribution from more limited data but somewhat higher concentrations of 0.3 to 0.4 mgl^{-1} were reported at intermediate depths. These discrepancies could be caused by differences in methodology. In the surface layers of the Gulf of St. Lawrence the highest concentrations of suspended matter are associated with seaward flowing water of the Gaspé Current. The lowest concentrations are associated with the saline water that flows towards the estuary along the shore of Anticosti Island and the Quebec north shore. In the northern part of the Gulf the surface concentrations of suspended matter vary considerably, but are not related to variations in salinity. Qualitative examinations of suspended matter revealed mostly biological material. It is interesting to note that the highest concentration was 3.5 mgl^{-1} at 9 m depth in the Esquiman Trough where a heavy algal bloom was encountered.

At intermediate depths the distribution of suspended matter is more homogeneous. Nevertheless, a relationship to the circulation pattern is still apparent (see Section 2.6). In Cabot Strait a comparison of current-meter results with the distribution of suspended matter showed that the highest concentrations (0.2 to 0.4 mgl^{-1}) were in the seagoing waters in the southern part of the Strait. The ocean water entering the Gulf was characterized by low (0.05 to 0.10 mgl^{-1}) concentrations of suspended matter. These observations are similar to those of Cook (1962), who concluded, from light-scattering photometric measurements, that the highest turbidity water in the Cabot Strait occurs at a depth of about 100 m in the southern part of the Strait.

The observed concentrations of suspended matter at intermediate depths at Pointe des Monts are not significantly different from those on the Scotian Shelf (Figure 23). In general, they are comparable to those of North Atlantic waters, for which Jacobs and Ewing (1969) reported an average of 0.05 mgl^{-1}. This finding is somewhat surprising for a body of water receiving the effluents of such a major river as the St. Lawrence. However, it is important to note that the suspended load of the St. Lawrence River is low in comparison with other large rivers. For example, whereas the St. Lawrence and the Mississippi are comparable in their water discharge, the suspended load of the Mississippi (344×10^6 ton/yr) is about two orders of magnitude greater than that of the St. Lawrence River (Holeman, 1968).

3.6.1 Suspended Matter Budget

A budget for suspended matter has been attempted for the Gulf of St. Lawrence. Across Cabot Strait the transport can be estimated using the water-transport data as presented in Section 2.8 and the suspended matter data of Sundby (1974). Using 0.1 mgl^{-1} and 0.3 mgl^{-1} as representative mean concentrations for suspended matter in the water entering and leaving the Gulf respectively a total of 2.4×10^6 ton/yr is calculated to enter the Gulf while a total of 7.9×10^6 ton/yr is estimated to be transported seaward. The net seaward transport of suspended matter of 5.5×10^6 ton/yr is about five times greater than the estimates of d'Anglejan (1969, 1970). These latter values, however, were based upon the assumption that concentrations of suspended matter are uniform across Cabot Strait, and would be larger if higher concentrations in the seaward-flowing water were postulated.

Other rivers discharging into the Gulf yield a volume about 25% that of the St. Lawrence River. If their suspended matter concentrations are assumed equal to that of the St. Lawrence River (Holeman, 1968; Loring and Nota, 1973), river input to the Gulf can be estimated to be 5×10^6 ton/yr.

The atmospheric contribution, 4×10^4 ton/yr, was calculated by assuming that the input to the Gulf of St. Lawrence is proportional on an area basis to the total global input to the oceans estimated at 0.6×10^8 ton/yr by Garrels and MacKenzie (1971).

As far as the sediments are concerned only the top 0.5 m is considered to have been deposited during the present circulation regime (Loring and Nota, 1973) over a maximum time period of ∿ 5000 years (Loring, personal communication, 1974).

Thus the total amount of suspended matter deposited is calculated to be about 10×10^6 ton/yr assuming an area of deposition of 75,000 km^2 and a sediment density of 1300 kg/m^3. The completed budget is shown in Figure 24. The most interesting conclusion to be drawn from this model is that internal sources must be contributing at least 10.5×10^6 ton/yr to the sediments. The contribution from biological production can only be a small fraction of this since the organic carbon is low in the sediments averaging only 2.3% by weight of the pelites (Loring and Nota, 1973).

Thus other internal sources, such as erosion of coastlines and reworking of older sediment deposits, must account for a major part of the material now being deposited in the Gulf. This conclusion is supported by the observations of Loring *et al.* (1970), and later studies by Loring and Nota (1973) which have confirmed an admixture of material from these regions in the pelitic sediments of the Laurentian trough.

4. BIOLOGICAL FEATURES

The most comprehensive body of knowledge on the Gulf of St. Lawrence as a biological production system is the result of the IBP investigation carried out by McGill University (Steven, 1974). Measurements made during this research program were restricted to the summer months (April-November) and there remains little biological information on the Gulf for the winter months. The most notable exception is information concerning the exploited seal stocks.

4.1 Surface Layer Nutrient Supply

The overall distribution of nutrients in the Gulf of St. Lawrence has been discussed in Section 3.2. In considering the supply of inorganic nutrients to the surface layer, which is basic to the maintenance of the marine food chain, Steven (1974) identifies two regimes. The first is the Maritime Gulf (east of a line running north-south from P.E.I. to Anticosti at about longitude 64°W, and comprising ∿ 83% of the total surface area of the Gulf) and the second is the estuarine gulf which includes the St. Lawrence estuary and the Gaspé current system (17% of the total surface area).

In the Maritime Gulf average integrated concentrations of inorganic nutrients in the upper 25 m, immediately prior to the spring phytoplankton bloom, are about 40 mg m^{-2} of nitrate, 20 mg m^{-2} phosphate, and nearly 100 mg m^{-2} of silicate. Rapid depletion, particularly of nitrate, takes place during the spring bloom. The monthly changes in the concentrations of nitrate, phosphate, and silicate in the top 25 m of the water column from April to September are shown synoptically in Figures 25, 26, and 27. In the Estuarine Gulf nutrient concentrations are considerably higher than in the Maritime section. Concentrations in the top 25 m in the estuary itself immediately prior to the spring bloom are more than 200 mg m^{-3} of nitrate, 20 mg m^{-3} of phosphate and 300 mg m^{-3} of silicate; they are almost as high in the Gaspé Current. Average nutrient concentrations do not fall below half of these values during the season of active phytoplankton growth. Local nitrate depletion of the surface water has been observed at times in the lower estuary and in the Gaspé Current in the summer, but it is apparently soon replenished by fresh, nutrient-rich water.

The mechanism of nutrient supply has been postulated by Steven (1974) horizontal transport in the surface layer eastwards following the Gaspé Current. At least three mechanisms could contribute to the enrichment of the surface water of the estuary with inorganic nutrients. The first is entrainment of deep water by the flow of the St. Lawrence River itself which generates the characteristic nutrient-rich surface layer of low salinity. This appears to be the principle mechanism in the upper part of the estuary near the head of the Laurentian Channel. A second mechanism is vertical oscillation of the whole water column through internal tides which may be of sufficient amplitude in the St. Lawrence estuary to bring intermediate layer water to the surface (see Section 2.5). A third possible mechanism is direct enrichment through fresh water drainage. It is calculated that about 10% of the nutrients in the surface layer at the head of the estuary are derived directly from the St. Lawrence drainage basin.

Steven (1974) calculates the annual input of nitrogen to the Gulf by the Gaspé Current to be about 1.8 x 10^6 metric tons. If, as seems likely, nearly all this is utilized by phytoplankton, it would yield about 10^7 tons of organic carbon or 3 x 10^7 tons of phytoplankton. A similar calculation for phosphate gives an annual transport of 4 x 10^5 tons of phosphorus which is equivalent to 1.6 x 10^7 tons of organic carbon or 5.4 x 10^7 tons of phytoplankton. Since these calculations are based on summer data only, they should probably be increased by at least 50% to give a more realistic annual figure.

4.2 Primary Production

The seasonal pattern of phytoplankton production in the Gulf is shown in Figure 28. From mid-April to mid-June carbon fixation is highest in the Gaspé Current and the northern parts of the Magdalen Shallows, but high rates often exceeding 200 mg C m^{-2} hr^{-1} are found almost anywhere during the spring phytoplankton bloom, except in the St. Lawrence estuary and the extreme northeastern part of the Gulf. From mid-summer to mid-September the very high rates of more than 200 mg C m^{-2} hr^{-1} are found in the estuary while elsewhere they are generally lower, averaging 50-60 mg C m^{-2} hr^{-1}, in most of the Gulf. Primary production is lowest in the nutrient-poor northeastern region where the average rate is less than 50 mg C m^{-2} hr^{-1} after mid-May and does not exceed 100 mg C m^{-2} hr^{-1} during the spring bloom. Unusually high production has been observed at the western end of the Jacques Cartier Passage in July and August, an area that frequently contains nutrient-rich surface water at this time. High production measured occasionally in Cabot Strait may be due to enriched water flowing in from the Atlantic (Figure 8). Steven (1974) estimates the annual production of the St. Lawrence estuary to be about 510 g C m^{-2}; for the Gaspé Current system about 390 g C m^{-2}; and for the central Gulf about 210 g C m^{-2}. These estimates are at the upper extremity of the range of published values for coastal waters.

Seasonal variation of chlorophyll concentration over the Gulf is shown in Figure 29. Chlorophyll concentrations are usually highest in the estuary and the Gaspé Current regions. The spring bloom of phytoplankton in the Gulf is characterized by a few species of diatoms: *Thalassiosira gravida, Thalassiosira nordenskioldii, Chaetoceros debile, Chaetoceros sociale, Skeletonema costatum.* After the bloom the importance of flagellates increases with increasing species diversity. The species of diatoms that dominate the spring bloom tend to remain the most common. The most frequently recorded genera are *Thalassiosira*, *Chaetoceros*, *Navicula*, *Melosira*, *Tabellaria*, *Fragilaria*, *Rhizosolenia*, *Biddulphia*, and *Coscinodiscus*. The most numerous dinoflagellates are *Peridinium*, *Gonyaulax*, *Certium*, *Dinobryon*, and *Gymnodinium* while Collolithophores and Silicoflagellates are also present.

4.3 Zooplankton Biomass

The seasonal variation of zooplankton biomass throughout the Gulf is shown in Figure 30. There is a decreasing gradient from west to east. The principle increases in zooplankton biomass in nearly all areas occur in May and in September. The biomass is relatively constant in the central Gulf and estuary averaging between 25 and 50 mg dry wt m^{-3} and about 60 mg m^{-3} respectively during the summer months. Except for a brief increase in May the zooplankton biomass is consistently less than 25 mg dry wt m^{-3} in and to the east of Cabot Strait. This indicates that the Gulf sustains larger populations of zooplankton than the adjacent waters of western Atlantic and is consistent with the view that it is a partially isolated system with a higher rate of biological production than the water outside. A large seasonal change in biomass has been observed only on the Magdalen Shallows where the values from June to September are about three times the average found in most of the deep water areas. The highest monthly average is $\sim$ 120 mg m^{-3} in August, but many values exceeding 200 mg m^{-3} have been obtained in each of the summer months. These high concentrations of zooplankton usually disappear by October when the average value falls to about 30 mg m^{-3}.

4.4 Fisheries Biology

Most of the more than 145 species of fish known to occur in the Gulf of St. Lawrence are permanent members of the biological community (Srivastava, 1971). Others, however, such as mackerel *(Scomber Scombrus)* and tuna *(Thunnus thynnus)* are only found in the Gulf in summer.

Apart from supporting a productive fishery, the southern Gulf of St. Lawrence serves as an important nursery area for numerous inshore and commercial fish species. In fact, the Magdalen Shelf (particularly around Chaleur Bay), is one of the most significant spawning areas. Here, American plaice *(Hippoglossoides platessoides)* is one of the first species to reproduce. Their spawning cycle begins in April and is virtually complete by the end of May (Powles, 1965). Plaice eggs are planktonic, about 2.8 mm in diameter, and hatch between 11-14 days, depending on the temperature. The post-larvae begin their short pelagic existence feeding on diatoms and copepods. However, once metamorphosis is complete, when the larvae are approximately 30-400 mm in length, they settle to the bottom and become true groundfish.

Herring are the next important commercial species to spawn on the Magdalen Shelf. They arrive early in May and lay their eggs on a gravel or well-sorted sand bottom, at depths of 2-30 fathoms. Newly hatched larvae, about 6 to 7 mm long, emerge after 10 to 15 days (longer when the water is colder), and begin feeding on diatoms and other small planktonic organisms until the yolk is absorbed. As the larvae grow, of course, larger copepods become increasingly more important in the diet.

A discrete fall-herring population also spawns off Chaleur Bay in mid-August. In this regard it is of interest to note that the reproductive activity of spring and fall herring, as well as plaice and cod occurs at times when the biomass of zooplankton in the southwest Magdalen Shelf is at the highest annual levels (Figure 30). Such a close connection between spawning times and the production cycle is common, and has been observed in other geographical areas such as the North Sea.

According to Messieh and Kohler (1972) spring- and fall-spawned herring larvae drift in a southeasterly direction over the Shelf. Although little is known of the movements of young herring, Messieh and Kohler observed large autumn-spawned fish early the following spring thus indicating that part of the larval population overwinters in the Gulf.

Herring form an important link in the Gulf food chain. They fall prey to many pelagic predators such as cod, salmon, tuna, seals, and whales. Indeed, they are of such importance that the slow growth rates of cod during 1957-59 can be associated, in part, with the reduced abundance of herring following an epidemic fungus disease (Kohler, 1964).

The spawning period of cod overlaps somewhat with herring and plaice. Mature cod migrate to the southwestern Gulf in May and commence spawning as soon as the water temperature is suitable. The spawning cycle extends from May to September, with peak spawning occurring in late June (Powles, 1958). Young cod are pelagic for several months, possibly longer, before they eventually settle near the bottom. According to Powles (1958), juveniles, 11 to 30 cm in length, are seldom found at depths greater than 60 m. The young seem to feed pelagically on mysids, euphausiids and amphipods, whereas the older fish feed mainly on bottom-living molluscs and annelids.

4.5 The Fishery

Though more than 25 fish species are caught commercially in the Gulf of St. Lawrence, three species - herring, redfish, and cod - have consistently made up more than 85% of the total fish catch. The following landing statistics (1973) indicate roughly where the major fisheries occur.

	Landings (metric tons)		
Area	Redfish	Cod	Herring
NW-NE Gulf (summer fishery)	115,668	54,505	27,747
Southern Gulf (summer fishery)	14,496	25,756	40,357
Cape Breton (winter fishery)	*	30,627	22,692
SW Newfoundland (winter fishery)	*	8,680	11,231
Totals	130,164	119,568	102,027

Recent increases in the catch of redfish from the northern Gulf account to a large extent for the current importance of that area. Before the decline in the abundance of herring and cod, landings from the Magdalen Shelf contributed a larger portion of the total fish catch.

4.5.1 Atlantic Herring *(Clupea harengus harengus)*

Spring- and fall-spawning populations of Atlantic herring occur largely in the southern Gulf of St. Lawrence. Spring herring first arrive on the spawning grounds around the Magdalen Islands and Chaleur Bay in late April-early May. After spawning the adults disperse into feeding concentrations over the Magdalen Shelf. Fall-spawning occurs primarily around Chaleur Bay in August.

Messieh and Tibbo (1971) suggest that the spring and autumn herring fisheries in the southern Gulf of St. Lawrence are supported by two discrete stocks. Traditionally, the herring catch depended almost exclusively on the spring-spawning stock. However, in recent years, with the declining abundance of spring herring the autumn fishery has become more important.

Herring are caught in traps and nets, but since 1967 the bulk of the catch has been taken by purse seiners. Following the rapid increase in fishing effort and the extraordinary success of the 1958 and 1959 year-classes, landings increased from 50,000 metric tons in 1964 to a record 300,000 tons in 1969, but have subsequently declined to around 60,000 tons.

The seasonal movements of the stock are fairly well known (Hodder and Parsons, 1971). Adults inhabiting the southern Gulf migrate eastward in October-November. The stock splits in the vicinity of the Magdalen Island, part of the population moves across the Gulf to overwinter in the fjords of southwest Newfoundland, whereas the remainder are thought to move eastward past Cape Breton and then southeastward along the Laurentian Channel. Both components of the stock support a winter fishery. The scarcity of immature herring on the winter grounds suggests that the juveniles do not migrate with the adults.

Quite apart from the effects of fishing, it appears that the abundance of herring would have declined significantly from 1965 to 1971 due to inadequate recruitment. In essence, the impact of man has been to increase the magnitude of the decline (Winters and Hodder, 1973). Herring stocks are particularly volatile, and are subject to natural catastrophes of epidemic proportions. From 1953-1957 the stock suffered widespread mortality from a fungus disease *(Ichthyosporidium hoferi)*, which, according to one estimate, may have destroyed over half the population.

4.5.2 Redfish *Sebastes marinus)*

Redfish inhabit the deep waters of the Esquiman and Laurentian Troughs in the Gulf of St. Lawrence. No appreciable amounts of redfish were landed from the Gulf until an otter-trawl fishery started in 1951. Fishing effort on the virgin stock increased rapidly in 1954, returning a peak yield of 50,000 metric tons in 1955. Thereafter landings declined dramatically to a low of 6500 metric tons in 1962. In the mid-1960s landings again increased, surpassing the catch from the virgin stock, and have remained above 70,000 metric tons since 1967 (Sandeman, 1973).

The future of the fishery is in doubt, however, due to consistently poor recruitment. Sandeman (1973) predicts that redfish catch/effort will decline with the passage of the large year-class. Fishing effort will then be directed primarily at the 1966 year-class which, though considerably more abundant than those immediately before or after it, is not as strong as the 1956 year-class.

4.5.3 Cod *(Gadus morhua)*

Prior to 1947 cod in the southern Gulf of St. Lawrence were caught primarily by hook and line. The annual yield from the stock at that time averaged about 30,000 metric tons. After 1947 otter-trawling gradually became more important, and the landings increased to a record level of 110,000 metric tons in 1956. Between 1966-1970 landings declined, and now average less than 60,000 metric tons. Increased fishing effort, as would be anticipated, has changed the composition of the stock by lowering the average size and abundance of commercially caught fish.

Tagging experiments indicate that southern Gulf of St. Lawrence cod are migratory. The adults move eastward along the Magdalen Shelf in the fall and overwinter on the southern slope of the Laurentian Channel off Cape Breton. As was the case for herring the migratory habit, inferred from differences in the age composition of the population on the winter and summer grounds, is more pronounced in older fish (Paloheimo and Kohler, 1968).

Fishing fleets understandably take advantage of the winter and summer concentrations. The Canadian fleet tends to concentrate its activity in the southern Gulf, whereas other nations fish the stock off Cape Breton.

The west Newfoundland cod population has been of equal importance to that of the southern Gulf cod fishery since about 1960. Tagging returns show that this stock spends the summer in the northern and northeastern Gulf of St. Lawrence, and overwinters predominantly off southwestern Newfoundland. The population supports a summer and winter fishery.

Landing statistics from 1954 to 1965 show that cod catches by trawlers from the northeastern Gulf have increased relative to inshore catches since 1960 (Wiles and May, 1968). Total landings from the stock during 1960-1973 have averaged a little less than 60,000 metric tons.

4.5.4 Lobster *(Homarus americanus)*

No discussion of the production characteristics of the Gulf of St. Lawrence would be complete without considering lobster. Although we have hitherto paid most of our attention to the fin fish species, it is important to emphasize that lobster is the single most valuable species in the Gulf. In 1970, for example, 9574 metric tons were landed for a market value of $15.3 million. The composite value of the 1970 Gulf lobster and shellfish catch was $20.8 million which is roughly equal to the estimated value of the entire 1970 fin-fish catch ($27.1 million).

Despite the decline in lobster catches from the southern Gulf of St. Lawrence during the last decade, the fishery seems to be relatively healthy. Catches have oscillated in the past: in the 1930s they declined, but subsequently increased during the 1940s and 1950s. Over the past 20 years a confirming decline in landings has occurred in the central portion of Northumberland Strait, whereas the landings have been relatively constant in the surrounding region. However, considering the historical fluctuations in the fishery, there is insufficient reason at this time to conclude that the current downward trend will continue indefinitely.

5. MAN-MADE CHANGES

5.1 Fisheries

Fisheries and associated industries constitute a major activity in the Gulf of St. Lawrence region and play a dominant role in regional development aspirations. With the exception of the cod fisheries, most Canadian open-water fisheries in the Gulf of St. Lawrence are of relatively recent origin and during the last 25 years much of the landings have been obtained by catching the accumulated stocks of old fish which are characteristic of virgin fisheries. Clearly, man has made a major impact on these stocks.

A phenomenon shown by most fish species is that of great variability in the success of spawning. In the Gulf of St. Lawrence this variability can be seen in abnormally successful spawnings which have produced exceptionally large year-classes and have in turn supported large fisheries for herring in the late 1960s and for redfish in the recent years of the 1970s. Such single year-class fisheries, while they can be managed to produce reasonably stable catches over a restricted period of years, are not sustainable on a longer term basis and as the year-class becomes depleted, landings must necessarily decline. This decline for the herring fishery took place in 1970-71 and is presently occurring (1974-75) for the redfish fishery. With none of the traditional species showing any likelihood of abnormally successful year-classes entering the commercial fisheries in the next few years, the prognosis for the immediate future is that landings will be established at a lower level than is currently enjoyed.

Some opportunities for expansion in terms of under-utilized species can be seen, but most of these (e.g., krill, capelin) are important food items for conventional species. In the past each species has been exploited independently with no regard for its place in the food webs. Cod and mackerel fisheries, for example, may influence the size of herring stocks. Pressures are developing to move towards multi-species management so that the interactions between different species can be considered. This would allow choices to be made concerning quantities of yield from various trophic levels (for example, krill or cod and herring, herring or mackerel). Unfortunately, present understanding is insufficient to make more than some initial moves in the direction of multi-species management at this time.

While man, through fishing activities, has likely had the greatest influence on the marine ecosystem, the effects of pollutants have also been important in localized areas, particularly in some of the estuaries and near-shore areas (see Section 5.2).

5.2 Pollution

5.2.1 Petroleum Residues

Studies of petroleum pollution in the Gulf of St. Lawrence began in the summer of 1970 following the sinking of the tanker, *Arrow*. At that time, samples were collected at 13 stations in the Gulf of St. Lawrence and the St. Lawrence River between Cabot Strait and Montreal (Levy, 1971). Oil concentrations in the Gulf varied between 1.3 and 3.0 μg/l with slightly higher values in the River itself. This distribution was rather surprising at first since it was anticipated that concentrations would steadily increase, particularly in the surface waters, as suspected land sources for oil pollution were approached. Subsequent investigations (Figure 31) showed that run-off from the St. Lawrence River is not the major source of oil in the Gulf as a whole. Indeed, ocean waters entering the Gulf through Cabot Strait together with shipping within the Gulf and its approaches appear to be the major sources of dissolved and dispersed petroleum residues. These studies further suggested that an effective mechanism for removing petroleum-derived substances from the water column is adsorption onto suspended mineral particles which subsequently settle out (Levy and Walton, 1973).

Substantial amounts of oil still remain deposited on beaches and in lagoons in the area near the *Arrow* grounding just outside the Gulf of St. Lawrence. These residues continue to contaminate inter- and sub-tidal organisms and it is expected that several years will elapse before all traces of oil disappear.

Several oil spills have occurred in the Gulf of St. Lawrence during the past few years. For example, in 1970 the barge *Irving Whale* sank on the Magdalen Shelf with a loss of an undetermined amount of Bunker C fuel oil. Gas chromatographic and ultraviolet spectrophotometric analyses positively identified samples from the beaches of the Magdalen Islands as coming from the *Whale*, but although considerable fouling of beaches occurred, the impact of this spill on the background dissolved and dispersed petroleum residues in the water column was not detectable.

A second spill occurred in the St. Lawrence estuary near the pilot station at Les Escoumains in July 1973, when the tanker *St. Spyridon* and the bulk carrier *Florence* collided. Chemical analyses of the samples collected from the surface of the estuary proved that the oil originated from the *Florence*, and that there was little oil spilled from the tanker. Oil on the surface was observed to move seaward at about 15 miles per day.

Studies of floating oil were also made in the Gulf of St. Lawrence as part of a much larger program to determine the occurrence and distribution of floating petroleum pollution, tar balls, on the surface of the North Atlantic. In contrast with much of the open North Atlantic, tar balls do not occur extensively in the Gulf of St. Lawrence, many of the samples collected there contain no evidence of floating oil. Generally speaking, when oil is encountered in the Gulf, it is in a relatively fresh form. This would suggest that it is of recent origin and has been discharged within the Gulf. Since the residence time of the water in the Gulf is believed to be a few months, floating oil probably does not remain sufficiently long within the Gulf for the formation of tar balls to occur at the low temperatures which prevail over most of that area.

5.2.2 Heavy Metals

The degree of pollution by heavy metals in the water column has been indirectly discussed in previous sections of this publication. In the main, pollution of this kind is minimal in the Gulf with isolated cases of local pollution occurring only from time to time in connection with industrial development (Bewers and Pearson, 1972). Of specific interest is the question of mercury pollution caused principally by the discharge of effluents from chlor-alkali plants in the Gulf region. The most comprehensive discussion of this subject is that of Loring (1975). In sediments collected from the Saguenay fjord, the St. Lawrence estuary, and open Gulf of St. Lawrence, total mercury (Figure 32) varied with sediment texture (Figure 17) and location over three orders of magnitude from 10 to 12,300 ppb (average 386 ppb). The highest concentrations occurred in the Saguenay fjord (average 2980 ppb) and the lowest in the open Gulf of St. Lawrence (average 150 ppb). The concentration of mercury increased with decreasing grain size, the highest concentrations occurring in the fine-grained sediments of the submarine troughs and shelf valleys and the lowest in the sandy shelf sediments. Analyses of the sediments from the Saguenay fjord, where mercury values ranged from 12,300 ppb at its head to 300 ppb in the lower reaches, indicated that most of the mercury (70 to 90% of the total) is held by the organic matter in the sediments. The distribution of mercury in the fjord is apparently controlled by the downstream dispersal from local industrial sources of mercury-rich organic matter, most likely of terrestrial origin because of its high C/N ratio. In the St. Lawrence estuary where mercury values ranged from 30 to 950 ppb, and in the open Gulf where correlations between variables are lower and scattered anomalies exist, analyses indicated that mercury accumulates along with the fine-grained inorganic and organic matter in response to the present depositional processes. The distribution of mercury appears to be controlled by the sedimentation pattern. Terrestrial organic matter and industrial waste originating in the Saguenay drainage area have the strongest influence on its distribution.

5.3 Fresh-water Regulation

The importance of fresh-water discharge in determining the physical oceanoographic characteristics of estuaries is widely recognized, although less well understood in quantitative terms than one might expect. In turn, the physical regime is an important cornerstone of biological productive processes.

Neu (1973) pointed out that changes in the fresh water discharging into the sea through river regulations or diversions may subsequently produce significant alterations in marine ecosystems. Since 1971, this problem has been studied by Neu and continued efforts have been aimed at identifying and quantifying the scope of the marine area that may be affected. His study has been focussed principally on the St. Lawrence River system. Large quantities of water from the spring run-off are retained in storage lakes and returned to the river during the low discharge period of autumn and winter in order to optimize power production. In order to evaluate the magnitude of this man-made interference the run-off from the St. Lawrence system was analyzed by Neu for the period from 1964 to 1970. This disclosed that on the average the ratio between the winter run-off and the spring run-off has been modified as follows.

	Ottawa River above Montreal	St. Lawrence River above Montreal	St. Lawrence River at Pointe des Monts
Natural	1:6	1:1.7	1:3.4
Regulated	1:2.7	1:1.3	1:1.8

During this seven-year period, the fresh-water inflow of the sector extending down to Pointe des Monts was artificially increased in February by an average of 3600 m /s with a maximum of 4200 m^3/s in 1967, and decreased in May by an average of 7800 m^3/s in 1970. More than two-thirds of this regulation occurs in the Province of Quebec while the remainder occurs in Ontario. The variation in the regulation in 1970 for four points along the system is shown in Figure 33.

From these results it can readily be seen that at Pointe des Monts, which is at the entrance of the Gulf of St. Lawrence, nearly half of the seasonal variation in discharge occurs as a result of water regulation. It has been argued (Neu, 1973) that these changes must have had a profound impact not only on the physics of the water, and the dynamics of the Gulf and the adjacent waters, but most probably on the entire ecosystem of a large part of the Atlantic region.

Recent studies by Sutcliffe (1972, 1973) and Sutcliffe *et al.* (1975) reveal that fluctuations of certain fish species, and hence the biological balance, are correlated with fresh water discharge of the St. Lawrence River system. Striking correlations were found between the River discharge and various parameters not only in the Gulf of St. Lawrence but on the Scotian Shelf and in the Gulf of Maine. From these correlation studies it was concluded that the effects of the River discharges probably progress at ocean drift speeds from the Gulf of St. Lawrence to the Gulf of Maine. Transports and salinity data also support this contention. Thus it is believed that variability in the St. Lawrence River discharge can cause some of the variability in the physical oceanographic characteristics that, in turn, affect fish productivity in this region.

At the present time several additional hydroelectric power schemes along the system are in the design or construction stage. The ultimate aim of power interests is to achieve optimum power production by increasing winter discharges to the point where they may even exceed the spring flow. In the light of the findings from the above-mentioned studies, immediate and comprehensive consideration should be given to the role fresh-water inflow plays in coastal ecosystems, before further man-made modifications are implemented.

6. SUMMARY

It is convenient to think of the Gulf of St. Lawrence as a large complex estuary, with physical oceanographic features determined by a spectrum of parameters, such as precipitation, fresh-water discharge, wind, topography, heat transfer, and tides and tidal currents. The fresh water is largely confined to the mixed surface layer which varies in thickness seasonally from approximately 10 m in July to about 100 m in March.

A much stronger thermocline, halocline and pycnocline is present during summer months than in winter. Although the mechanisms determining the vertical structure are not particularly well known, the very stable summer conditions are brought about through increased fresh-water discharge in spring, increased solar heating, and decreased wind action. Winter conditions are the result of decreased fresh-water discharge, rapid heat loss through the sea surface, and strong winds. Mixing energy, supplied by the tides, appears to be of lesser importance except in the St. Lawrence estuary and in restricted straits and passages.

Flushing time of fresh water in the Gulf appears on average to be somewhat less than one year. However, the internal circulation pattern is such that the bulk of the fresh water does not move simply through the Gulf but probably makes one or more 'circuits' before exiting through Cabot or Belle Isle Straits.

The relatively high biological productivity of the Gulf of St. Lawrence is undoubtedly related to the vertical water circulation and mixing patterns which in turn depends upon fresh-water run-off and wind-stress factors. The distribution of many chemical substances, within the Gulf, indicates that Atlantic water inflows along the Laurentian Trough receiving biological detritus from the surface waters. The oxidation of this organic material places a substantial drain upon dissolved oxygen reserves of the deep water while producing increased concentrations of dissolved carbon dioxide and free nutrients. At the head of the Laurentian Trough, near the Saguenay, the deep water appears to upwell and bring to the surface nutrient-rich saline water which gives rise to intense biological activity in the immediate area. In addition the Gulf acts as a trap for nutrients brought in from the Atlantic.

Surface layer nutrient concentrations are highest in the St. Lawrence estuary and Gaspé Current system. From mid-April to mid-June, phytoplankton production is highest in the Gaspé Current system and the northern part of the Magdalen Shelf, and lowest in the northeast Gulf. Zooplankton populations reach their maximum values in summer months and are generally sustained at higher levels than those found seaward of Cabot Strait. This is consistent with the view that the partially isolated Gulf system has a higher rate of biological production than the water outside.

Although more than 25 fish species are caught commercially in the Gulf, three species (herring, redfish and cod) have consistently constituted more than 85% by weight of the total fin-fish catch. In terms of dollar value, however, lobster is the single most valuable species with a value roughly equal to that of the total fin-fish catch. The total annual fish catch has increased substantially over the last 25 years but recently it has stabilized. The original increases were achieved largely by the removal of the accumulated stocks of old fish which are characteristic of virgin fisheries.

While fishing activities have probably had the greatest influence upon the overall marine ecosystem, the effects of anthropogenic discharges have been substantial in particular estuarine and near-shore areas. Thus, terrigenous organic material, discharged in abnormal quantities from pulp and paper operations, have given rise to significant increases in the organic content of the local sediments, as evidenced by high organic carbon and carbon to nitrogen ratios. Organophyllic substances discharged in effluents would be expected to be found principally in the organic fraction of the sediments and indeed the mercury distribution in the Gulf can be shown to reflect the effect of discharges from the chlor-alkali industry.

Hydrocarbon-related substances in the water of the Gulf are predominantly derived from the North Atlantic rather than from its drainage basin, and the water circulation patterns so far elucidated indicate that such substances are also likely to be trapped within the system. In other respects, such as suspended particulate matter and trace metal concentrations, the bulk of the intermediate depth waters of the Gulf have chemical characteristics similar to those of North Atlantic intermediate water.

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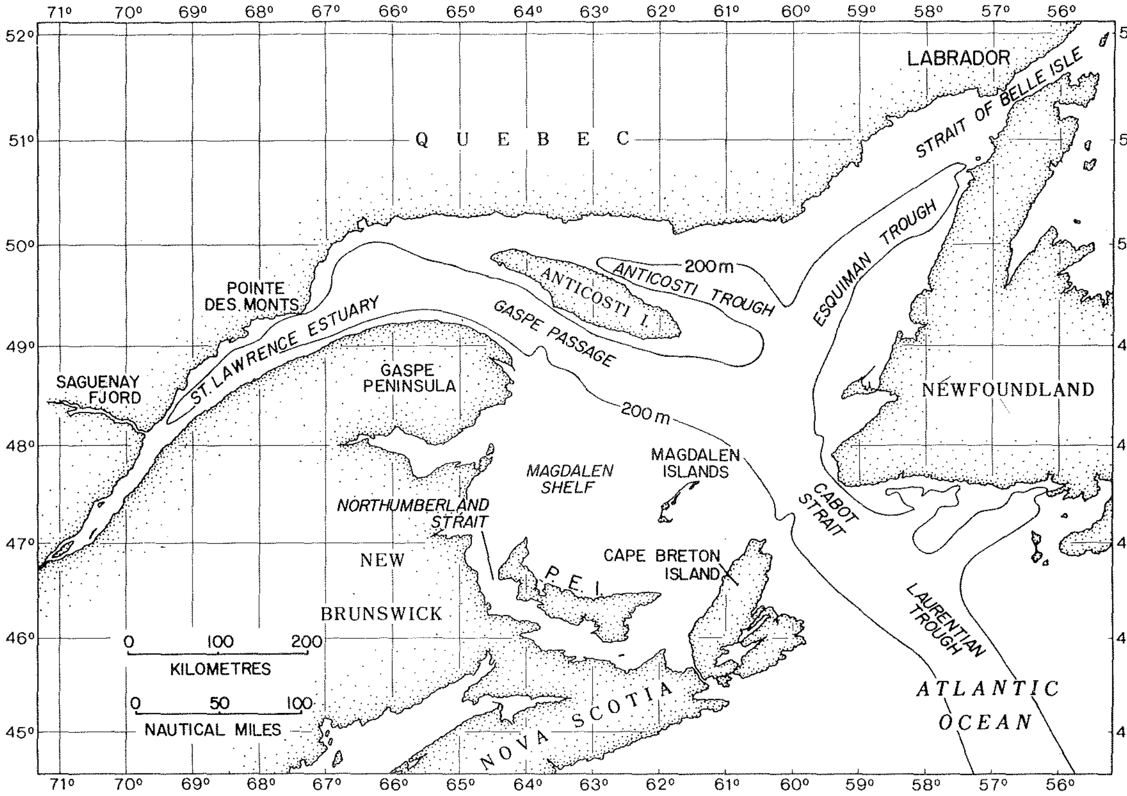


Fig. 1. Map of Gulf of St. Lawrence and Estuary

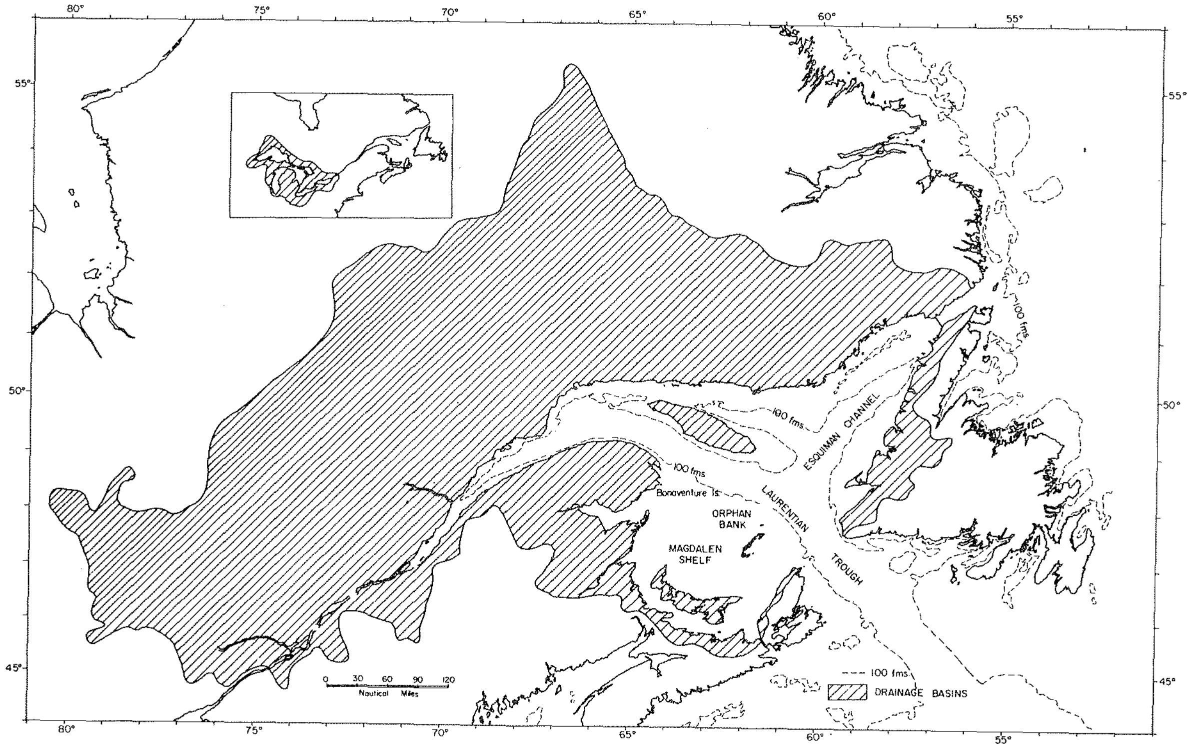


Fig. 2. Map showing Drainage Basin of Gulf of St. Lawrence

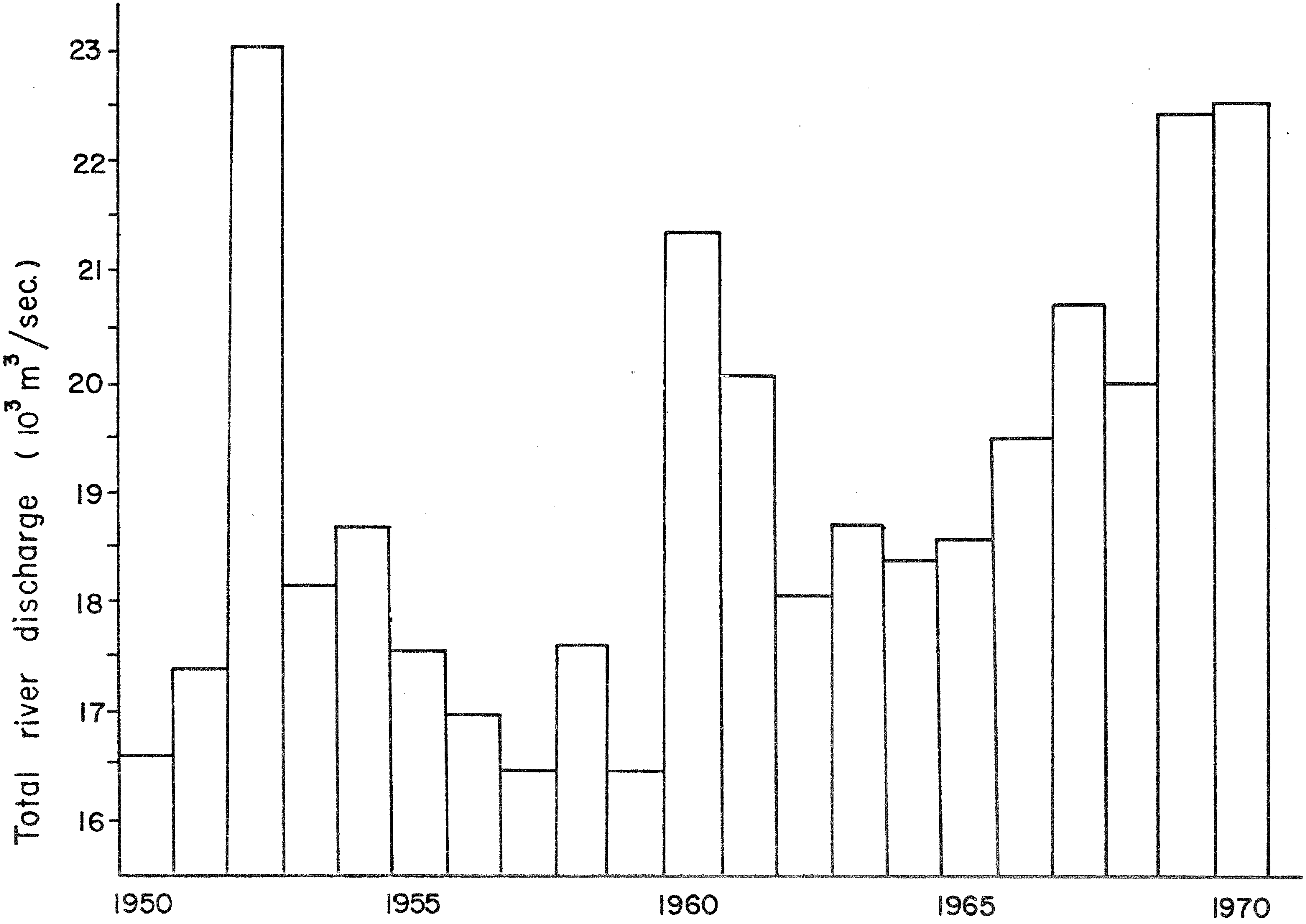


Fig. 3. Mean annual variations of the total river discharge into the Gulf of St. Lawrence (from El Sabh, 1975)

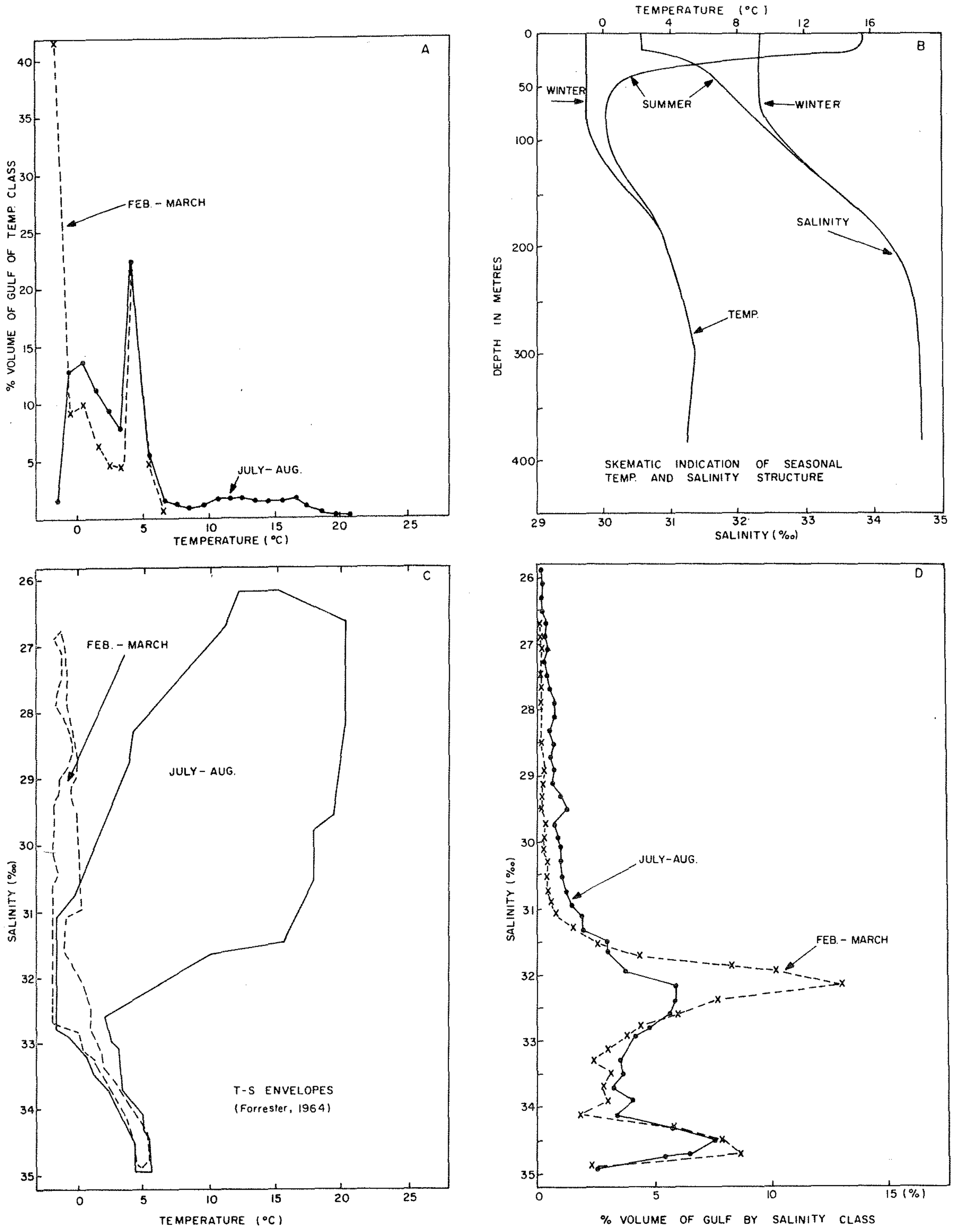
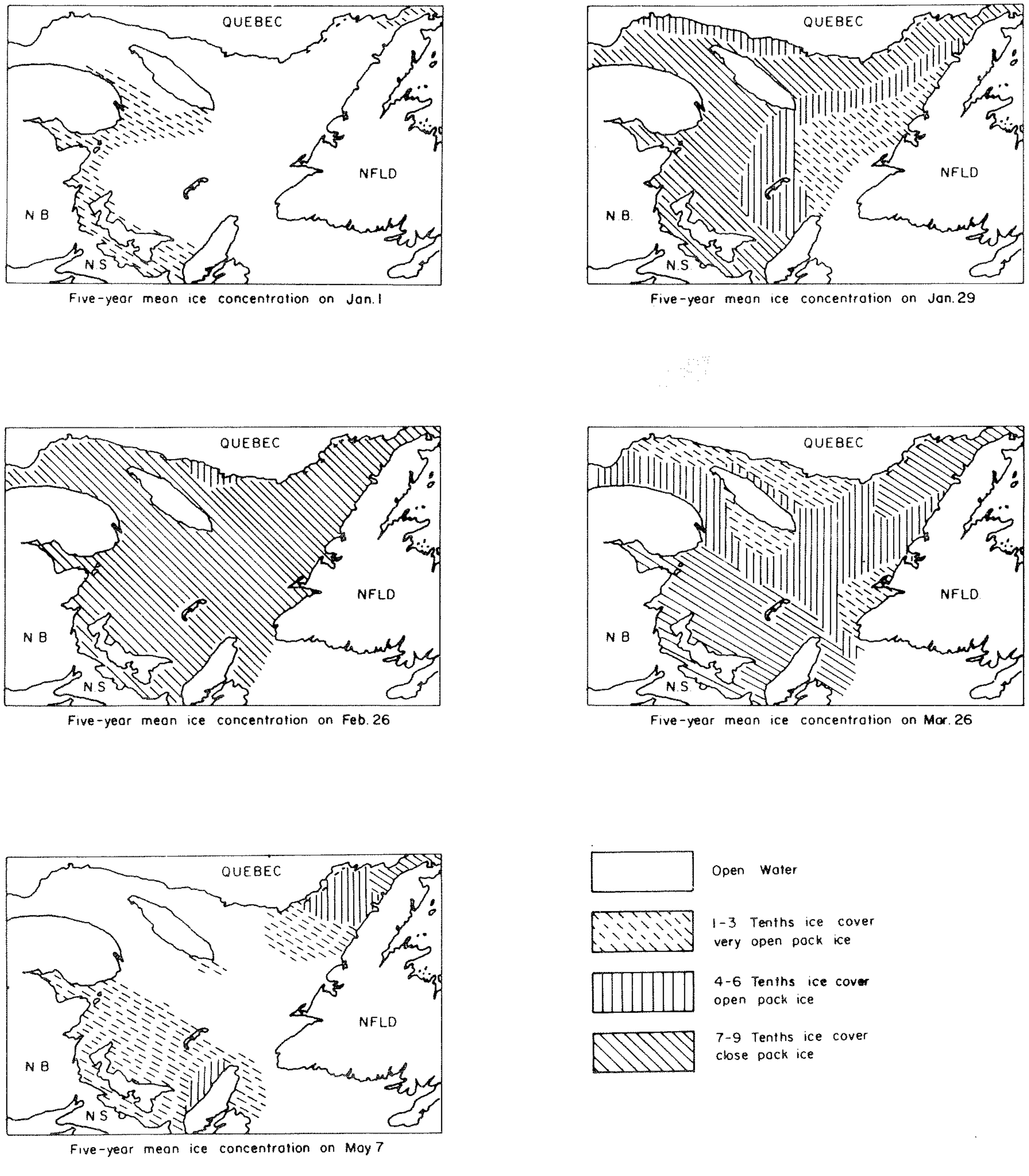


Fig. 4. A) Percent volume of Gulf of St. Lawrence waters by temperature class (data from Forrester, 1964), B) Schematic indication of seasonal temperature and salinity structure (from Trites, 1972), C) T-S envelopes for February-March and July-August in Gulf of St. Lawrence (after Forrester, 1964), D) Percent volume of Gulf of St. Lawrence waters by salinity class (data from Forrester, 1964)



Open Water ☐

1-3 Tenths ice cover very open pack ice ▨

4-6 Tenths ice cover open pack ice ▥

7-9 Tenths ice cover close pack ice ▧

Five-year mean ice concentration on Jan. 1

Five-year mean ice concentration on Jan. 29

Five-year mean ice concentration on Feb. 26

Five-year mean ice concentration on Mar. 26

Five-year mean ice concentration on May 7

Fig. 5. Five-year mean ice concentration in Gulf of St. Lawrence (after Matheson, 1967)

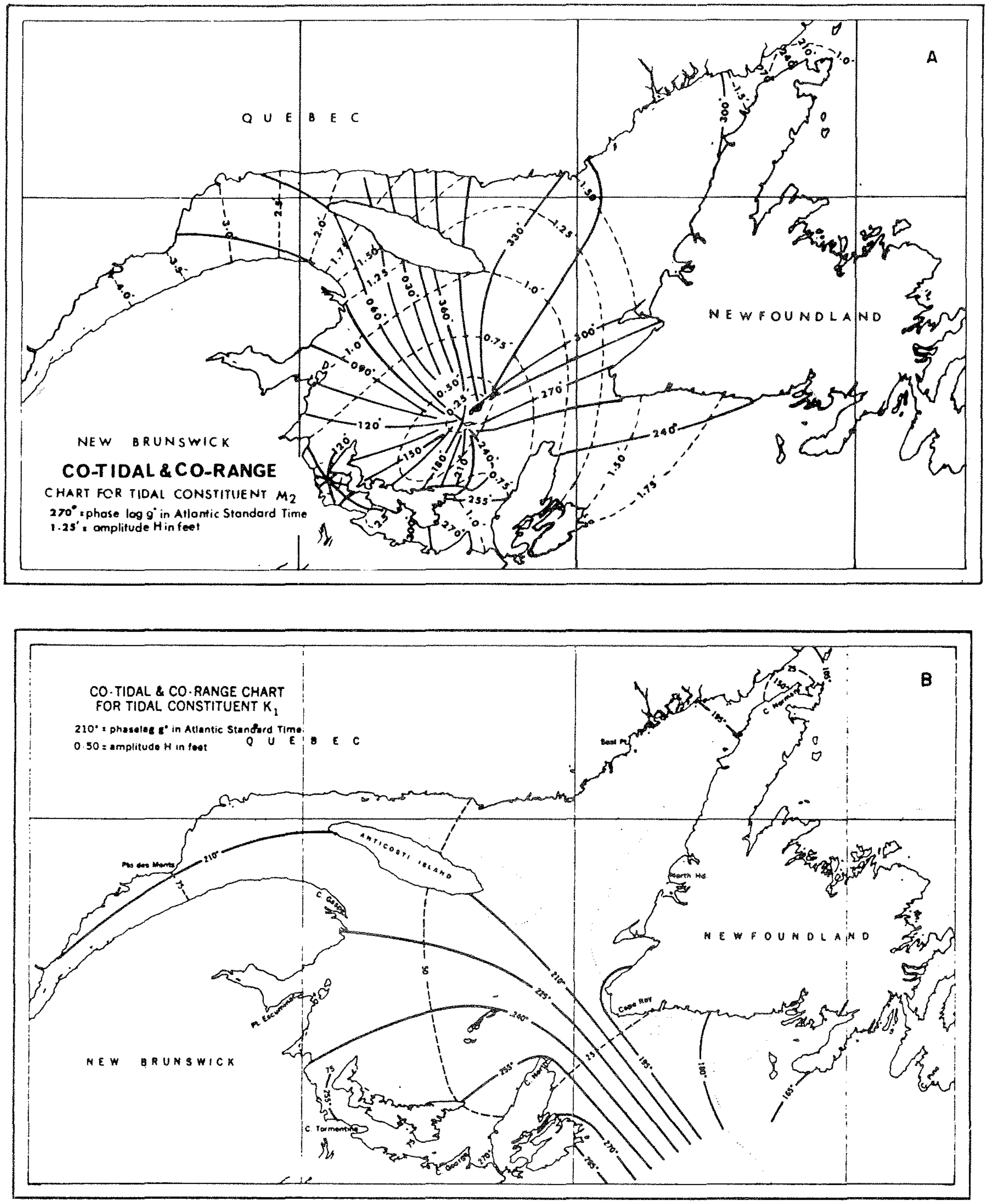


Fig. 6. A) Semi-diurnal lunar tidal constituent, M_2 (after Farquharson, 1962), B) Lunisolar diurnal tidal constituent, K_1 (after Farquharson, 1962)

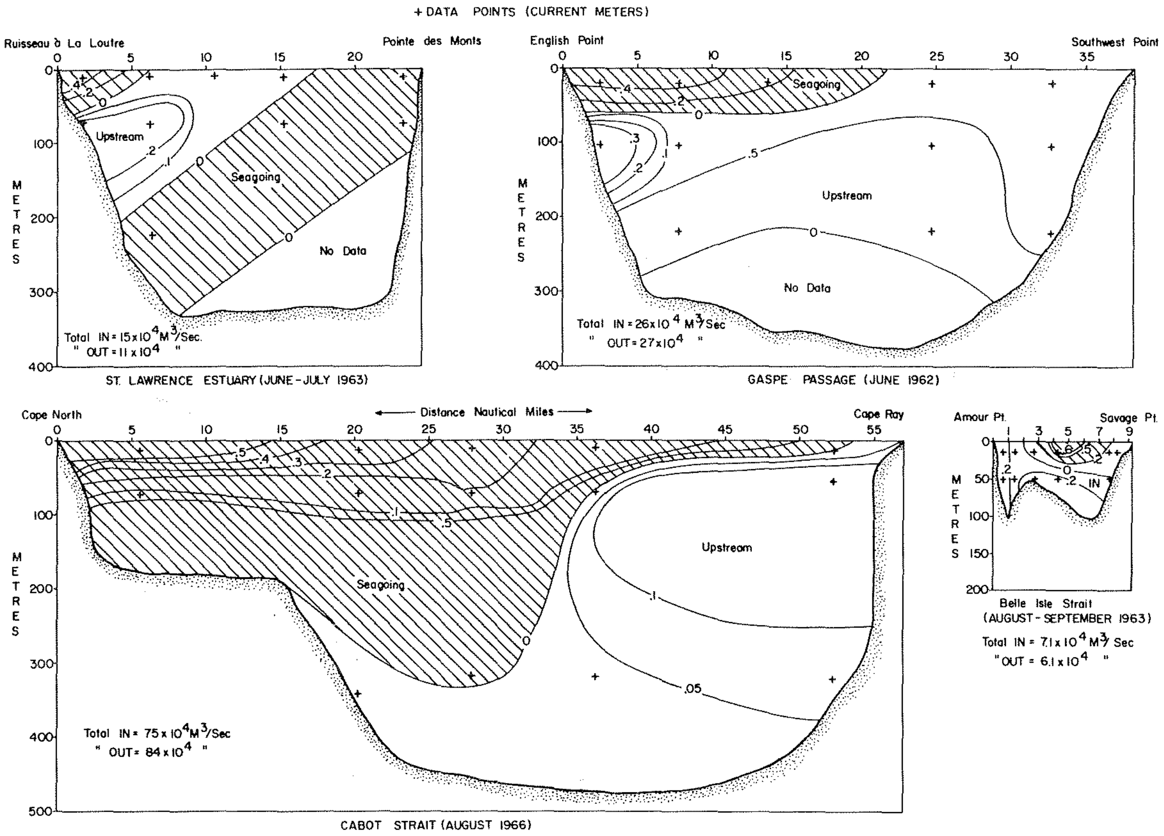


Fig. 7. Residual currents through four sections in Gulf of St. Lawrence as determined by direct current measurements (from Trites, 1972)

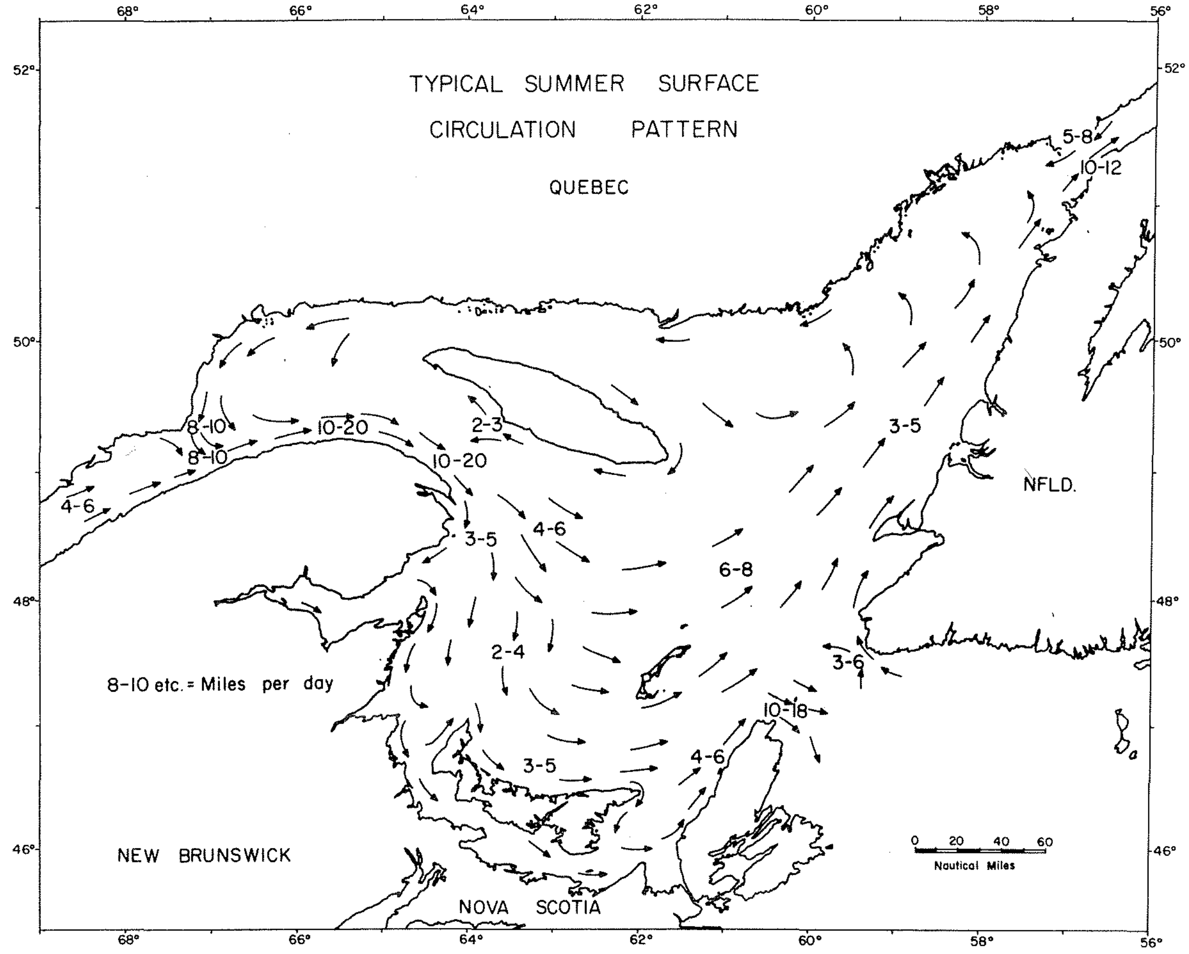


Fig. 8. Typical summer surface circulation pattern (from Trites, 1972)

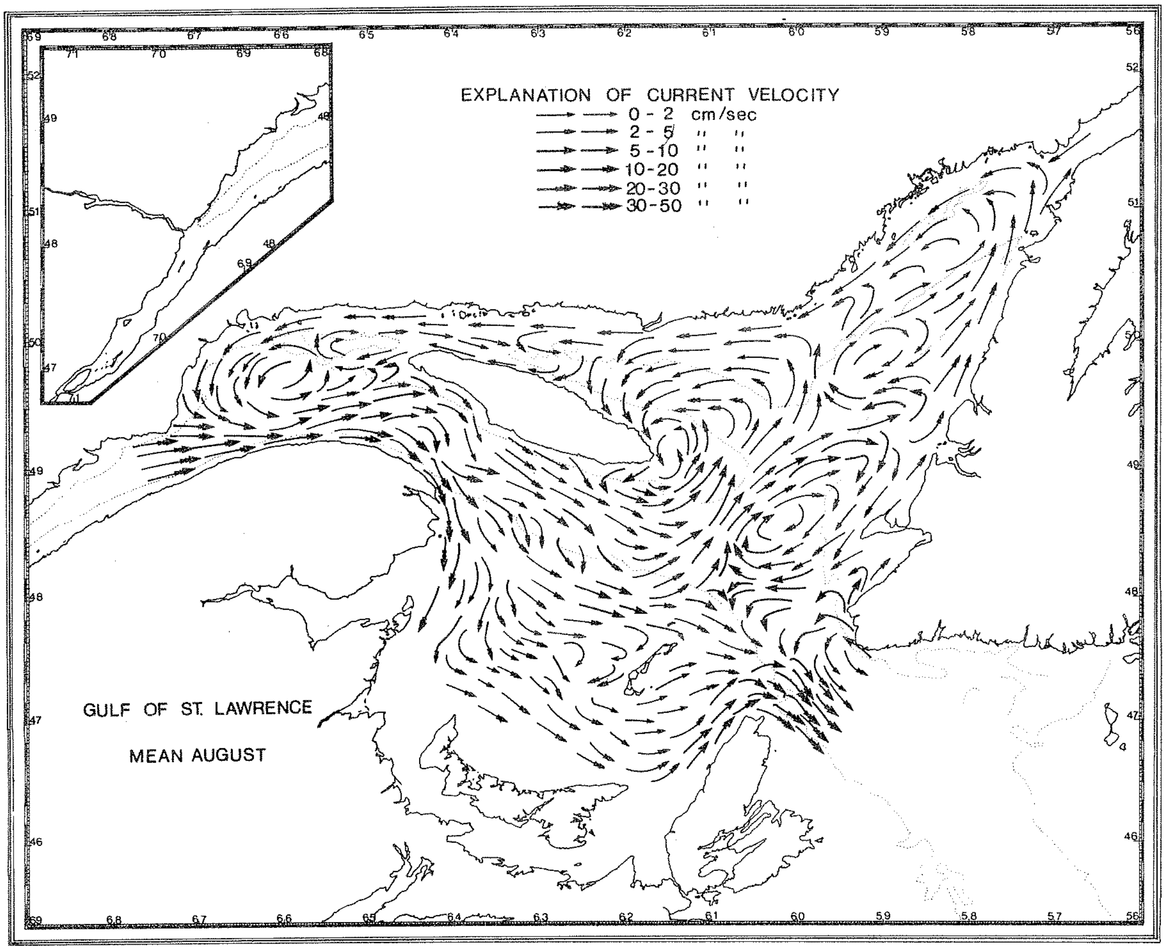


Fig. 9. Field of the surface geostrophic currents in the Gulf of St. Lawrence during August (from El Sabh, 1975)

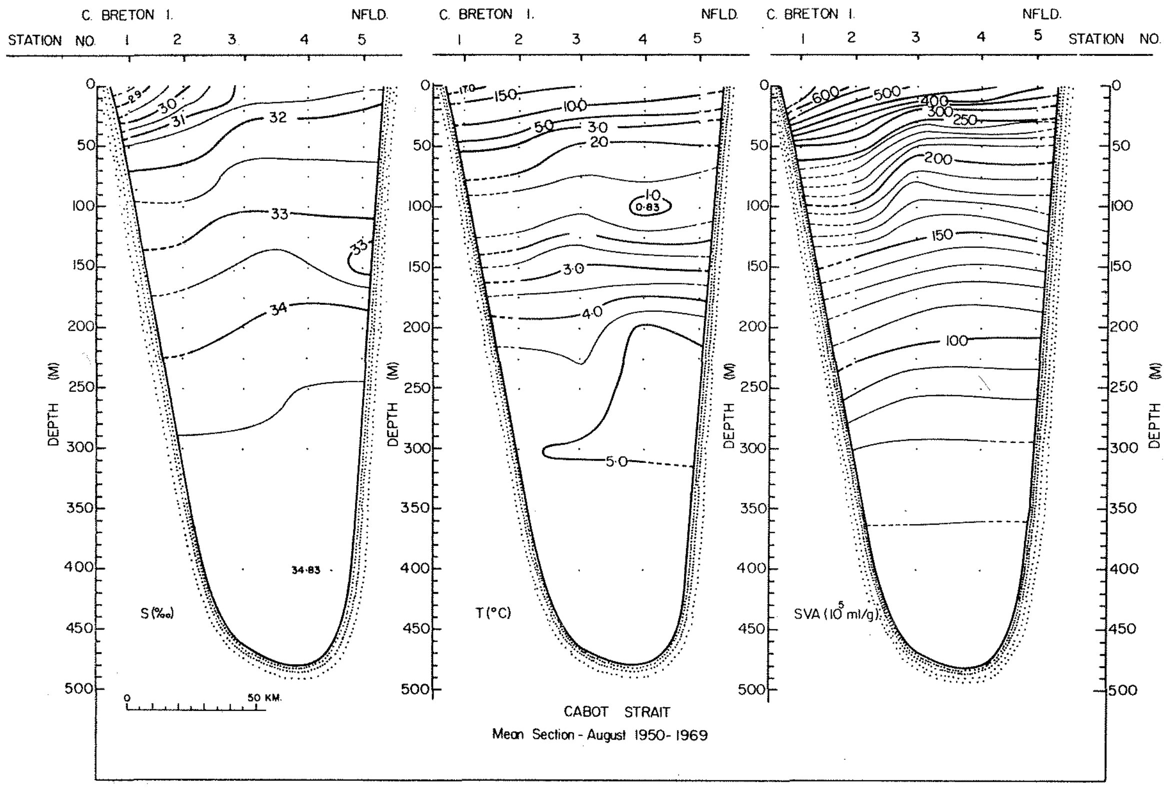


Fig. 10. Vertical distribution of salinity, temperature and specific volume anomaly for the mean section of Cabot Strait in August (from El Sabh, 1975)

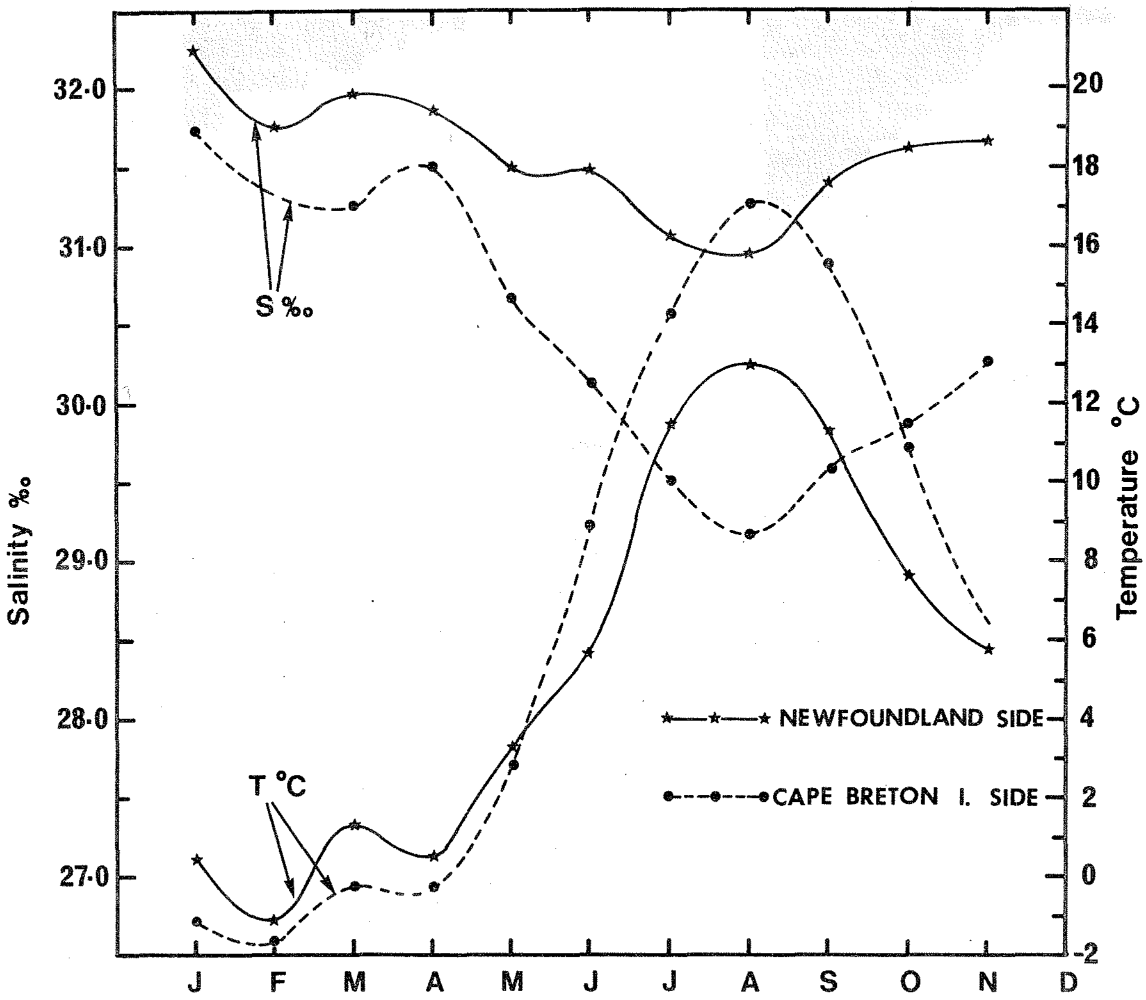


Fig. 11. Average monthly variations of the surface salinity and temperature in Cabot Strait (from El Sabh, 1975)

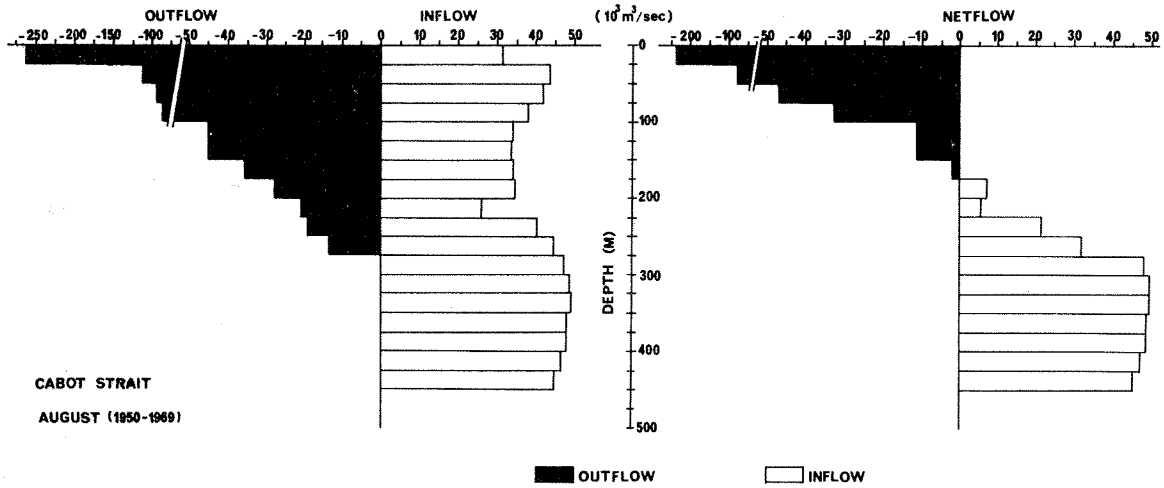


Fig. 12. Vertical variation in horizontal flow through Cabot Strait section, August (1950-1969), (from El Sabh, 1975)

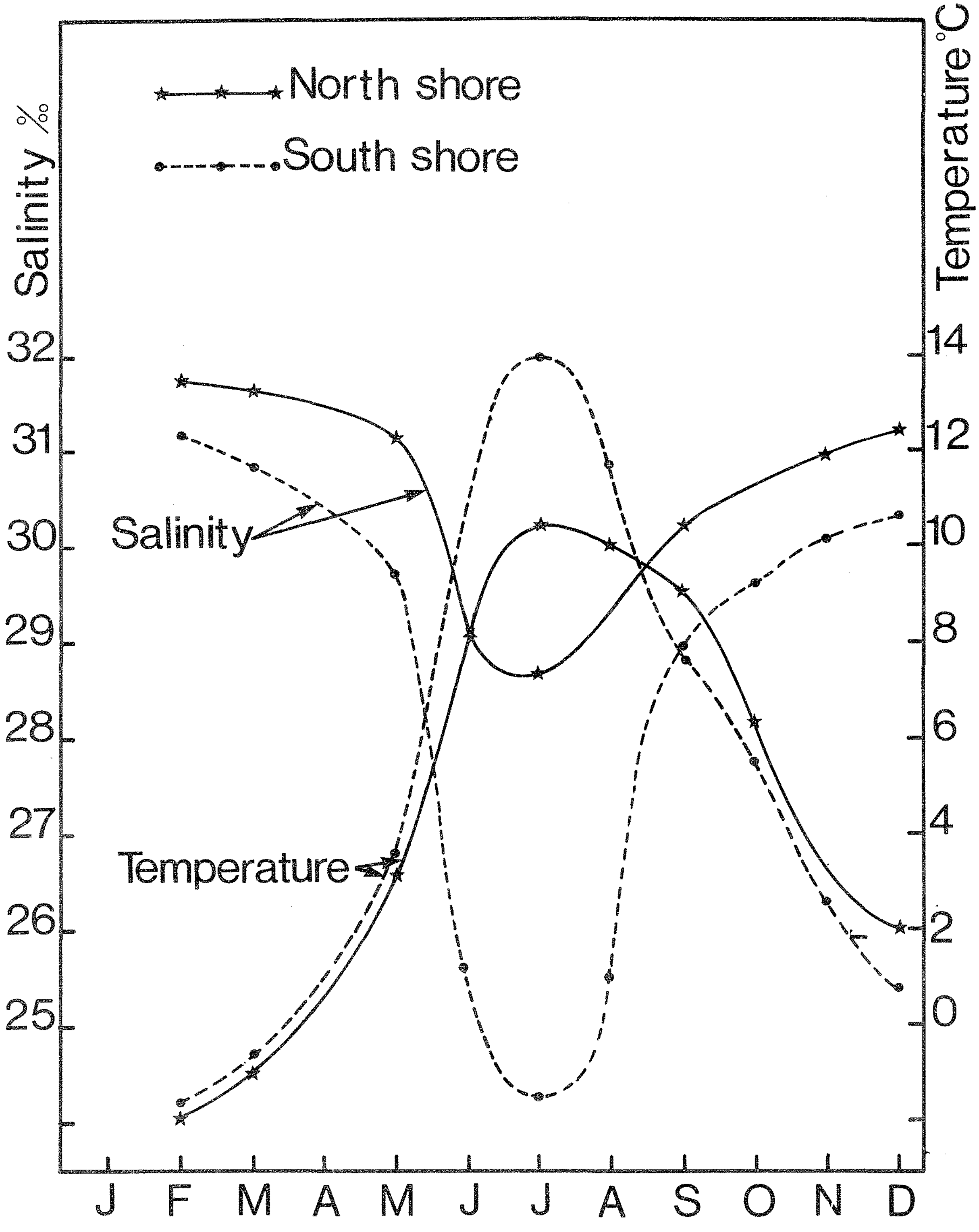


Fig. 13. Average monthly variations of the surface salinity and temperature in the St. Lawrence Estuary entrance (from El Sabh, 1975)

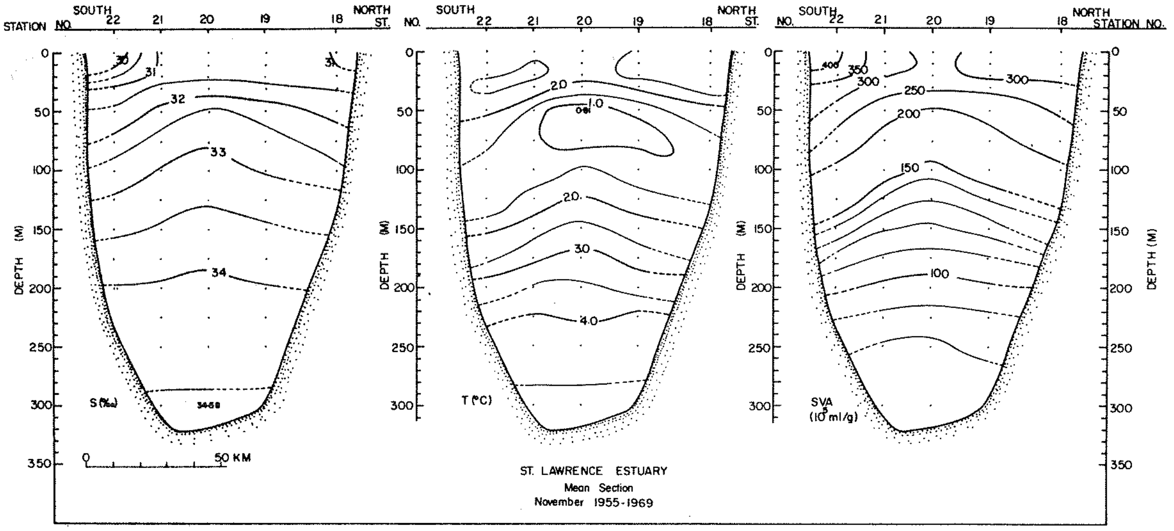


Fig. 14. Vertical distribution of salinity, temperature and specific volume anomaly for the mean section of St. Lawrence Estuary in November (1955-1969), (from El Sabh, 1975)

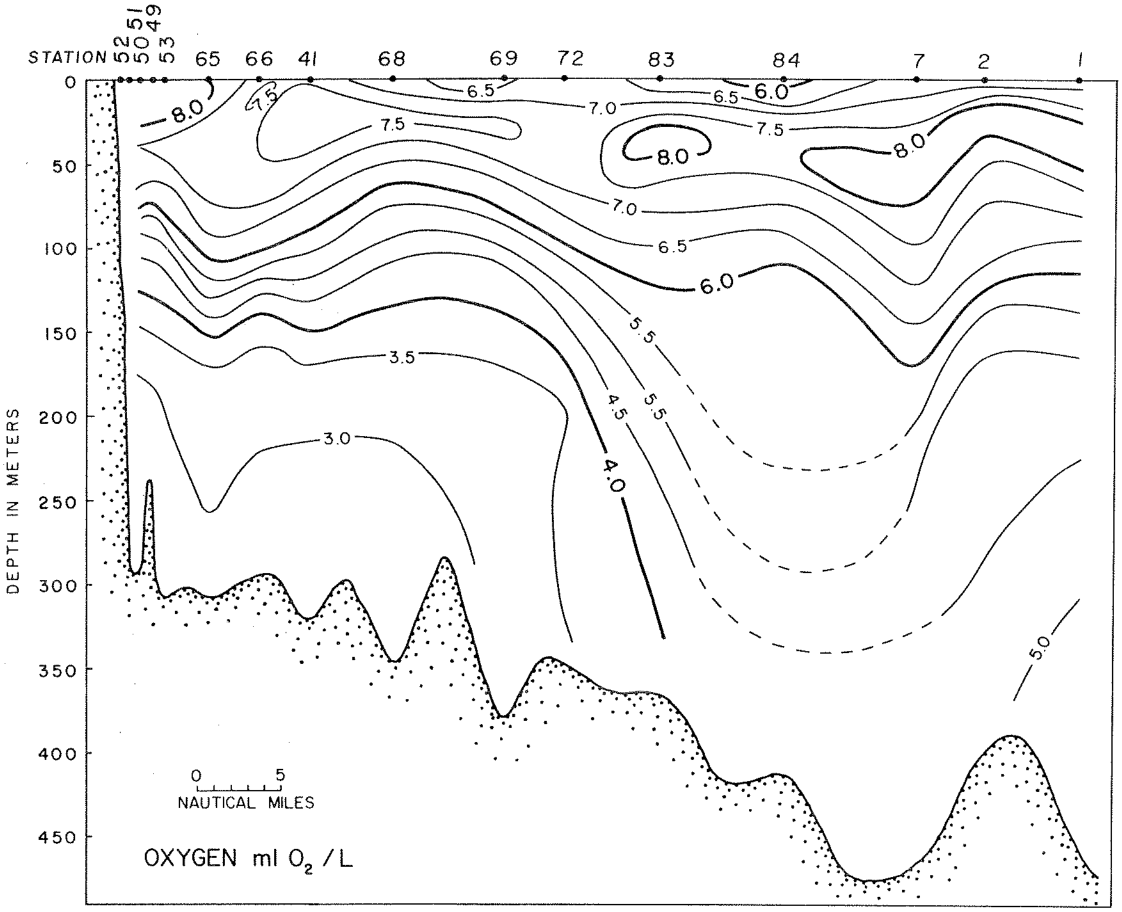


Fig. 15. Oxygen distribution on a section along the Laurentian Trough (from Levy and Walton, 1972)

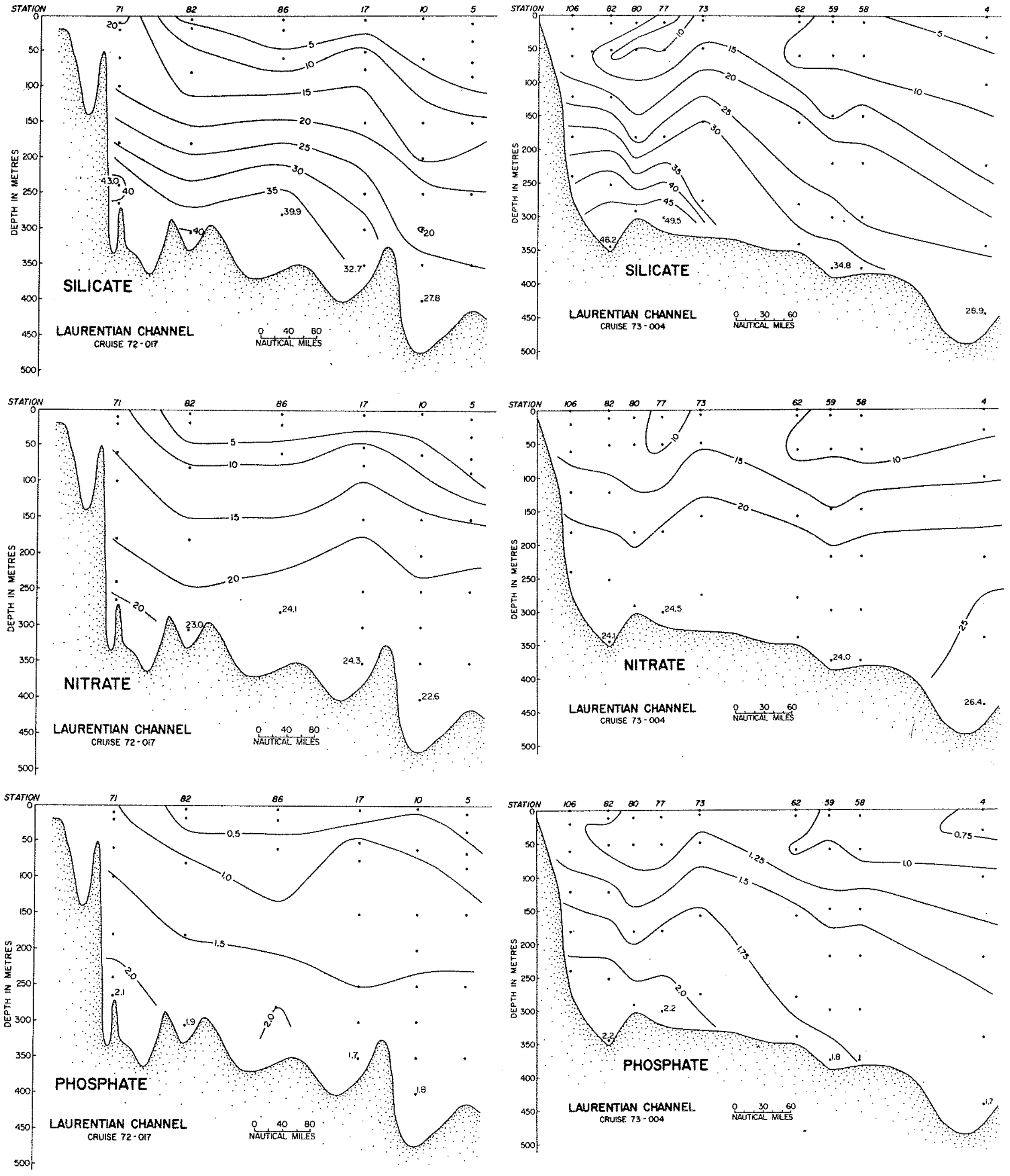


Fig. 16. Phosphate, silicate and nitrate distribution on a section along the Laurentian Trough
(a) in summer (cruise 72-017)
(b) in winter (cruise 73-004)
(from Coote and Hiltz, 1975)

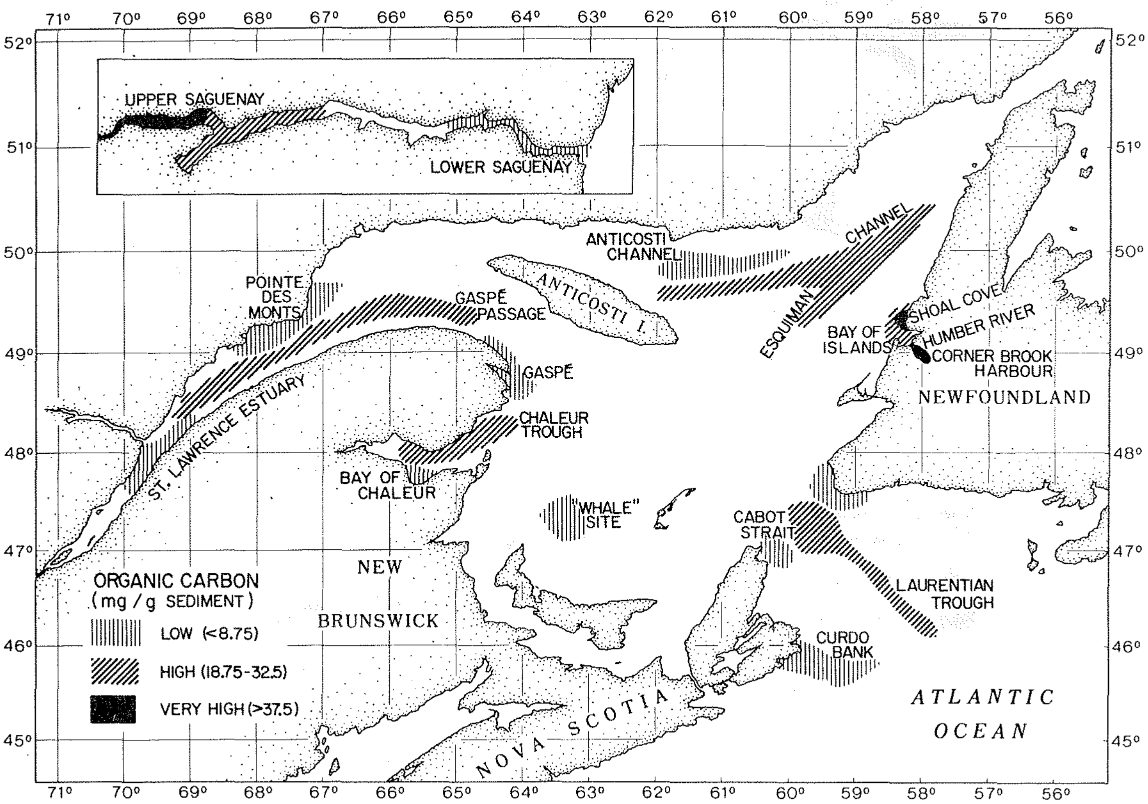


Fig. 17. Distribution of organic carbon in sediments in the Gulf of St. Lawrence (after Pocklington, 1975a)

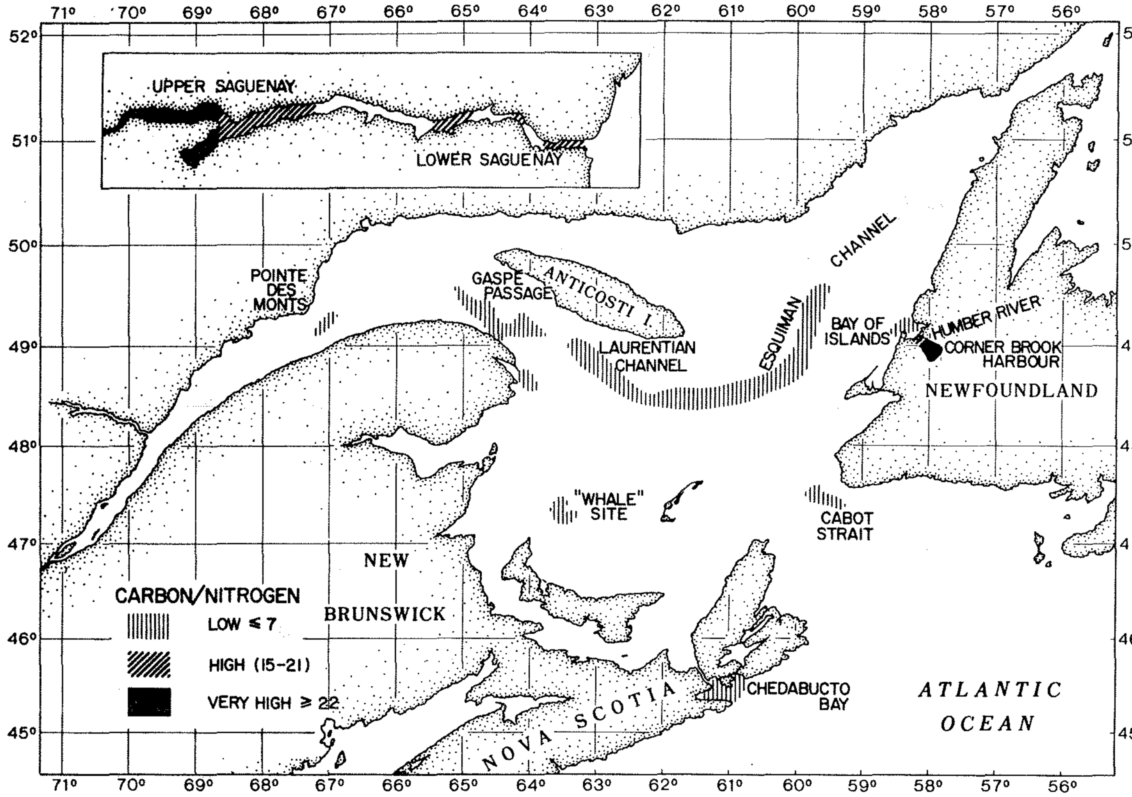


Fig. 18. Carbon/nitrogen ratio distribution in the Gulf of St. Lawrence (after Pocklington, 1975a)

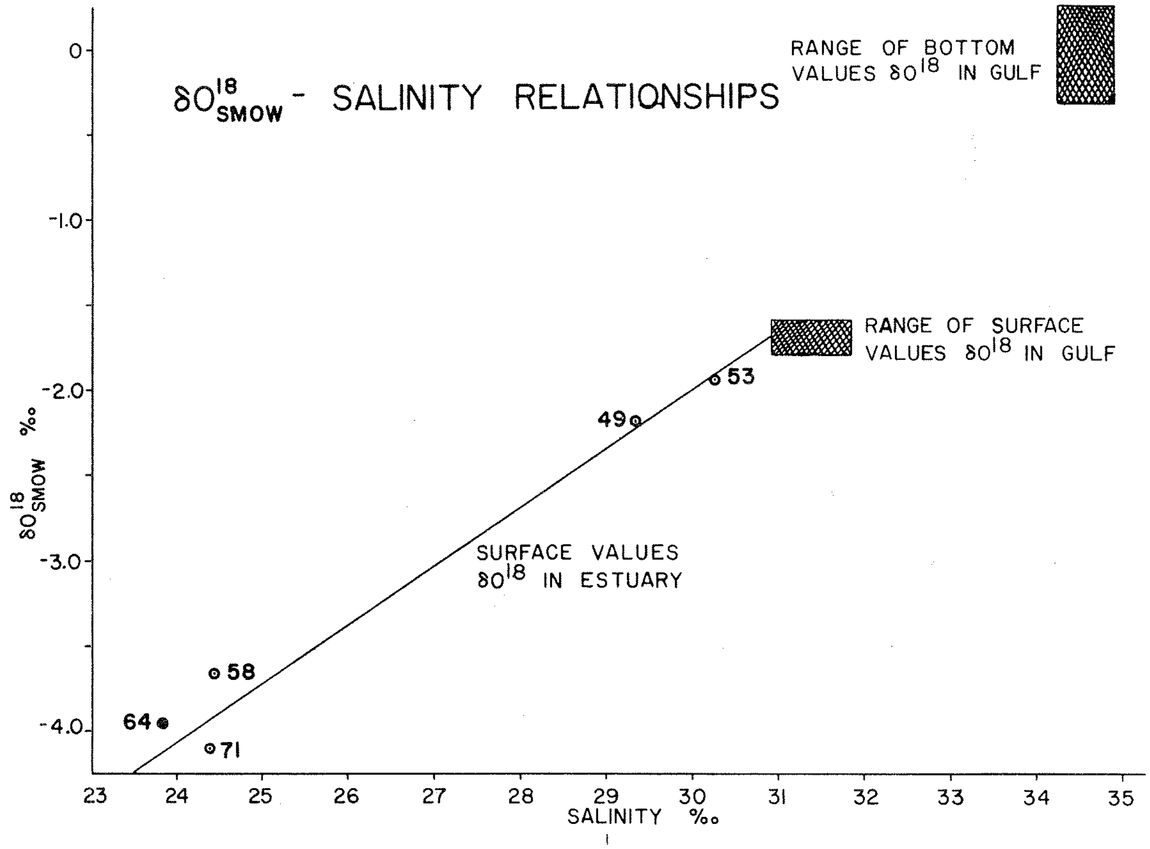


Fig. 19. Plot of delta 0^{18} versus salinity in the Estuary and Gulf of St. Lawrence (from Tan *et al*, 1974)

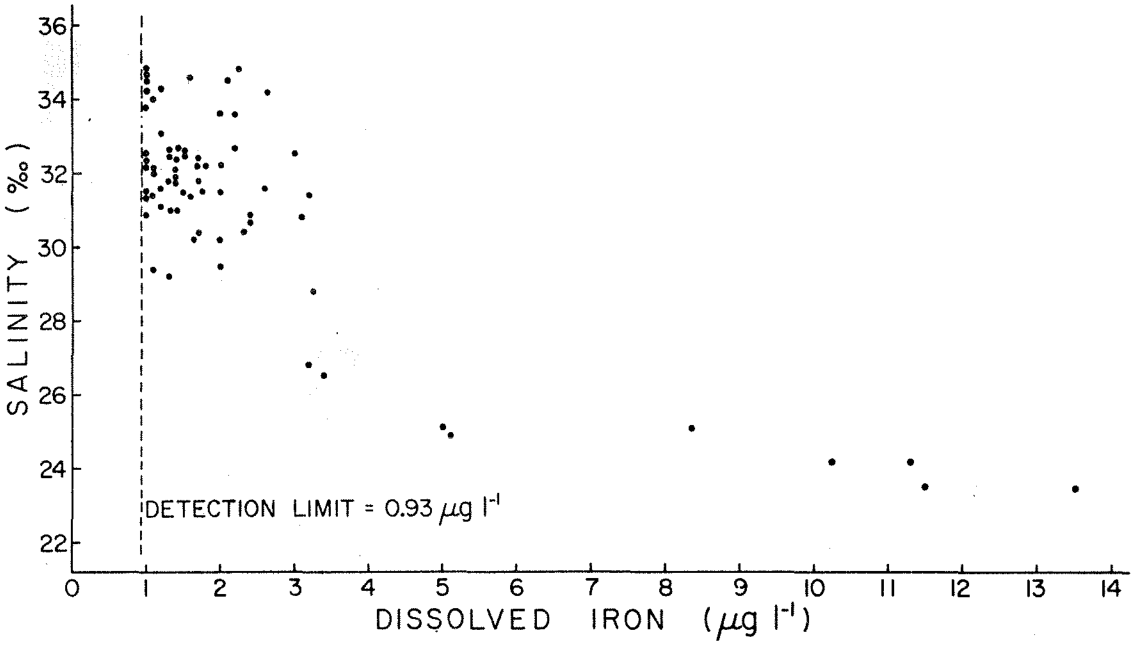


Fig. 20. Relationship between dissolved iron and salinity in the Gulf of St. Lawrence (from Bewers *et al*, 1974)

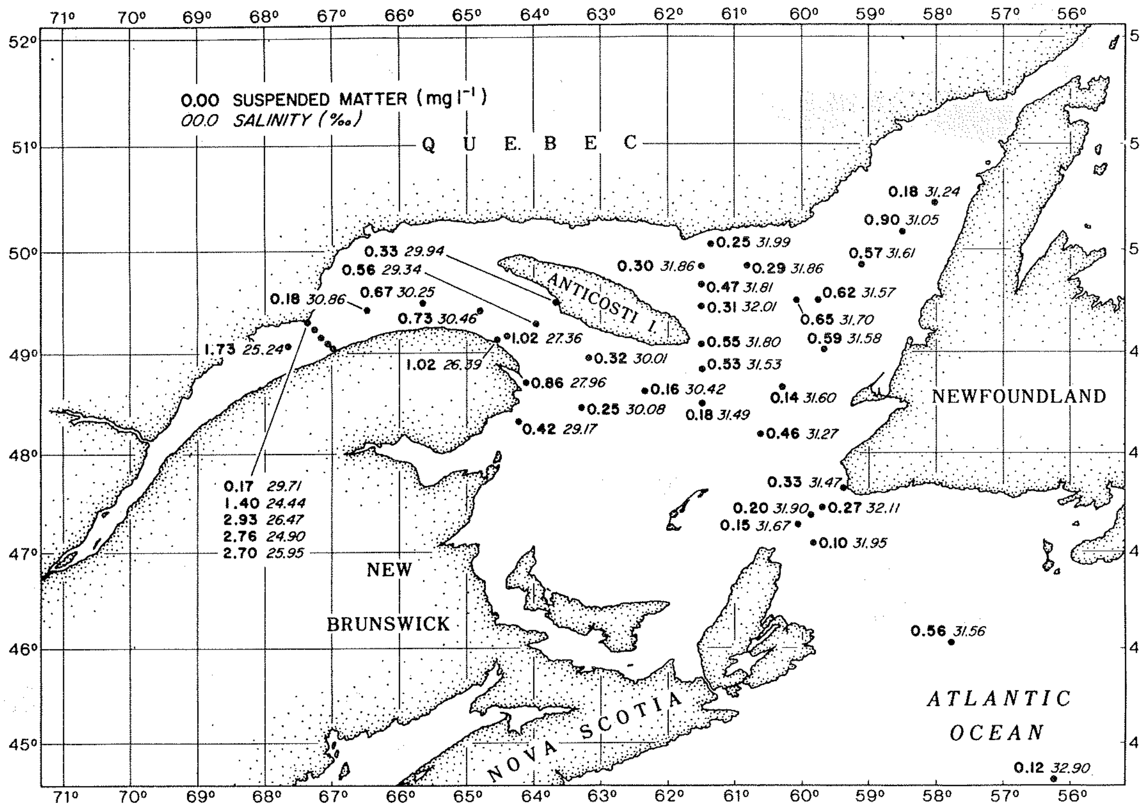


Fig. 21. Surface distribution of suspended particulate matter and salinity in the Gulf of St. Lawrence (from Sundby, 1974)

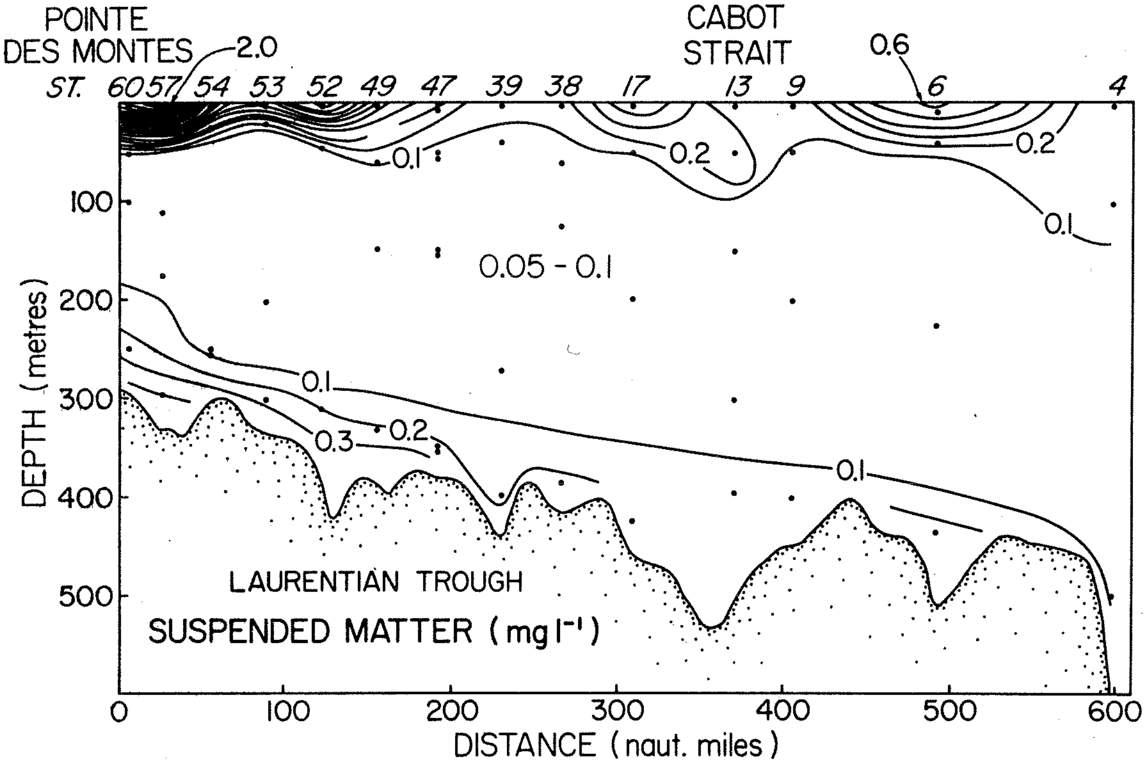


Fig. 22. Distribution of the suspended particulate matter on a section along the Laurentian Trough (from Sundby, 1974)

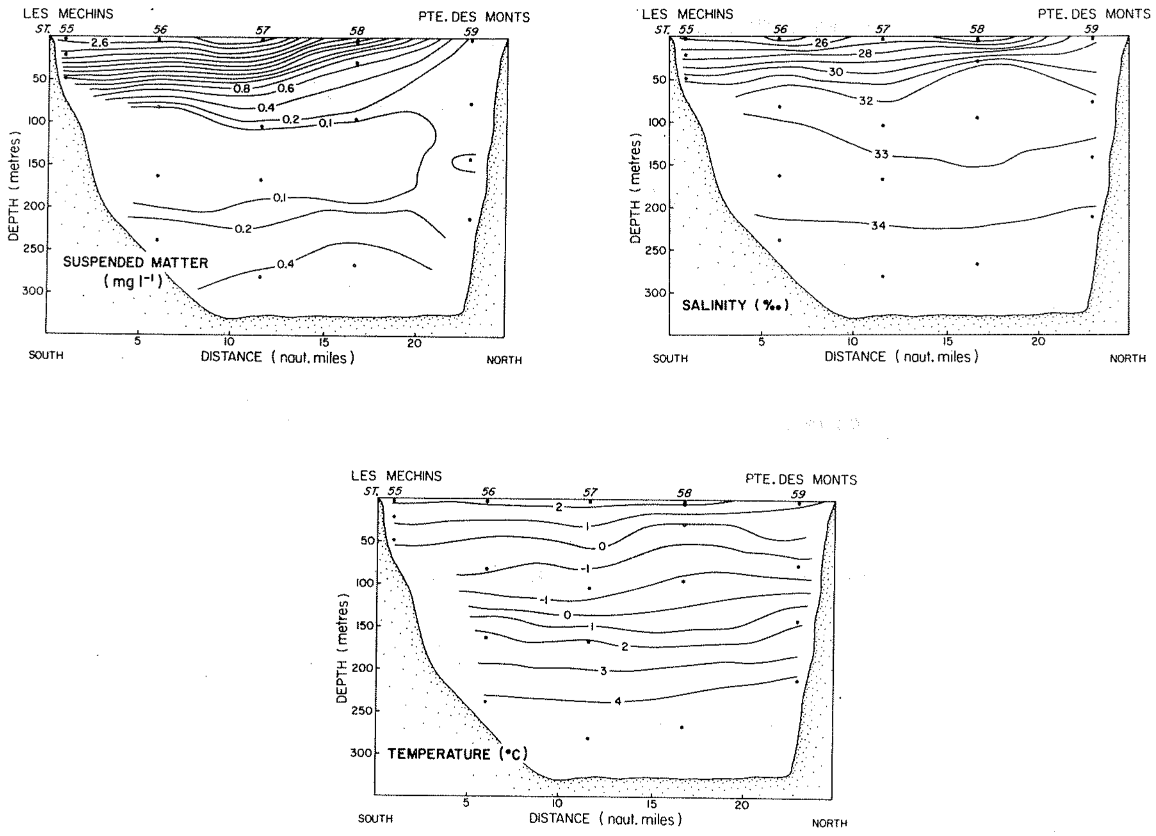


Fig. 23. Vertical distribution of suspended particulate matter, temperature and salinity across the Laurentian Channel at Pointe des Monts (from Sundby, 1974)

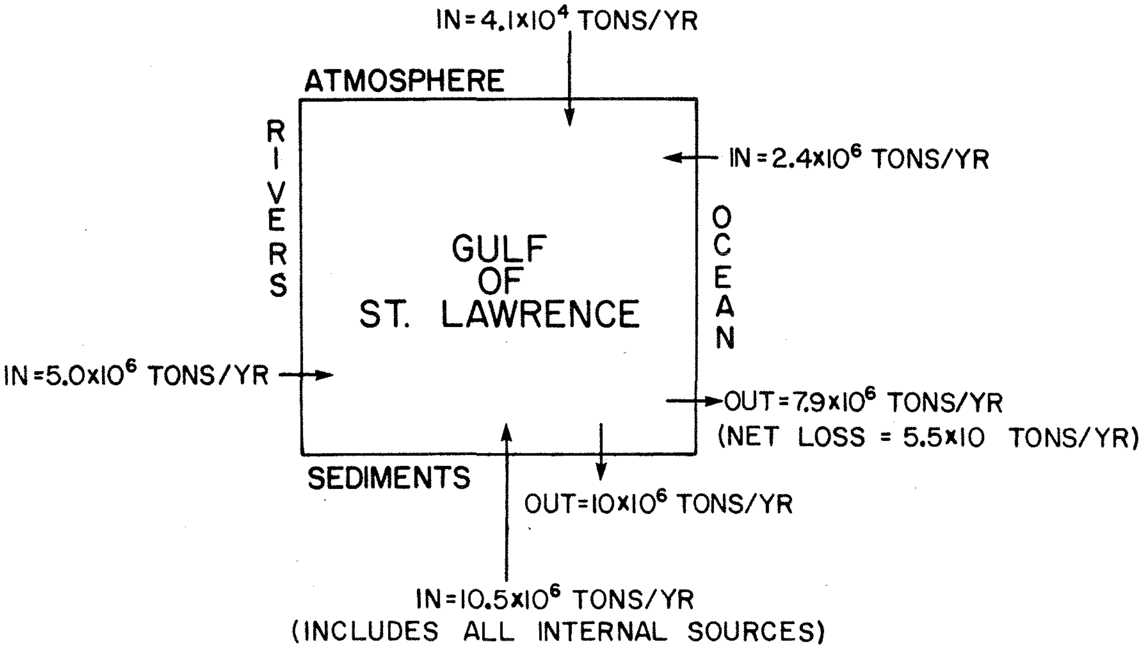


Fig. 24. Budget of suspended particulate matter in the Gulf of St. Lawrence (from Sundby, 1974)

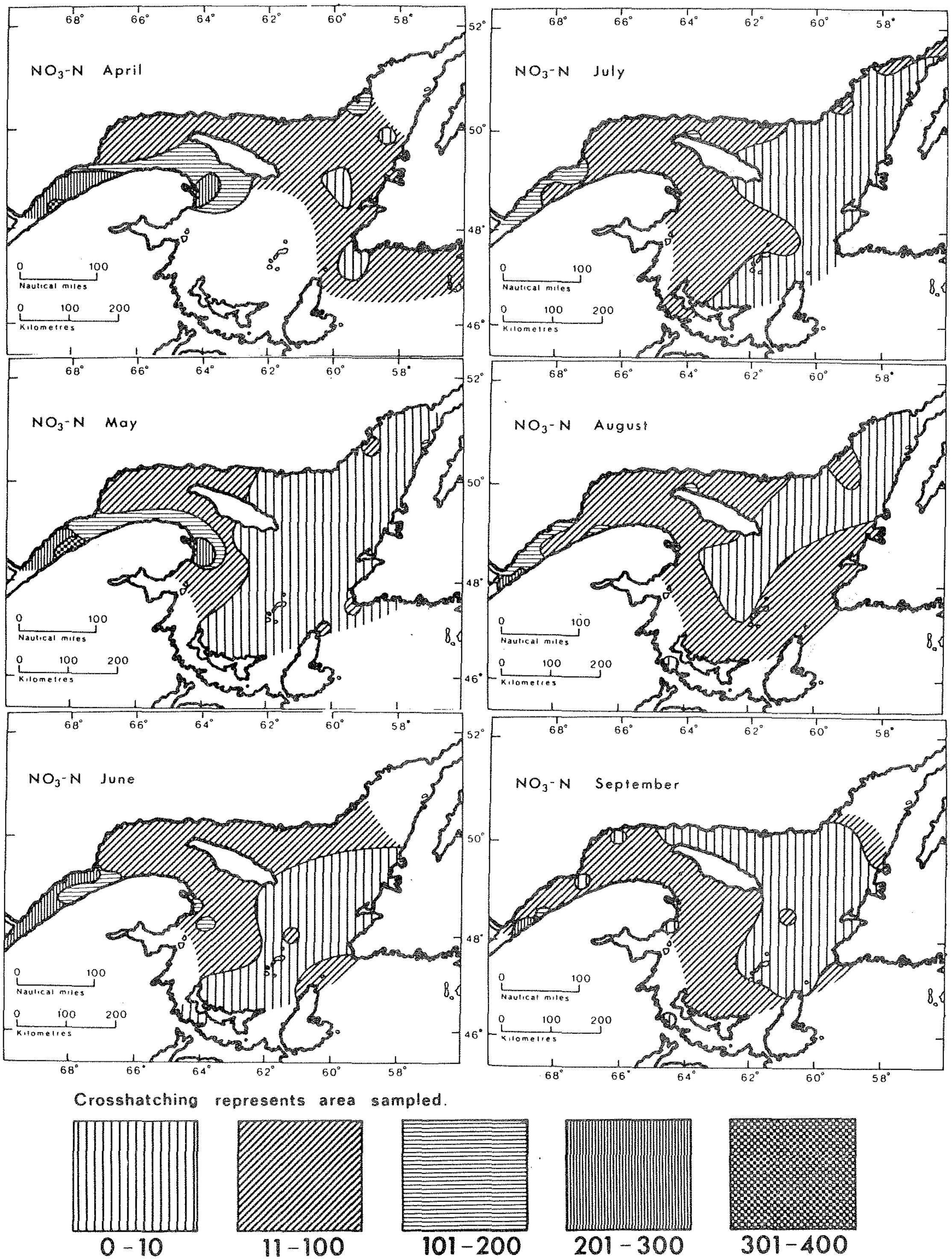


Fig. 25. Average integrated concentration of nitrate, mg at/m^2, 0-25 m, April-September 1969-72. (from Steven, 1974)

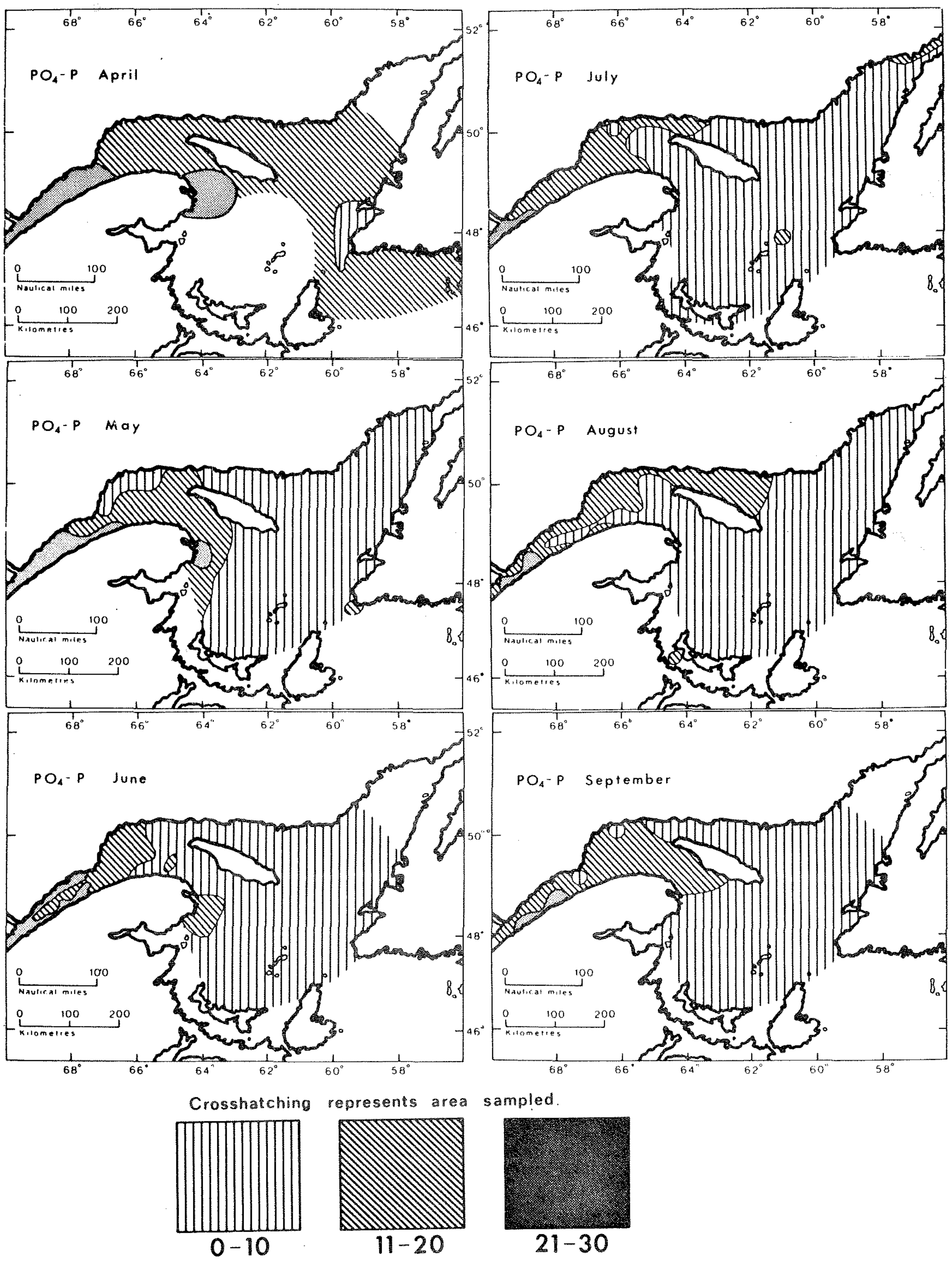


Fig. 26. Average integrated concentration of phosphate, mg at/m^2, 0-25 m, April-September 1969-72. (from Steven, 1974)

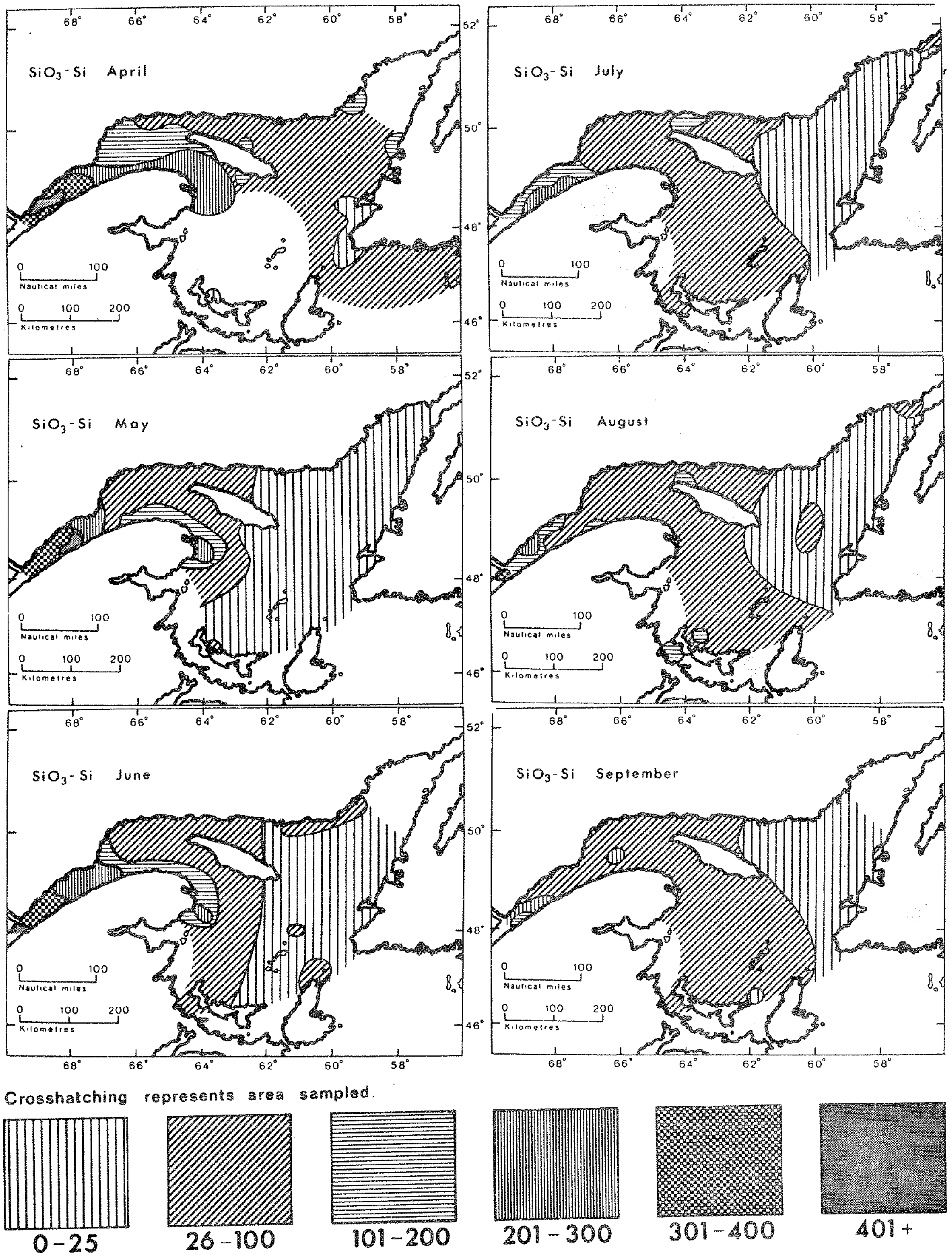


Fig. 27. Average integrated concentration of silicate, mg at/m^2, 0-25 m, April-September 1969-72. (from Steven, 1974)

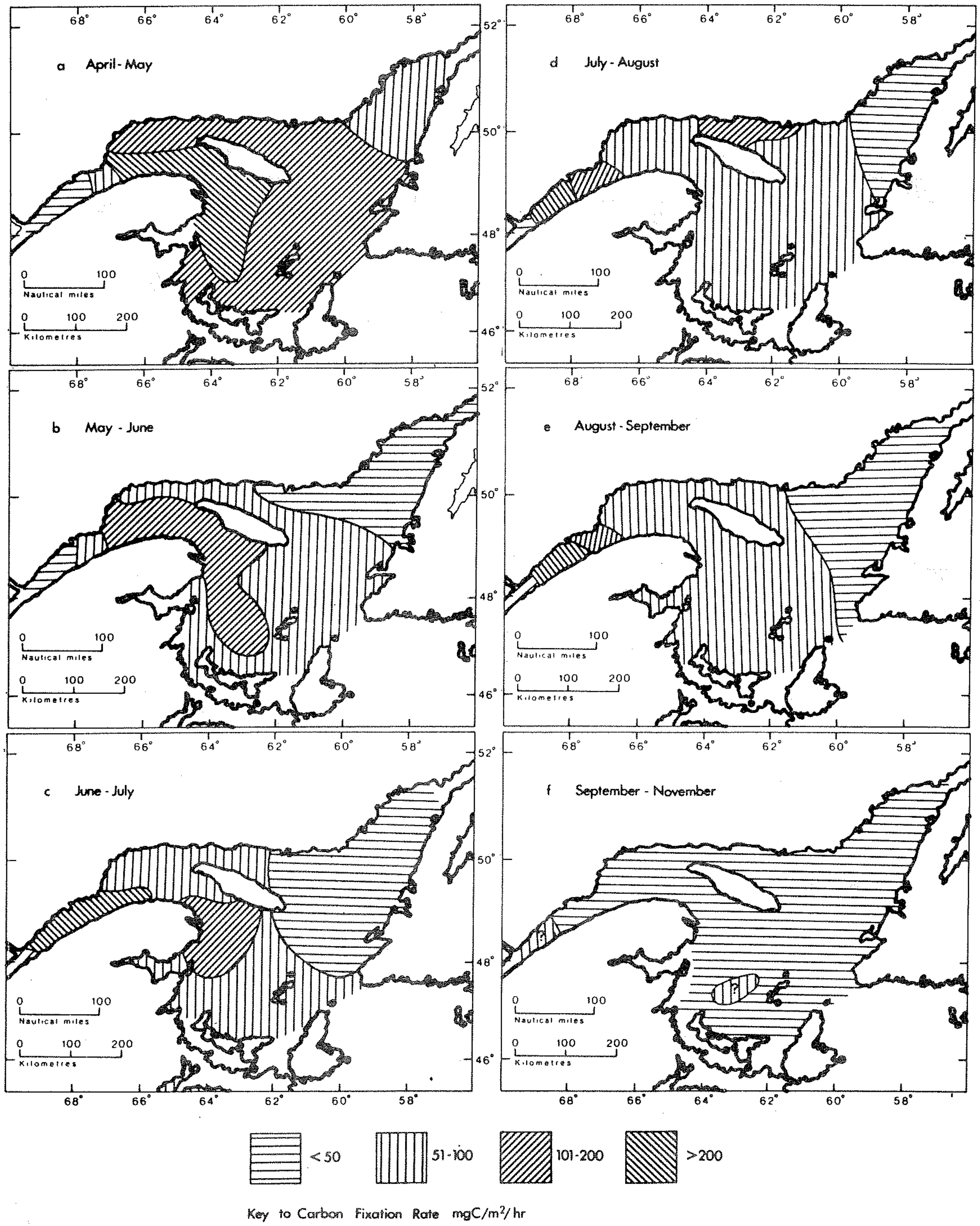


Fig. 28. Average carbon fixation rates for 30 day periods from mid-April to mid-September (a-e) and for September to November (f), 1969-72. (from Steven, 1974)

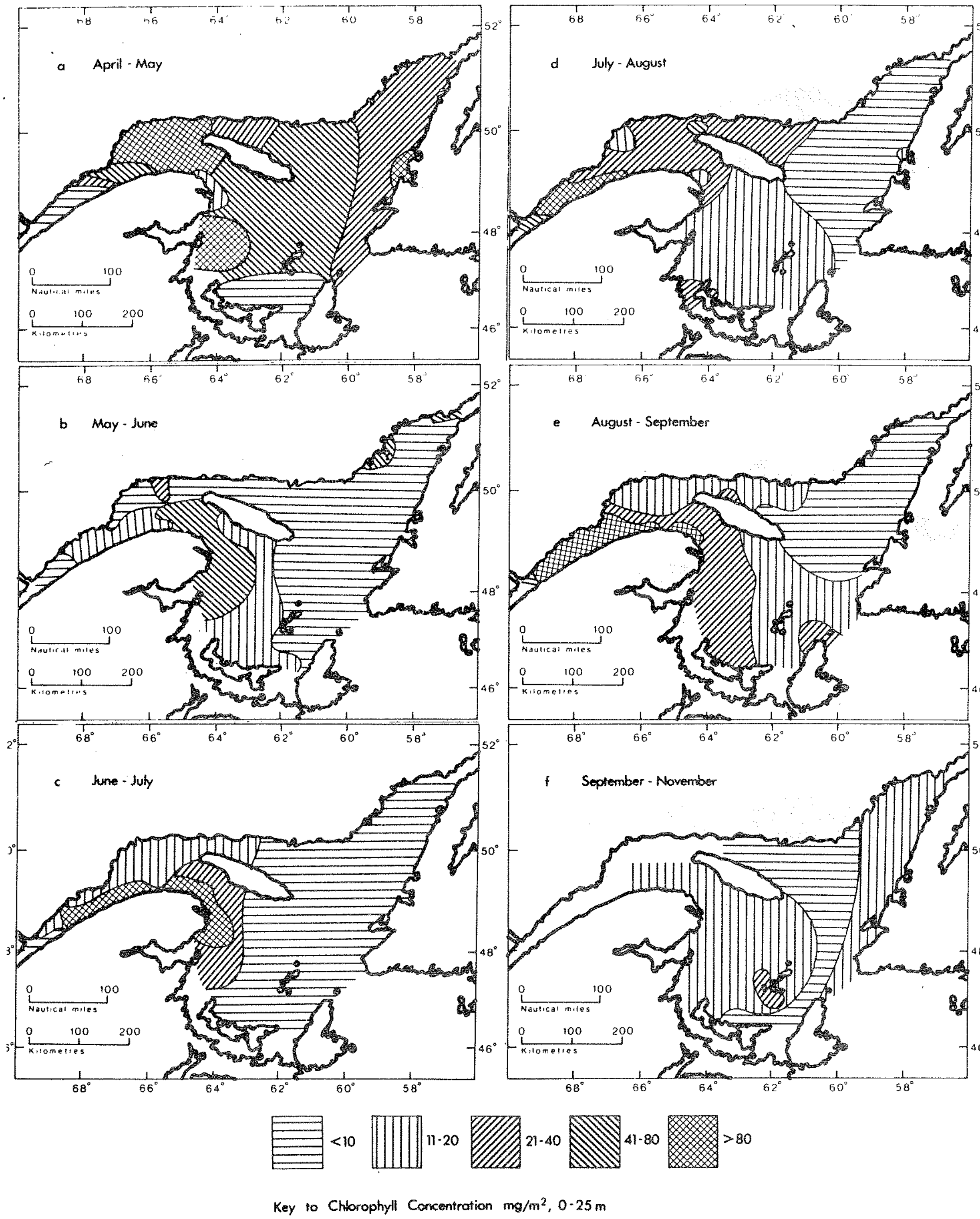


Fig. 29. Average integrated chlorophyll concentration, 0-25 m, for 30 day periods from mid-April to mid-September (a-e) and mid-September to November (f).
(from Steven, 1974)

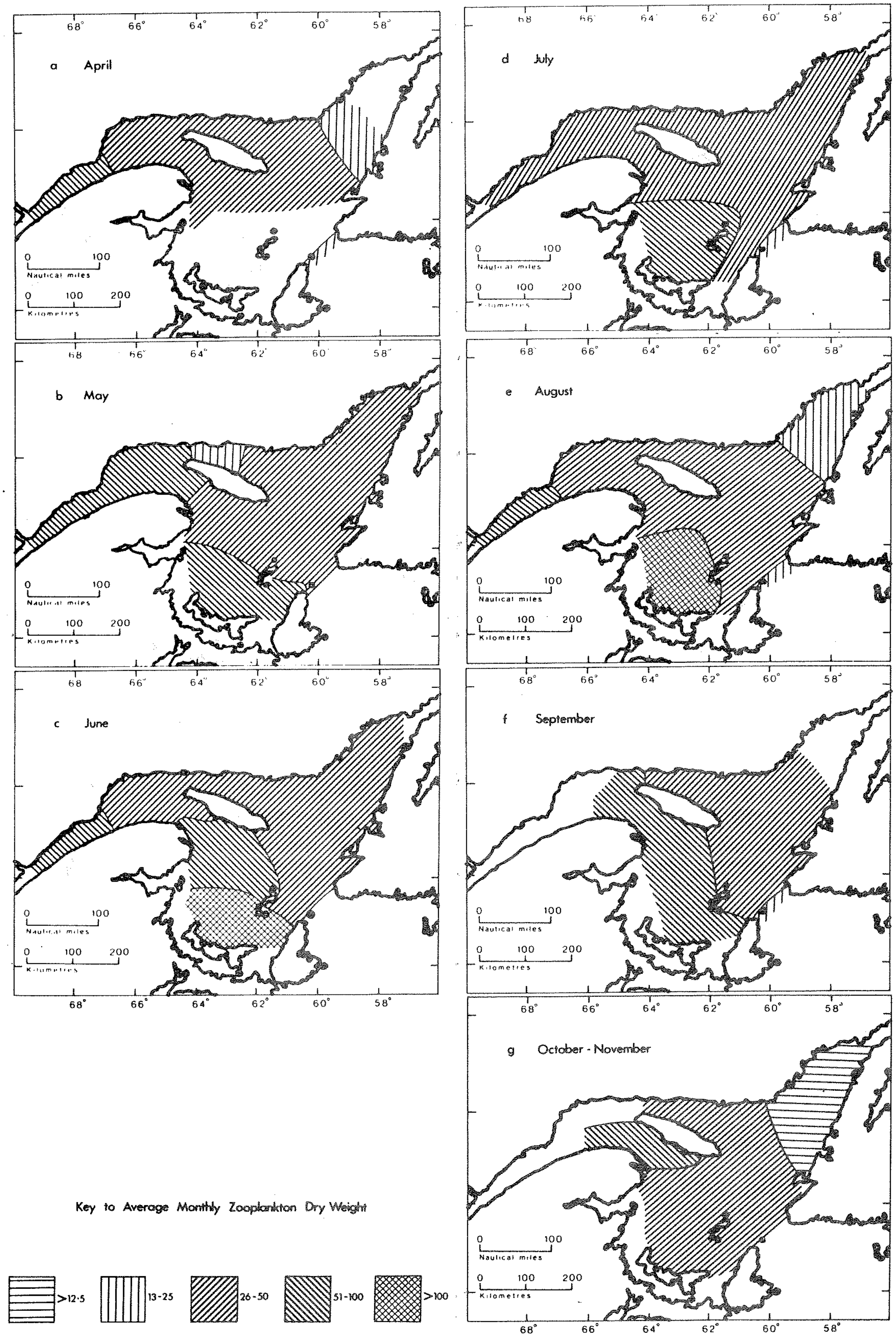


Fig. 30. Average monthly zooplankton dry weight, mg/m^3, April to September (a-f) and October-November (g), 1969-72. (from Steven, 1974)

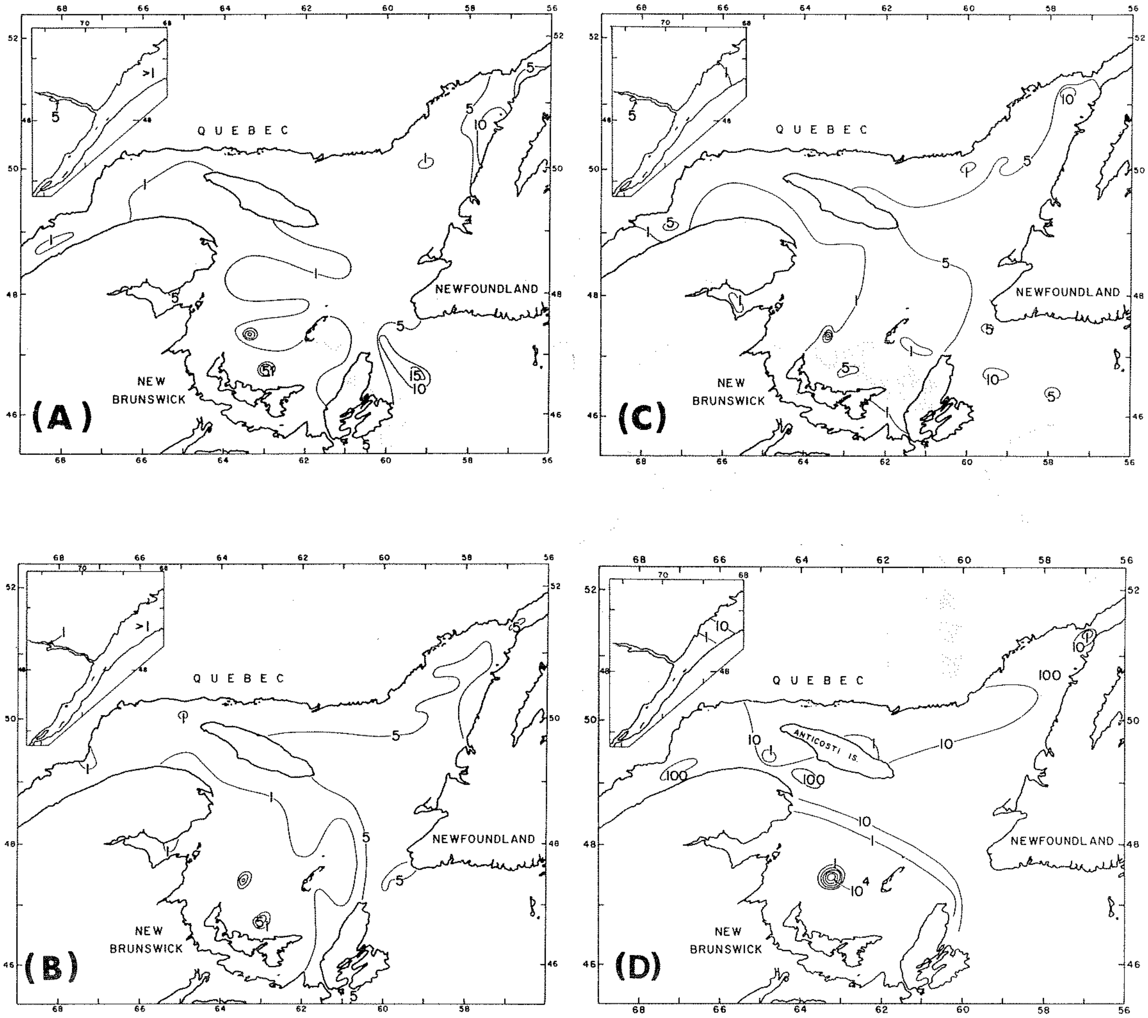


Fig. 31. Distribution (μg/liter) of petroleum residues in dissolved forms at the surface (A), mid-depth (B), and bottom (C) in the Gulf of St. Lawrence and of particulate and "fresh" petroleum residues ($\mu g/m^2$) floating on the surface (D) July 12-August 8, 1971 (from Levy and Walton, 1973)

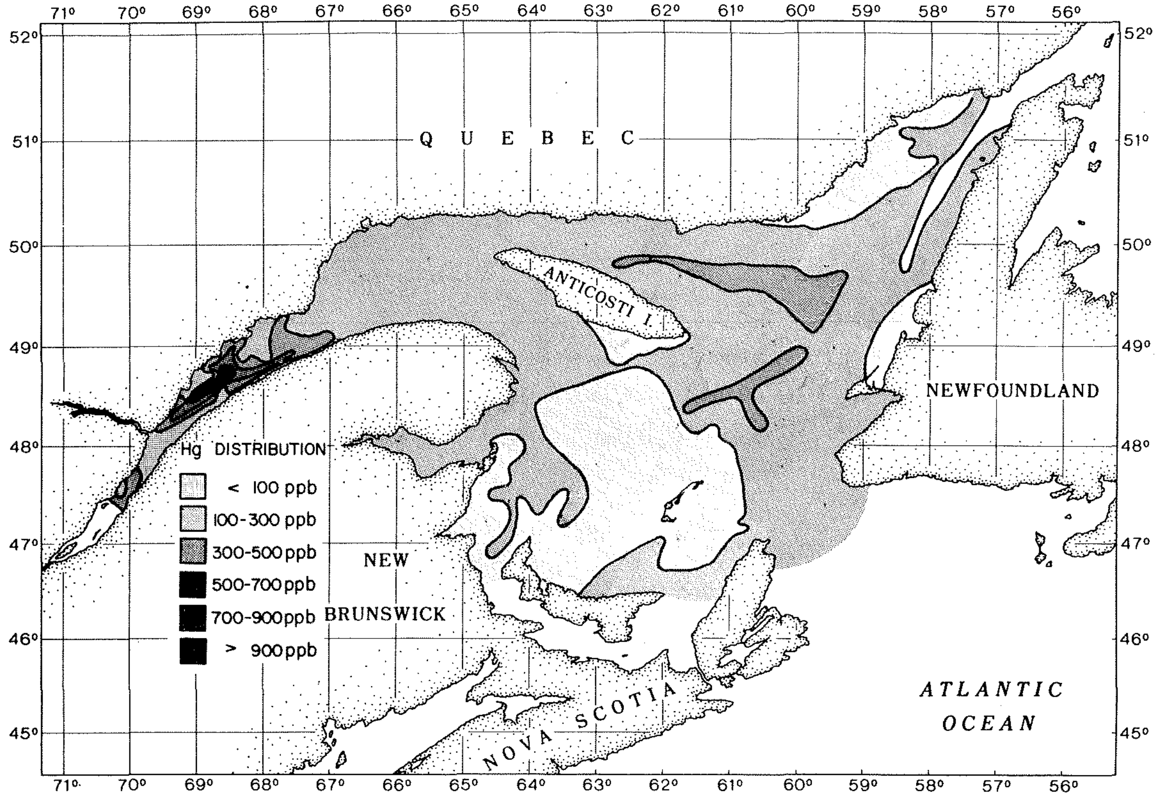


Fig. 32. Distribution of mercury in the sediments of the Gulf of St. Lawrence (from Loring, 1975)

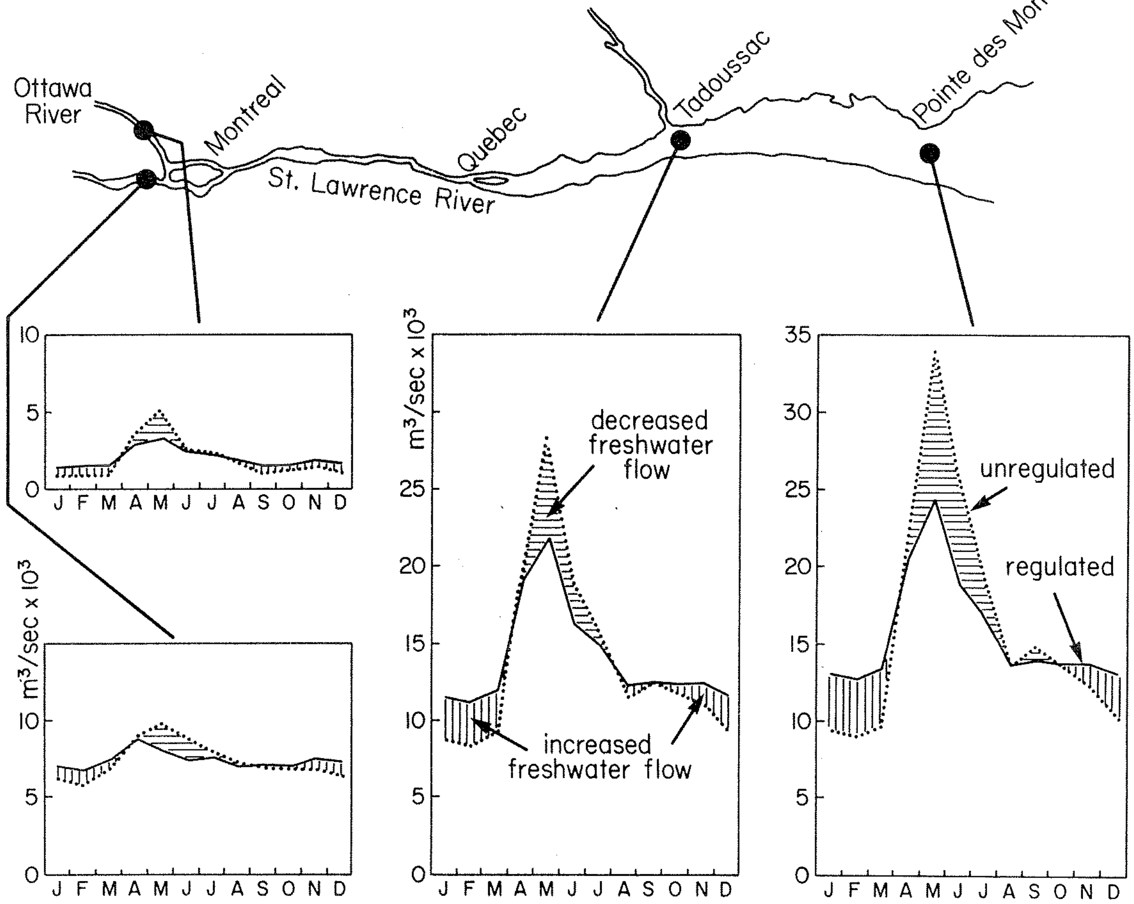


Fig. 33. Regulated freshwater flow in St. Lawrence System (1970) (from Neu, 1973)