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LAKE ONTARIO WATER CHEMISTRY ATLAS

by

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EXECUTIVE SUMMARY

Lake Ontario was observed by analytical chemistry methods since 1966. The data are, in large part, displayed and interpreted in this atlas. Three structural features, thermal bar (spring), intermittent upwelling (summer), and a sub-surface chlorophyll maximum (July), required a detailed sampling program for trophic assessment. The lake's recent recovery from eutrophication is a major success story in environmental control. Phosphorus levels in the lake are now near the target. Among four trophic indicators, only particulate organic carbon showed a decline like phosphorus, maybe because zooplankton biomass was significant. Increased nitrogen-to-phosphorus ratios, due to excess nitrate and decreased phosphorus, will probably prevent the lake from having noxious blue-green algal types. The governments and the public should be satisfied with their choice of controlling phosphorus loadings, and control should definitely continue while the human population still rises.

"We are on the threshold of a very major
success story in environmental control,
the rehabilitation of Lakes Erie and
Ontario."

- J.P. Bruce, 1972.

For my dear wife, Carmelita, and my
daughters, Laura and Susan.

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ABSTRACT

The main content of this atlas is a broad assessment of the results of phosphorus loading reduction in the 1970's, including the in-lake phosphorus concentration reduction, but also trends of some other indicators of recovery from eutrophication. The summer Secchi-depths and summer oxygen depletion rates were fairly stable in the 1970's, whereas they would have worsened without phosphorus control. Particulate organic carbon in offshore surface waters during August/September declined steadily by 20% from 1975 to 1981.

Also illustrated are the chemical/biological aspects of the springtime thermal bar, and lakewide upwelling/downwelling in response to winds in summer.

In July of 1972 there was a prominent lakewide chlorophyll maximum at about 10 metres depth.

The springtime diatom crop was located near the lake-bottom in summer, as indicated by abundant particulate organic matter and near-bottom release of soluble reactive silica.

March/April (nitrate + nitrite) had steadily increasing values, from 215 $\mu\text{g N/L}$ in 1968 to 340 $\mu\text{g N/L}$ in 1981. There was a

residual level of (nitrate + nitrite) in surface waters during late summer in the later years, amounting to about 100 $\mu\text{g N/L}$, which, along with decreased phosphorus and increased N:P ratios, means that troublesome blue-green algal blooms and scums will not occur.

In summary, the phosphorus control program and a lucky increase of soluble reactive nitrogen have resulted in very good metabolic conditions in Lake Ontario, with moderate phosphorus and plankton contents, and prevention of troublesome plankton blooms, and excellent oxygen conditions too. It is strongly recommended that the phosphorus loading control program for Lake Ontario and upstream Lake Erie be continued, to maintain the presently-ideal trophic conditions in Lake Ontario.

PART 1. INTRODUCTION

Lake Ontario is located at the downstream end of the Great Lakes chain, and receives the waters of Lake Erie as well as the runoff from of its own basin. The growing human population (Figure 1) uses Lake Ontario waters for drinking-water supply, industrial uses, fishing, and recreation. In recent decades the quality of the waters of Lake Ontario has deteriorated from the increasing human influences. During the 1960's and 1970's, the main perceived and visible problem was an increasing eutrophication, with increased abundance of pelagic phytoplankton, and foul beaches due to the shore alga Cladophora. Eutrophication came under some control in the late 1970's. The continuing remedial measure of phosphorus loading reduction and adjustment to an ideal value is being accomplished by an early shift to household detergents low in phosphorus, and later by phosphorus removal at municipal sewage treatment facilities. As will be shown, these phosphorus loading control measures are producing the desired eutrophication status of Lake Ontario in the 1980's. The related scientific information on nutrients in the main basin of Lake Ontario forms the major part of this atlas.

While there has been success with phosphorus loading control and thereby the adjustment of Lake Ontario's basic productivity, now in the 1980's there is a new problem to be faced: the contamination

of fish, especially large fish, and perhaps also the drinking-water, with trace chemical compounds, introduced by industries, agriculture, and even drinking-water treatment, and recently studied in the lake by the sensitive instruments of modern analytical chemistry (Allan, R.J. et al, 1983)¹. Except for a brief consideration of some trace-metals data, the trace poisons in Lake Ontario's waters and biota are not considered in the present atlas.

This atlas is about nutrients. Such atlases for Lake Ontario have been published before, but they used different, more limited data bases. The present atlas gives a broad graphical representation of the lake's structure (spatial and temporal features) and trends. An atlas of the Canadian nearshore waters in springtime was recently published by the Province of Ontario: the present atlas is different in dealing with the whole lake throughout more years (Ontario Ministry of the Environment, Water Resources Branch, 1980). An atlas by E.R. Allen (1977) considered some of the scientific literature on the lake but was not an attempt to display a new and large data base as is the present effort.

Lake-wide measurements of water quality of Lake Ontario, with emphasis on plant nutrients, phytoplankton abundance, and

¹ Complete references are located at the end of this atlas.

dissolved oxygen, began in 1966, and continue to be carried out by the Canadian Federal Government's "Canada Centre for Inland Waters" situated at the west end of Lake Ontario, inside Hamilton Harbour and in the city of Burlington. Among many other functions, the Centre uses oceanographic sized ships to carry out water quality surveys of the main basin and the northeast outlet area of Lake Ontario, at approximately one month intervals (data inventory: Kwiatkowski, R.E., and M.A.T. Neilson, 1983). The present atlas displays a large part of the data from those surveys, in a variety of kinds of plots, and interprets the distributions in a descriptive text. Graphs and text together form a new chemical geography of Lake Ontario.

Data from the surveys are stored in vaults and in a computer system, at CCIW Burlington. Any use of a distinct methodology for a measured parameter resulted in the data being given a special code number. There is a manual listing the methods for all the code numbers (CCIW, National Water Research Institute, Data Management Group, 1982, etc.). The analytical team has made a large and ongoing effort towards accuracy, precision, and consistency of data. Any data strongly believed to be wrong were discarded and do not appear in the files. Occasional high outliers may appear, sometimes due to a key-punching error. Cruise-mean values for each Lake Ontario water-mass, shown later in this atlas, have therefore been subjected to trimming of gross outliers.

The following papers describe the CCIW analytical methods: Chawla and Traversy, 1968; Traversy, 1971; Philbert, 1973; Philbert and Traversy, 1973; Strachan, 1973; Carew and Williams, 1975; Philbert, El-Kei, Blythe, and Sheikh, 1975; and Water Quality Branch, Inland Waters Directorate, Ottawa, 1983. This laboratory performed well in the ongoing interlaboratory analytical quality control program of the Great Lakes region (Aspila, White, and Clark, 1983).

For data development, the long-term set of observations of Lake Ontario's water quality was available in two forms: digital data listings by cruise, station, and depth, in "report" format, and the same information for all cruises in the main CCIW computer. The graphs containing individual values were plotted by hand, and contouring was done by hand. But in the major chapter on seasonal cycles and long-term trends (Part 2(c)), mostly the mean-values on each cruise, for particular shallow or deep offshore (= sounding > 100 m) water-masses, were used. These were trimmed mean values computed automatically and then plotted by hand. The output of the averaging program lists a number of other factors such as standard deviation, number of values, the effect of trimming of outliers, associated mean temperature, and the mean date of the data sub-set. All this would be a valuable foundation for limnological modelling research which might be stimulated by the data-displays of this atlas.

Acknowledgments are in order. A large team at the Canada Centre for Inland Waters carried out the surveys of Lake Ontario's water quality since 1966. Special thanks to: the ships' captains and crews; the Technical Operations group led by H.B. (Barrie) Macdonald; shipboard chemists led by Francis Philbert and Omar El-Kei; data managers led by John Rogalsky and Wes Nagel; and the Drafting group led by Bill Finn. I am thankful for the work of Mr. Bob Gottinger (died 1983) in a masterful piece of programming, and I thank Wes Nagel for many runs of the "Gottinger Program". Thanks also to Murray Charlton and Dr. Jan Barica for support, encouragement and critical review of this atlas, and to Dr. D.R.S. Lean for valuable advice.

Lake Ontario is a large lake (Figure 2): its length is 309 meters or 192 statute miles, its mean width is 60 kilometers or 37 statute miles, it has a mean depth of 86 metres or 280 feet, and the ratio of its length to mean depth is 3600:1. Let us now plunge into this lake, or rather, small ocean, and find out its chemical distributions.

PART 2 (the main part):**DISTRIBUTIONS IN SPACE AND TIME, IN LAKE ONTARIO WATERS, OF A NUMBER OF CONSTITUENTS RELATED TO LAKE PRODUCTIVITY MANAGEMENT VIA PHOSPHORUS LOADING CONTROL****2(a) Spatial features plotted on spatial coordinates:****2(a)(1) Vertical profiles.**

Vertical profiles of concentration versus depth indicate the stratification or vertical structure in a simple way. Biochemical stratification develops in a temperate lake in spring and summer in the presence of thermal stratification. Stratification disappears when there is strong vertical mixing to the lake-bottom, which as we will see occurs in this lake in December/January and May/June.

Water-temperature profiles.

A thermocline, having continuous density change with depth, can be tilted by the wind stress, and can develop wave action within itself. The waves have signatures in the form of fine structure in the vertical profile.

Samples collected at a few discrete depths through a thermocline tend to miss the fine structure of the water-chemistry profiles. The investigator must often be satisfied with a modest sampling effort in order to have a sufficiently small number of chemical analyses on each survey.

Some data for Lake Ontario's temperatures at 32 stations and at different depths, in September 1972, are shown in Figure 3. At depths from 10 to 40 metres, the temperatures were variable at each depth across the lake. Above about 10 metres, there was a mixed surface layer from wind or from cooling. Below 50 metres, the temperatures were near 4°C.

Soluble reactive phosphorus profiles.

Figures 4, 5, and 6 show the vertical profiles of soluble reactive phosphorus at a mid-lake station at different times during the years 1972 and 1973. This fraction of dissolved phosphorus is the one most readily used for algal growth. The most homogeneous profiles were those of May and June (Figure 4), at a time of year when the entire water column, at this mid-lake station, was overturning or convecting while being warmed at the surface from 3°C up to 4°C. Later, during summer, the surface mixed layer became depleted of this

fraction of phosphorus (Figures 4 and 5). In mid-winter, some deep stratification occurred (Figure 6).

Total chlorophyll a profiles

There was a wide range of chlorophyll values in the upper 25 metres of Lake Ontario in summer (Figures 7 and 8). In July 1972, highest values were at about 10 metres depth (Figure 7); in September, 1972, highest values were at the lake surface (Figure 8). Such a large range of values requires that synoptic spatial distributions be shown for the upper waters, and this is done further on in this atlas. Due to this large variability, year-to-year changes and long-term trends of the phytoplankton abundance in Lake Ontario will be difficult to discern.

Nitrite profiles.

Nitrite can be produced by bacteria, as an intermediate stage of nitrification or denitrification; also nitrite can be excreted by phytoplankton. Nitrite was measured on the earliest surveys of Lake Ontario. A nitrite maximum of about 15 micrograms nitrogen per

litre, at depths near 30 metres below the lake-surface, occurred in August 1966 and August 1967 (Figures 9 and 10).

Particulate nitrogen profiles.

Vertical profiles of particulate nitrogen in July 1972 and September 1972 (Figures 11 and 12) are similar to the corresponding profiles of chlorophyll (Figures 7 and 8).

Vertical profile of dissolved oxygen in September.

The solubility of oxygen in the water at the surface of Lake Ontario varies with the water-temperature, as follows:

0.0°C	14.4 mg O ₂ /L
5.0	12.6
10.0	11.2
15.0	10.0
20.0	9.0
25.0	8.2

Usually the deviation from atmospheric equilibrium is quantified by the oxygen % saturation value:

$$\frac{\text{observed mg O}_2/\text{L}}{\text{solubility (mg O}_2/\text{L) at same temperature}} \times 100\%.$$

Another way to show departure from air-equilibrium values is to give the absolute deviations from those values:

Observed O₂ (mg/L) minus the
solubility value (mg O₂/L) at
the same temperature.

The vertical distribution of oxygen deviations at offshore stations in mid-September 1970 (Figure 13) shows small positive deviations at the surface, a minimum with negative deviations at about 30 metres, a broad maximum with slightly negative deviations from 50 to 100 metres, and below that, scattered deviations averaging about -2 mg O₂/L, or 11 mg/L oxygen concentration in 4°C water whose solubility value is 13 mg/L. Adverse effects on fishes occur below 6 or 4 mg O₂/L (see: Davis, 1975), so Lake Ontario's main basin oxygen levels are satisfactory.

Vertical profile of pH.

In Lake Ontario during September 1966, the pH ranged from 7.8 to 8.6, deep values averaged 8.1 and surface values averaged about 8.4 (Figure 14). These are similar to oceanic values. In Central Lake Erie bottom waters, the pH goes down to about 7.2 in late summer, accompanying the increase in carbon dioxide when dissolved oxygen is nearly entirely depleted. To know whether pH values in the Great Lakes are slightly depressed by "acid rain", e.g., in Lake Superior, requires further advanced study.

2(a)(ii) Spatial features of Lake Ontario: the "thermal bar"Description of the thermal bar phenomenon.

Fresh water has maximum density at 4°C. In a very large lake, this results in a special phenomenon during the springtime warming period. Water colder than 4°C, when warmed at the surface, circulates vertically because the warmed upper part is heaviest. But water warmer than 4°C, warmed at the surface, develops stratification because the warmed upper part becomes more buoyant. In a very wide Great Lake in springtime, there is an offshore core of cold unstratified water convecting vertically, and a nearshore ring of warmer stratified water. At the lake-surface the 4°C isotherm gradually

contracts towards the deepest part of the lake, and when the entire lake-surface becomes warmer than 4°C , very late in the spring, a lake-wide thermocline forms rapidly. In Lake Ontario, the date of this transition is usually about June 20.

The thermal bar phenomenon influences nutrients and phytoplankton in the Great Lakes mainly by influencing the light regime of the upper waters. In the nearshore stratified area, the mixing-depth is small, light conditions are good, and plant production occurs. In the offshore part, the mixed surface layer has a thickness of 100 metres or more, its average light conditions are poor, and there the plant production per unit volume is minimal in the season preceding stratification.

Some observations of temperature and total chlorophyll a in Lake Ontario during "thermal bar" time.

On May 1, 1968, the water warmer than 4°C was discontinuous along the shores of Lake Ontario, and most of the lake-surface was still below 4° (Figure 15).

On June 21, 1972, the thermal bar was present well offshore where the soundings were about 160 metres (Figure 16). Shoreward of

the edge of the cold convecting core, the surface temperatures were in the range 8 to 16°C. In the cold core the surface temperatures were near 4°C, and were about to begin a rapid warming trend.

In early April and early May of 1972, the surface chlorophyll levels were about 2 µg/L in the cold core, and much higher in irregular patches along the shore (Figures 17 and 18).

On about June 22, 1972, temperatures and chlorophyll in vertical north-south sections (location map: Figure 19) showed the profound influence of the thermal bar on phytoplankton abundances via the light regime. The chlorophyll level of about 3 µg/L at the lake surface marks the location of the thermal bar in the sections (Figures 20 to 25). In the western-most section, "A", the thermocline had already spread across the entire section, but in the other two sections, further east where Lake Ontario is deepest, there was still a core of very low chlorophyll levels, about 2 µg/L. The northern warm layer is wider than the southern one, every year, because Lake Ontario's deepest areas are closer to the south shore. The thermal bar tends to match a particular bottom-depth-contour, at any one time in spring, as the thermal bar migrates offshore.

Particulate nitrogen: inshore-offshore differences at thermal bar time.

Particulate nitrogen at 1 metre depth, versus the sounding (used as an indicator of distance from shore) is illustrated in Figures 26 and 27, for May 26 and June 21, 1972. In Figure 27, the lower values in the extreme nearshore locations may be the result of edge-effects such as increased vertical mixing or upwelling.

Soluble reactive silica at thermal bar time.

Soluble reactive nutrients become depleted in spring in surface waters shoreward of the thermal bar, but remain abundant in the cold core offshore (eg., Figure 28, soluble reactive silica on June 21, 1972). This agrees logically with the knowledge that in springtime only the nearshore part produces abundant phytoplankton.

2(a)(iii) The phenomenon of "upwelling".

Temperature distributions during upwelling.

The thermocline of a lake in summer can be tilted by the wind stress. The thermocline is pushed down to leeward and up to

windward. In an extreme case, the coldest hypolimnetic water mass can be exposed along the windward shore. In a lake as large as Lake Ontario, the cold area at the lake surface is somewhat to the left of the downstream wind direction, due to the Earth's rotation. Winds from the west are common over Lake Ontario, and upwelling is common in the vicinity of Toronto and Oshawa. An example is given in Figure 29.

In autumn, the density differences associated with the thermal stratification are quite small, and winds are often stronger, so then the movements of isotherms can be large (eg., Figure 30).

The wind speeds and directions are of course highly variable. Further, the stress on the water-surface is proportional to the speed squared, and thus the stress is highly variable indeed. An example of summer winds during eleven days is given in Figure 31. Temperature distributions in the upper part of Lake Ontario near the end of this period are mapped in Figures 32, 33, and 34. The profound lake-wide character of this upwelling/downwelling is apparent. The transient distributions of water masses and nutrients must have the effect of causing extreme variability in the growth of phytoplankton.

Although most of this atlas deals with the offshore part of Lake Ontario, it is appropriate in the context of upwelling to show the extreme effect at the shore. Variations of water temperatures at

the Hamilton Water Intake in 1959 and 1960 (Figure 35) show that the upwelling episodes are different each year, and could not be forecasted because the winds cannot be forecasted.

Soluble reactive nutrients re-distributed by upwelling.

Lake-wide distributions of soluble reactive nutrients in Lake Ontario are strongly influenced by the surface winds (Figures 36 and 37), and therefore an extremum along the shore may be due either to a shore discharge (eg., in Figure 36, low (nitrate + nitrite) values of the Niagara River plume), or due to upwelling (in Figure 36, high (nitrate + nitrite) near Toronto, not due to discharges from the city).

2(a)(iv) Additional vertical sections.

A longitudinal temperature section in summer.

A typical vertical, longitudinal section showing temperatures in summer, on August 9 to 13, 1971, Figure 38, indicates that the mixed surface layer and the thermocline are shallow features in Lake Ontario in summer. Below about 50 metres depth each summer there is a large water-mass with temperatures near 3.8°C.

Transverse sections of total chlorophyll a in summer.

The sub-surface vertical structure of chlorophyll in Lake Ontario was observed on the cruises of the year 1972 only. Chlorophyll distributions in three vertical sections, on about July 19, 1972, show irregular higher concentrations near about 10 metres depth (Figures 39 to 42).

By September 6, 1972, the chlorophyll distributions became simpler, with more uniform values in the mixed surface layer (Figures 43, 44, and 45). In late summer (August and September), surface chlorophyll values alone become more representative of the upper waters. This will be considered (pages ³⁰~~21~~f) in the search for long-term trends using surface values available from surveys of 1971 and earlier, together with integrated 0 to 20 m chlorophyll data available for the years 1974 and after.

Longitudinal sections of (nitrate + nitrite) and soluble reactive silica in November.

A vertical, longitudinal section of (nitrate + nitrite) in November, 1971, shows strongest vertical gradients at about 30 to

50 metres depth, with only slight vertical gradients near the bottom (Figure 46). In contrast, a soluble reactive silica section for November, 1971, shows strongest vertical gradients near the bottom (Figure 47). The seasonal cycles near the lake-bottom, considered further on, give more insight into this puzzle and suggest that, in the case of silica (but not (nitrate + nitrite)), the deep dissolution and recycling are important.

2(b) Water-chemistry data for a mid-lake station, shown in time/depth diagrams.

Diagrams with time-of-year on the x-axis, and depth within the lake on the y-axis, are a powerful way to show conditions at a single location in a lake. On such a diagram, contours of concentration are vertical when there are changes with time, and horizontal when there is strong vertical stratification.

Time-series data are available for mid-Lake Ontario during 1972 and early 1973. The station is designated "P-19". The sounding there is about 180 metres.

Soluble reactive phosphorus at the mid-lake station, time/depth diagram.

In a time/depth diagram of soluble reactive phosphorus at station P-19, Figure 48, the mixed surface layer shows as a phosphate-depleted layer in the upper 20 metres in July, August, and September. In the offshore area, only the upper layer of summer has phosphate-limited plankton content. At all other times and depths at this location there is excess phosphate and therefore potential for algal stocks to increase.

In summer at station P-19, there are sometimes extra high soluble reactive phosphorus concentrations near the bottom. These transient events could be local releases in deep water or from the mid-water interface, or they could be intrusions of high phosphate water from the deeper area further east, caused by horizontal currents in the deep water in response to surface wind stress.

Nitrite in time/depth diagrams: averages at each time and depth for the whole offshore area.

In Lake Ontario during August, 1966 and 1967, there was a nitrite maximum layer at a depth of 30 metres (Figures 49 and 50).

The phenomenon was wide-spread; the values on these particular diagrams are averages at each depth for the whole offshore area.

Particulate nitrogen, time/depth diagram.

The time/depth diagram for mid-Lake Ontario for particulate nitrogen, Figure 51, shows most abundant plankton in the near-surface waters in summer. Other times and other depths had low values of 20 to 30 $\mu\text{g N/L}$, except for some transient higher levels near the lake-bottom, which was probably the spring growth of diatoms, settling out to the bottom in summer (see also: Munawar and Nauwerck, 1971, and: Sandilands and Mudroch, 1983).

Particulate organic carbon, time/depth diagram.

The time/depth plot of particulate organic carbon at station P-19, Figure 52, shows the same principal features as particulate nitrogen, with highest concentrations in surface waters in summer, and accumulations near the bottom in summer also.

Particulate carbon-to-nitrogen ratios, time/depth diagram.

Low ratios of particulate carbon-to-nitrogen in lake-waters indicate particulate matter with high nitrogen and protein contents. High ratios indicate particulates that are aged or partially digested (Russell-Hunter, 1970). The particulate carbon/nitrogen ratios in a time/depth plane at station P-19, Figure 53, show high values near the bottom in September and October: perhaps this is caused by the aging diatom crop of the preceding spring, in the process of sedimentation.

Soluble reactive silica, time/depth diagram.

The plot of soluble reactive silica at P-19 in the years 1972/73, Figure 54, shows depletion in the warm surface layer of summer. This depletion of silica could cause diatoms to be replaced by other algal groups in offshore surface waters in summer (see also: Munawar and Nauwerck, 1971, and : Schelske and Stoermer, 1971). Highest values of soluble reactive silica occurred at the lake-bottom in summer and early autumn. The high values may have been from dissolution of diatom frustules that were in the process of sedimentation (see: Sandilands and Mudroch, 1983).

Oxygen percent saturation, time/depth diagram.

Oxygen percent saturation values at P-19 during 1972/73, Figure 55, indicate that mid-Lake Ontario had excellent and high dissolved oxygen values. Surface waters were supersaturated, especially during July. There was a slight minimum layer at thermocline depth during September, and values near 90 percent at the lake-bottom in September. Other times and depths at this mid-lake station had values in the range 90 to 105 percent saturation, which shows dominance of the process of physical equilibration with air at the lake-surface.

2 (c) Seasonal cycles and long-term trends of nutrients and related factors.

Seasonal cycles and long-term trends are best considered together. Trends must be studied in the context of seasonal cycles, the latter being strong oscillations which, if not considered, might hide the long-term trends.

The offshore part of Lake Ontario is herein selected for the cycles-and-trends study. The nearshore part of the lake would be more influenced by upwelling episodes and variable plumes, and was

undersampled in the time-domain in the monthly CCIW surveys. The data resulting from such undersampling shows apparent fluctuations that are erroneous. The problem, called aliasing, was explained in Pickard (1963).

Temperatures: seasonal cycle.

The seasonal cycle of surface temperatures, (Figure 56: unweighted cruise-mean surface temperatures for the area where the soundings are greater than 100 metres), indicates extremely delayed warming of the offshore area in springtime. The critical 4°C temperature level is reached near June 1, followed by rapid warming to 17°C during June. In this offshore zone, "summer" can be defined as the period of warmest surface temperatures: July, August, and September. Limnological autumn can be taken to be the period of cooling down to 4°C: October, November, and December. Winter can be taken to be the period of further cooling: January, February, and March. The coldest cruise-mean temperature in this data-set was 0.5°C: the offshore area of Lake Ontario is usually free of ice in winter. April and May may be called "early spring" or the slow warming period, and June, with rapid warming, may be called "late spring". Warming of the offshore part is slow in early spring because warming at the surface, still below 4°C, is accompanied by convection and warming at all the deeper depths too.

Soluble reactive phosphorus: seasonal cycles and trends in surface and bottom waters

This section deals with changes in soluble reactive phosphorus in Lake Ontario during the last decade, due to changes in the external loading of phosphorus to the lake in the same period.

The seasonal cycle of soluble reactive phosphorus in off-shore near-surface waters, Figure 57, indicates nearly-complete depletion during the summer period only, due to plankton growth. Phosphorus-limited plankton stocks would occur only in summer in this part of Lake Ontario. Long-term trends of soluble reactive phosphorus would best be studied by comparing winter or early spring concentrations in different years. Long-term trends of plankton stock indicators would best be studied only in the summer period in this part of the lake (but also in spring in the nearshore part where surface warming occurs earlier).

All cruise-mean values of soluble reactive phosphorus in the years 1969 to 1982 in the offshore zone are plotted in Figure 58 (surface values) and Figure 60 (bottom values). March/April surface values, Figure 59, had a peak in 1973, followed by declining values to 1981-1983, when values were close to an appropriate goal of $6 \mu\text{g P/L}$ (0.6 times the total phosphorus goal of $10 \mu\text{g P/L}$, based on the average ratio of soluble reactive phosphorus to total phosphorus in March/April in the early 1970's).

Total phosphorus, fluctuations and trends in the offshore surface waters, 1969 to 1982.

Cruise-mean values of total phosphorus in unfiltered samples, and unweighted annual mean values of total phosphorus, in Figure 61, show considerable variability within each year, but still a decline after 1973, to values just above the goal of 10 $\mu\text{g P/L}$, which was proposed in: Great Lakes Research Advisory Board, Annual Report 1978. ^{in March/April}

Remarks on the external phosphorus loadings to Lake Ontario.

Modern lake science holds that a lake's plankton populations respond to influxes of the nutrient that happens to be in shortest supply relative to the needs of the plankton. Often, the stock-limiting nutrient is phosphorus. Sometimes, it is nitrogen. Elsewhere, some new evidence confirming phosphorus limitation of plankton stocks in Lake Ontario will be presented (Dobson, 1983, in preparation).

The recent history of the external phosphorus loading gives a clue as to likely trends in the lake's plankton abundance. Also, knowledge of the magnitudes of various components of the external loading at the onset of control programs gives insight into phosphorus loading manageability.

Chapra (1977) published a reconstruction of external phosphorus loadings to Lake Ontario in the period 1800 to 1970. In 1970 about one half of the total loading was potentially controllable. The controllable fractions were those from detergents, and from human wastes within the Lake Ontario basin, and some portion of the influx from Lake Erie if that lake were managed too.

Chapra (1980) showed that phosphorus loadings to Lake Ontario peaked in about 1972, and declined thereafter, with about a 40% decline by 1978. (The external total phosphorus loading to Lake Ontario is difficult to measure, as indicated by disagreement between different estimates shown by Chapra (1980).)

The steady-state phosphorus "calibration curves" for Lake Ontario, according to a number of different workers, were published together in Chapra (1980). This is the within-lake concentration of total phosphorus, versus the external phosphorus loading. This curve allows the required external loading to be estimated for any chosen concentration of total phosphorus within the lake. Theory to solve this relationship must account for sedimentation of planktonic phosphorus. The curves suggest that, for Lake Ontario, ^a ~~an annual mean~~ ^{in March/April} within-lake concentration of 10 $\mu\text{g P/L}$ requires an external loading of about 6000 metric tons phosphorus per year. The work of Chapra (1977) suggests that such a loading is achievable at present population

levels, given stringent controls of phosphorus in detergents and sewage outfalls, if such controls are applied in the Lake Erie basin as well as the Lake Ontario basin. Depending on future trends of population and technology, the phosphorus loading might rise again in future decades, despite control efforts.

Trend analysis of within-lake properties: the summer-mean Secchi-depth transparencies, 1965 to 1982.

Transparency of Lake Ontario's near-surface waters is probably influenced by the phytoplankton and, to some unknown extent, by suspensions of calcium carbonate precipitates which are induced by algal metabolism each spring and summer (Strong and Eadie, 1978). Recent limnological papers have emphasized that transparency is influenced by particle size (Lorenzen et al, 1980) and zooplankton abundance (Edmondson and Litt, 1982).

In the offshore area of Lake Ontario, the summer-mean Secchi depths were 3.8 metres in 1965, 2.1 metres in 1971 and 1972, 3.4 metres in 1977, and 2.2 metres in 1982 (Figure 62). The conclusion must be made that transparency in summer has not followed the trend of March/April soluble reactive phosphorus (Figure 59). But probably the lake in summer would have been much less transparent than 2.2 metres in 1982 without the phosphorus control program.

Fluctuations and trends of total chlorophyll a in the offshore near-surface waters, 1967 to 1981.

In the CCIW water-quality surveys of Lake Ontario, the sampling scheme for particulate organic matter shifted from 1 metre samples before 1972, to a number of discrete depths in 1972, and then to integrated 0 to 20 metre samples in 1974 and thereafter. The changes in sampling strategy complicate the comparison of early and more recent chlorophyll values. Comparison of shallow and integrated chlorophyll data is possible with the data of 1972 only, and this is done in Part 3, pages 38 to 40.

Cruise-mean chlorophyll values over all the years of observation, for near-surface offshore waters, Figure 63, had great seasonal variability with highest values in summer. Phaeopigments (degraded or inactive chlorophyll) were small fractions of the total chlorophyll.

For chlorophyll trend analysis, the months of August and September in different years were compared (Figure 64). The month of July was avoided because of its extreme vertical stratification of chlorophyll, already shown (eg., Figure 41). The August/September mean values of 1967 to 1981 had only random fluctuations; thus there was no resolved trend. Chlorophyll values may have been too variable

in the upper offshore waters each summer for any trend to be discerned.

Seasonal cycles and long-term trend of (nitrate + nitrite) in surface and bottom waters.

The sum (nitrate + nitrite) was measured, but nitrite was probably low. Nitrate + nitrite in Lake Ontario increased steadily in the years 1968 to 1981 (Figures 65, 66, & 67). Values in surface waters in summer were very low, about 10 $\mu\text{g N/L}$, up to the year 1972, but in the most recent years there was a residual (nitrate + nitrite) level of about 100 $\mu\text{g N/L}$. Nitrate + nitrite may have been co-limiting the plankton stocks in the earlier years, along with phosphorus, but in later years, excess (nitrate + nitrite) meant that phosphorus alone was the stock-limiting factor. Excess (nitrate + nitrite) in surface waters in summer will prevent the occurrence of troublesome nitrogen-fixing kinds of blue-green algae, and thus excess nitrogen together with phosphorus control measures may be understood as good. High phosphorus levels and medium or high nitrogen levels would make Lake Ontario over-productive of algae - thus the phosphorus control measures should definitely be continued.

Nitrate (+ nitrite) is increasing rapidly in the other Great Lakes, even in Lake Superior (Dobson, 1981; Bennett, 1982). Acid rain is probably a major source of nitrate to the Great Lakes (Bennett, 1982).

Near the bottom of Lake Ontario, seasonal fluctuations of nitrate + nitrite have been small (Figure 67), whereas the fluctuations were large in surface waters (Figure 65).

Fluctuations and trend of ammonia.

Ammonia data for offshore near-surface waters of Lake Ontario from 1969 to 1980 show a decline to extremely low values, below 5 $\mu\text{g N/L}$ (Figure 68). Explanations for the decline of ammonia seem to be too speculative.

Summary graph of trends of total inorganic combined nitrogen (nitrate + nitrite + ammonia).

Utilization of inorganic nitrogen (winter value minus summer value) remained fairly constant, while the values in winter and summer increased (Figure 69).

Particulate nitrogen : seasonal cycle, and a search for a trend.

Particulate nitrogen in offshore near-surface waters was highest in summer (Figure 70).

In recent years, the August/September mean values of particulate nitrogen in offshore near-surface waters remained fairly constant (Figure 71). This is similar to summertime Secchi transparencies (Figure 62), and chlorophyll in late summer (Figure 64), but dissimilar to the declining values of soluble reactive phosphorus in March/April (Figure 59). This enigma disturbs our belief that phosphorus might have controlled all of Lake Ontario's plankton stock indicators in a simple direct manner.

Carbon trends: soluble reactive carbon indicated by alkalinity, and particulate organic carbon.

Alkalinity, mostly bicarbonate-ion in Lake Ontario, was depleted only slightly in summer, relative to March/April (Figure 72). In a measurement of alkalinity (a titration with strong acid), 1 mg CaCO_3/L is equivalent to 240 $\mu\text{g C/L}$ as bicarbonate. Thus the levels of soluble reactive carbon in Lake Ontario are about 90 mg CaCO_3/L , equals 90 x 240 or 22,000 $\mu\text{g C/L}$. With such abundance of

bicarbonate, the element carbon could not be limiting the lake's plankton stocks.

Particulate organic carbon in the offshore upper waters in August/September declined steadily from 1975 to 1981, with a 20% reduction occurring (Figure 73). Among the four plankton indicators (Secchi; chlorophyll; particulate nitrogen; particulate organic carbon) only carbon has responded like phosphorus. Perhaps zooplankton contributed significantly to these particulate organic carbon values.

Soluble reactive silica: seasonal cycles and trends in the offshore part of Lake Ontario.

Soluble reactive silica values were low in near-surface waters in summer (Figures 74 and 75). Silica shortage could be limiting the stocks of diatoms in summer, and allowing other kinds of phytoplankton to replace diatoms in summer. Soluble reactive silica values increased in the bottom waters in summer (Figure 76). This suggests that there was a considerable internal loading, i.e., recycling, of silica: a cycle of uptake near the lake-surface, sedimentation of diatom frustules, and their dissolution near the bottom.

The March/April values in surface waters fluctuated in the years 1968 to 1982, but the August/September surface values were always low, near $100 \mu\text{g SiO}_2/\text{L}$ (Figure 77). The external loadings of silica to Lake Ontario probably influence the species composition of the phytoplankton, but external silica loadings cannot be known except by more analytical effort on tributary waters.

Dissolved oxygen in the main basin of Lake Ontario: seasonal cycles, and a search for long-term trends in the deep consumption.

In the years 1966 to 1981, oxygen in the offshore upper waters followed a regular cycle in its concentration-values. Minimum values occurred in August and September, in the range 9 to 11 mg/L (Figure 78).

The seasonal cycle of oxygen concentrations, together with the cycle of surface temperatures (Figure 56), produce a third, different cycle of the near-surface oxygen percent saturation values, with supersaturation of oxygen in June, July, and August (Figure 79).

Cruise-mean values of oxygen percent saturation in offshore samples having temperatures from 10 to 15°C , in many years, are plotted in Figure 80. In late summer, these values were near 100%

saturation, which suggests that the oxygen minimum layer found at a mid-lake station in September 1972 (Figure 55) does not involve the whole thermocline, or might not occur every year. (See also: Boyd, 1980.)

"Deep Water" is here defined as water colder than 4.0°C and not within 10 metres of the lake-bottom. The Deep Water in late summer, 1966 to 1978, had a mean depletion rate of about 1.0 mg/L/3 months (Figure 81). The cold water within 10 metres of the bottom often had lower oxygen values than the Deep Water above it (Figure 82). Periods with least hypolimnetic oxygen stratification were December/January and May/June, when temperatures very close to 4°C allowed overturning to the bottom. (Here oxygen is giving insight into a physical process.)

Oxygen depletion rates in the Deep Water in summer/autumn were derived graphically, as in Figure 83. In the years 1966 to 1981, there was no apparent long-term trend of the oxygen depletion rates (Table 1).

To sum up the Main Basin oxygen study : this part of Lake Ontario had excellent oxygen conditions throughout the first period of its cultural eutrophication.

Table 1. Lake Ontario, dissolved oxygen, measured depletion rates in the Deep Water (temperature 4°C and not within 10 m of the bottom) in summer, the years 1966 to 1981.

Year	Oxygen depletion rate (mg/L/3 months)
1966	0.7
1967	0.6
1968	1.3
1969	0.9
1970	0.9
1972	0.9
1974	1.0
1976	0.6
1977	0.9
1978	0.7
1979	1.4
1981	1.0
Range	0.6 to 1.4
Mean	0.9

There was no apparent long-term trend.

Oxygen in the Bottom Water of Prince Edward Bay, a sensitive water-mass of limited extent in Lake Ontario.

Prince Edward Bay is located on the west side of Lake Ontario's Northeast Outlet Region (Figure 2). Observations of dissolved oxygen near the bottom in Prince Edward Bay showed depletion in late summer down to 4 mg/L (Figure 84). This region has some importance for commercial fishing, and the Bay's oxygen levels have approached critical levels for fish (Davis, 1975; Great Lakes Water Quality Board and Research Advisory Board, 1977). The sensitivity to seasonal oxygen depletion in this area is due to the small thickness of its Bottom Water Layer, due to the Bay's shallowness. This morphometric influence on oxygen is similar to that of Central Lake Erie (Charlton, 1980; Chapra and Dobson, 1981).

Part 3. An examination of the strategy of vertically integrated sampling, 0 to 20 metres depth, and a recommendation for improved surveillance, based on a critical comparison of two observational strategies for chlorophyll and other plankton-stock parameters using the detailed chlorophyll sampling of the year 1972.

In the CCIW observational data-sets for particulate organic matter in Lake Ontario, three observational strategies were used: 1967

to 1971, samples from 1 metre depth; 1972 only, samples from many discrete depths; and 1974 to 1982, vertically integrated samples in the interval 0 to 20 metres. The detailed sampling of 1972 allows a study comparing the earlier and later strategies.

Two chlorophyll values at each station, a 1 metre value, and a numerically integrated 0 to 20 metre value derived from contoured transverse vertical sections with observations from many discrete depths, are here compared. The locations of the sections are shown in Figures 19 and 39.

In the three sections near June 21, 1972, the integrated values were most often slightly lower than the 1 metre values in the nearshore, with one exception, the north end of Section "B" (see Figures 85 to 87).

Near July 20, 1972, integrated chlorophyll values were much lower than the 1 m values at the southernmost stations, but integrated values were much higher than 1 m values at offshore stations (Figures 88 to 90). Near July 20, 1972, at all stations on the three sections, the grand mean integrated value was 8.9 $\mu\text{g/L}$, and the grand mean 1 m value was 3.9 $\mu\text{g/L}$.

Near September 7, 1972, integrated values were lower than 1 m values at all the stations (Figures 91 to 93). Grand mean values were: integrated, 4.9 $\mu\text{g/L}$, and 1 m, 6.8 $\mu\text{g/L}$.

Clearly the earlier and later data cannot easily be compared to derive long-term trends for particulate organic matter. The most adequate sampling strategy is the one used in 1972, which allows the vertical structure of the population of plankton to be known, and for which the values at any depth, and numerically integrated values, can all be known.

In an annual report of the International Joint Commission on Great Lakes water quality, 1974, the following was stated: "The ultimate assessment of the effectiveness of phosphorus reduction programs must be made in terms of the changes in algal biomass in the Great Lakes." With inadequate sampling of the plankton, such changes will be most poorly detected.

Part 4. Major ions: indication of significance, and their trends, 1906 to 1981.

At the concentrations found in Lake Ontario, the major ions probably have negligible influence on the abundance and species

composition of the plankton, which are more likely influenced by the principal limiting nutrients P, N, and Si, and perhaps microconstituents (nutrients and contaminants), in addition to the influences of grazing and physical processes. Beeton (1965) used major ions to "indicate" eutrophication, but probably there is no causative relationship.

In Lake Ontario, the small spatial variability of major ions is difficult to measure. Surface waters in summer have slightly lowered values of calcium and alkalinity.

Major-ions data for the period 1906 to 1966 were published in detail earlier (Dobson 1967).

In Figure 94, the mean values in different early years are from Dobson 1967, and the more recent data are late-winter mean values in offshore waters, from the CCIW data files.

Bicarbonate, magnesium, and potassium have remained constant over the years, within measurement resolution (Figure 94). The other four major ions have increased since 1906: calcium by 30%; sulphate by 110%; chloride by 250%; and sodium by 160%. Chloride, sulphate, and perhaps calcium, have decreased slightly in the late 1970's.

The sum of the seven major ions in Lake Ontario in 1981 was 230 mg/L. Mean seawater has a salinity of 34.7 mg/g and a density of 1.026 g/ml, giving a total salt content of 35,600 mg/L. Thus Lake Ontario in 1981 had a salt content which was $230/35,600 = .0065 = 0.65\%$ of the salt content of mean seawater.

Part 5. Simplified data on some trace chemical constituents in Lake Ontario, from the CCIW files.

Median values for ten elements in the offshore part of Lake Ontario in the 1970's are compiled in Table 2, along with their percentages of the maximum values accepted for drinking by humans, the latter being taken from: Canada, Department of National Health and Welfare, 1978. Although the study of metals and organic contaminants in Lake Ontario waters, colloids, and biota, and their biological effects, may be very difficult, clearly more work could be done to learn their vertical distributions, seasonal cycles, and levels in the biota.

Table 2. Lake Ontario: median values of some trace constituents in the offshore part in the 1970's (CCIW data). Units are micrograms per litre.

Constituent	median-values		% of maximum value acceptable for drinking
	dissolved	total	
aluminum		5.0	
arsenic		0.7	1.4%
boron		19.	0.4%
copper	2.6		0.3%
fluoride (1968)	120.		8.%
iron	1.8	10.8	4%
iron (acid digested)	4.2		
lithium	1.6		
manganese	0.5	1.2	2.4%
strontium	180.		
zinc	7.6		0.15%

Part 6. Conclusions of the Atlas.

1. Phosphorus levels in Lake Ontario are now (1982) almost at the target established for the Great Lakes Water Quality Agreement, ^{This} ~~which~~ is the result of the phosphorus control program for the Lake Erie and Lake Ontario basins.
2. Excess (nitrate + nitrite) in surface waters of Lake Ontario in August and September, amounting to about 100 µg N/L, is judged to be beneficial and, along with control of phosphorus, serving to prevent noxious blue-green algal blooms.
3. Dissolved oxygen in the main basin of Lake Ontario remained abundant throughout the first period of the lake's cultural eutrophication during the 1970's, which indicates that future limited eutrophication of this lake, even if it occurs, will produce the problem of overabundant phytoplankton and shore-algae without endangering the oxygen regime.
4. Given the above three points, the open waters of Lake Ontario seem to be in healthy condition in ~~its~~ ^{their} nutrient-related aspects, so that the governments and the public should be satisfied in their roles as the lake's users and caretakers, who deliberately and

wisely chose to control phosphorus. However, there may be continuing growth of shore-algae (*Cladophora*) and some taste and odor problems with the drinking water, which perhaps cannot be totally prevented.

5. Phosphorus loading controls should continue in the Lake Erie and Lake Ontario basins. The two control measures (use of household detergents low in phosphorus, and chemical precipitation of phosphorus at municipal sewage treatment plants) should continue to prevent catastrophic eutrophication from the still-rising human population. Because Lake Ontario will have abundant nitrate from now on, eutrophication must definitely be suppressed via phosphorus controls.

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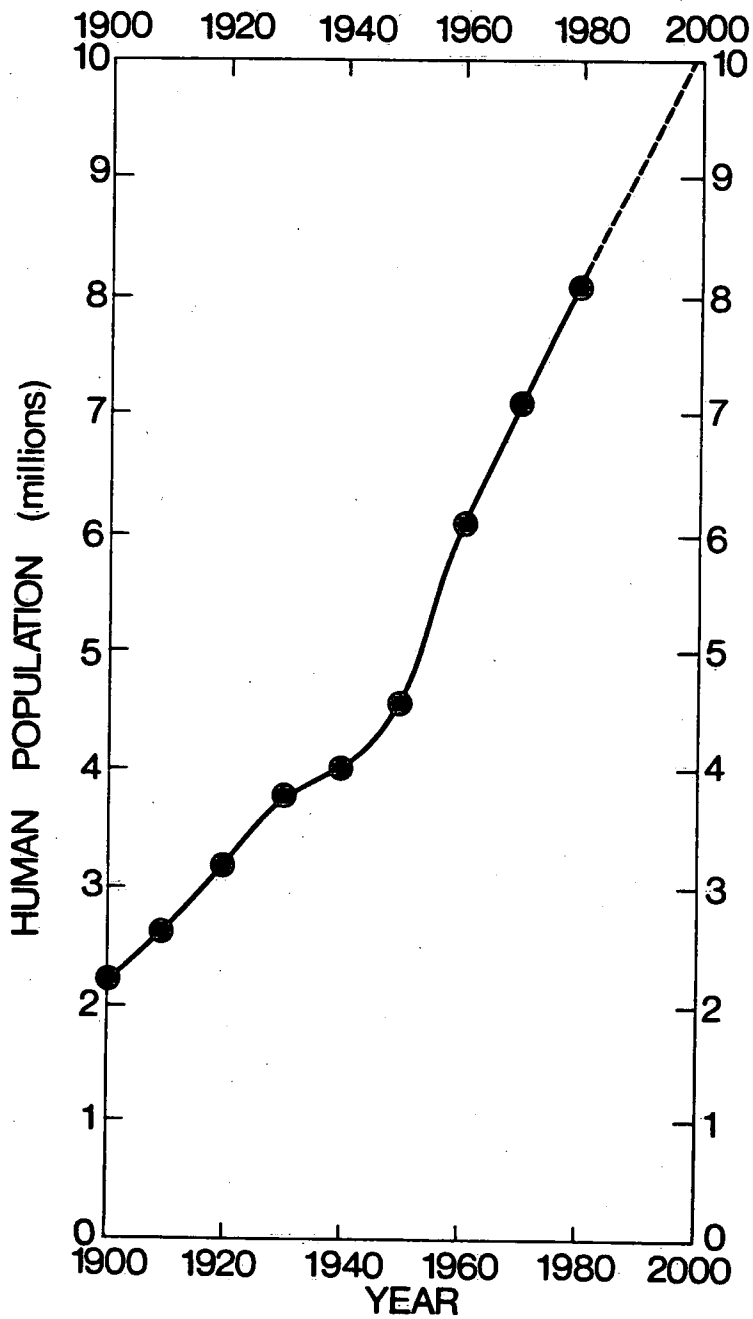
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 61. Lake Ontario, total phosphorus in near-surface waters at offshore stations having soundings >100 m, 1969 to 1982. Dots are cruise-mean values; bars are unweighted annual mean values. Data of CCIW.
 62. Lake Ontario, Secchi-depth transparency, mean values for summer (July, August, and September), 1965 to 1982, in the offshore area where soundings >100 m. Reciprocal values were used in the calculations of summer-means.
 63. Lake Ontario, chlorophyll a and phaeopigments in offshore, near-surface waters, cruise-mean values in the years 1967 to 1981.
 64. Lake Ontario, total chlorophyll a, mean values for August/September in offshore, near-surface waters, observed by CCIW, 1967 to 1981.
 65. Lake Ontario, nitrate + nitrite in offshore, near-surface waters in the years 1968 to 1981, cruise-mean values. The seasonal minimum was poorly-defined in the years 1977 to 1980 which lacked data for August.
 66. Lake Ontario, nitrate + nitrite, mean values in offshore, near-surface waters during March and April, 1968 to 1981.
 67. Lake Ontario, nitrate + nitrite in offshore, near-bottom waters in the years 1969 to 1981, cruise-mean values.
 68. Lake Ontario, ammonia in offshore, near-surface waters in the years 1969 to 1981. Dots are cruise-mean values; bars are unweighted annual mean values.
 69. Lake Ontario, nitrate + nitrite + ammonia, 1968 to 1982, CCIW data.
 70. Lake Ontario, particulate nitrogen in offshore, near-surface waters, cruise-mean values in the years 1972 to 1979.

71. Lake Ontario, particulate nitrogen, mean values for August/September in offshore, near-surface waters, observed by CCIW, 1972 to 1981.
72. Lake Ontario, alkalinity in offshore surface water: spring overturn period; summer (August 1 to September 15); and their difference. Error bars are 95% confidence intervals.
73. Lake Ontario, particulate organic carbon, mean values for August/September in offshore near-surface waters, observed by CCIW, 1972 to 1981.
74. Lake Ontario, soluble reactive silica, seasonal cycle in offshore, near-surface waters: cruise-means and one standard deviation, for 30 cruises in the years 1969 to 1973, data of CCIW. Soundings >100 m; sample-depths ≤ 10 m.
75. Lake Ontario, soluble reactive silica in offshore, near-surface waters: cruise-mean values, 1969 to 1981.
76. Lake Ontario, soluble reactive silica in offshore, near-bottom waters: cruise-mean values, 1969 to 1981.
77. Lake Ontario, mean values of soluble reactive silica in offshore, near-surface waters, 1968 to 1982, data of CCIW: winter values, summer values, and their difference.
78. Lake Ontario, dissolved oxygen (mg/L) in offshore, near-surface water: 124 cruise-mean values in the years 1966 to 1981, data of CCIW. Soundings >100 m; sample-depths ≤ 10 m.
79. Lake Ontario, oxygen % saturation in offshore, near-surface waters: 124 cruise-mean values in the years 1966 to 1981, data of CCIW. Sounding >100 m; sample-depth ≤ 10 m.
80. Lake Ontario, oxygen % saturation, cruise-mean values at offshore stations (soundings >100 m), for samples with temperatures in the range 10 to 15°C, data of CCIW, from 33 cruises in the years 1966 to 1981.
81. Lake Ontario, dissolved oxygen (mg/L): mean values on each cruise, all years from 1966 to 1978, for samples colder than 4.00°C and not within 10 m of the lake bottom (offshore part where sounding is >50 m).
82. Lake Ontario, dissolved oxygen (mg/L): mean value of near-bottom samples (within 10 m of bottom), minus mean value of other samples colder than 4.00°C, on each cruise in the years 1967 to 1978 (offshore part where sounding is >50 m).

83. Lake Ontario, dissolved oxygen (mg/L) in the Deep Water (samples with temperature $< 4^{\circ}\text{C}$ and not within 10 m of the bottom), the year 1970, data from 12 cruises of the vessel "Martin Karlsen".
84. Seasonal cycle of dissolved oxygen in the bottom water of Prince Edward Bay (Lake Ontario), 1966 to 1975: data of CCIW.
85. Lake Ontario, total chlorophyll a in transverse section "A", June 20, 1972, vessel "Martin Karlsen": comparison of 1 m values and integrated 0 to 20 m values.
86. Lake Ontario, total chlorophyll a in transverse section "B", June 20 and 21, 1972, vessel "Martin Karlsen": comparison of 1 m values and integrated 0 to 20 m values.
87. Lake Ontario, total chlorophyll a in transverse section "C", June 22 and 23, 1972, vessel "Martin Karlsen": comparison of 1 m values and integrated 0 to 20 m values.
88. Lake Ontario, total chlorophyll a in transverse section "A", July 18, 1972, vessel "Martin Karlsen": comparison of 1 m values and integrated 0 to 20 m values.
89. Lake Ontario, total chlorophyll a in transverse section "B", July 18 and 19, 1972, vessel "Martin Karlsen": comparison of 1 m values and integrated 0 to 20 m values.
90. Lake Ontario, total chlorophyll a in transverse section "C", July 20 and 21, 1972, vessel "Martin Karlsen": comparison of 1 m values and integrated 0 to 20 m values.
91. Lake Ontario, total chlorophyll a in transverse section "A", September 6, 1972, vessel "Martin Karlsen": comparison of 1 m values and integrated 0 to 20 m values.
92. Lake Ontario, total chlorophyll a in transverse section "B", September 6 and 7, 1972, vessel "Martin Karlsen": comparison of 1 m values and integrated 0 to 20 m values.
93. Lake Ontario, total chlorophyll a in transverse section "C", September 8 and 9, 1972, vessel "Martin Karlsen": comparison of 1 m values and integrated 0 to 20 m values.
94. Lake Ontario: trends in the concentrations of seven major ions, 1906 to 1981.



Lake Ontario, human population, 1900 to 2000 A.D. (Lake Ontario basin + City of Buffalo).

Figure 1.

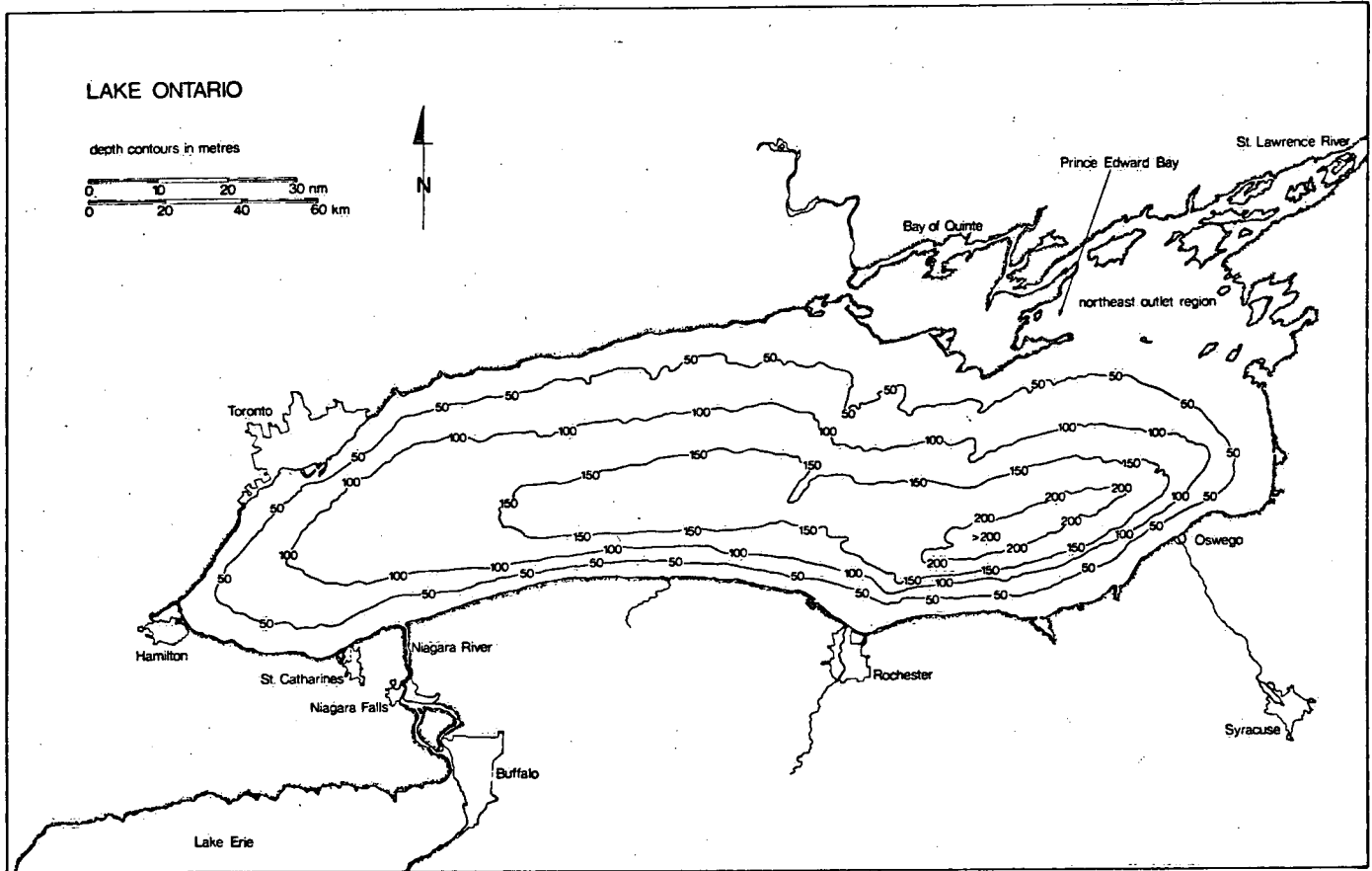
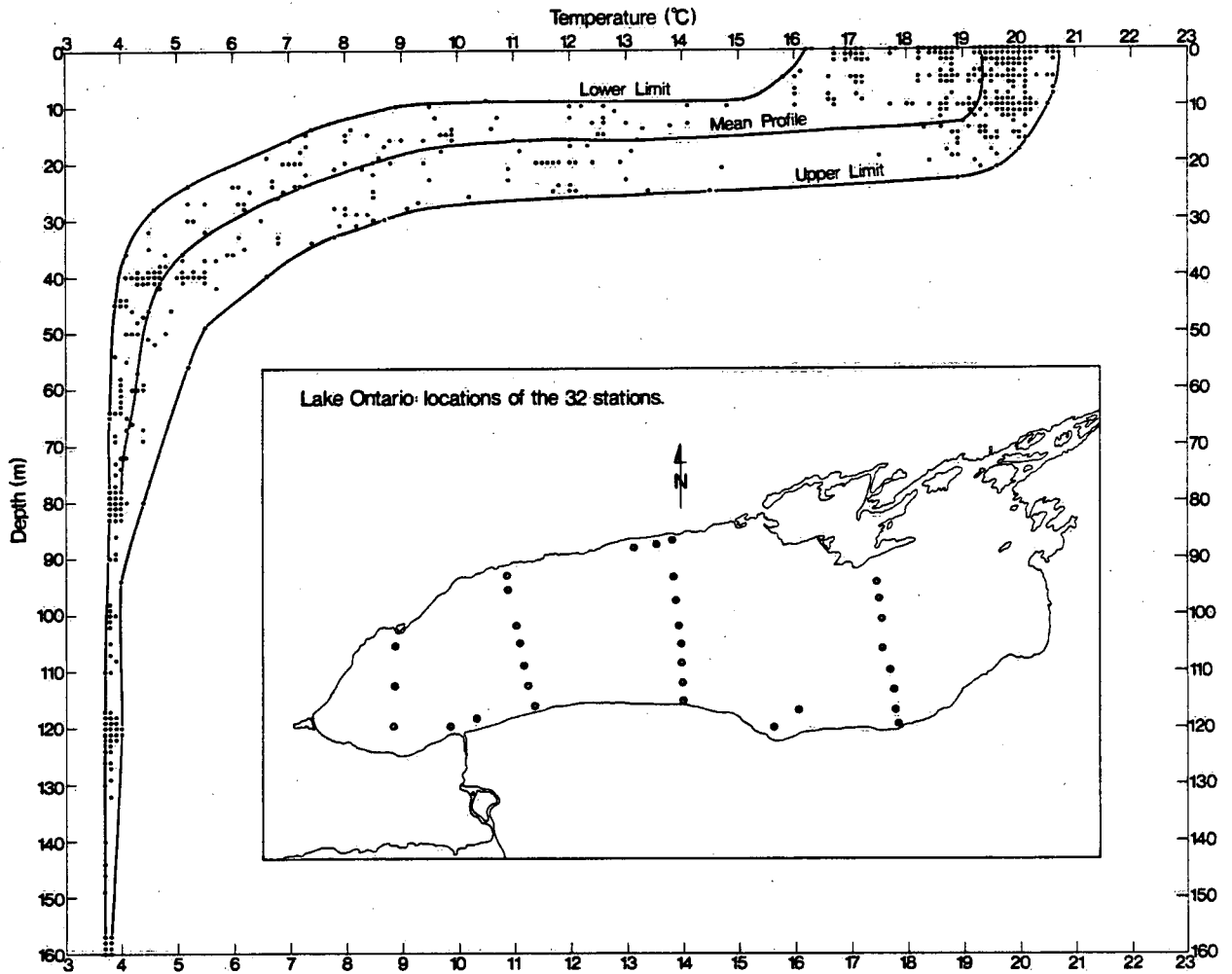
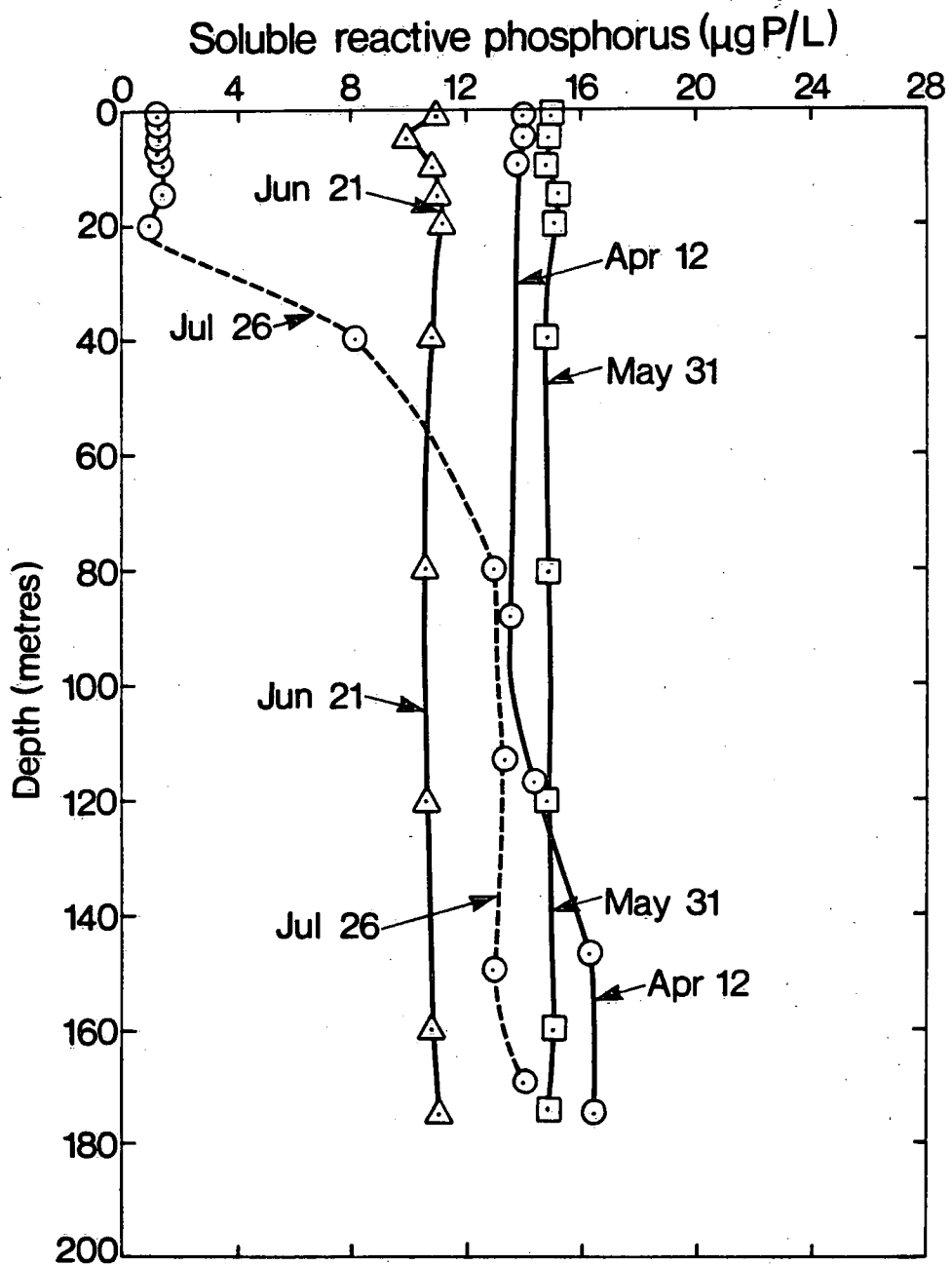


Figure 2.



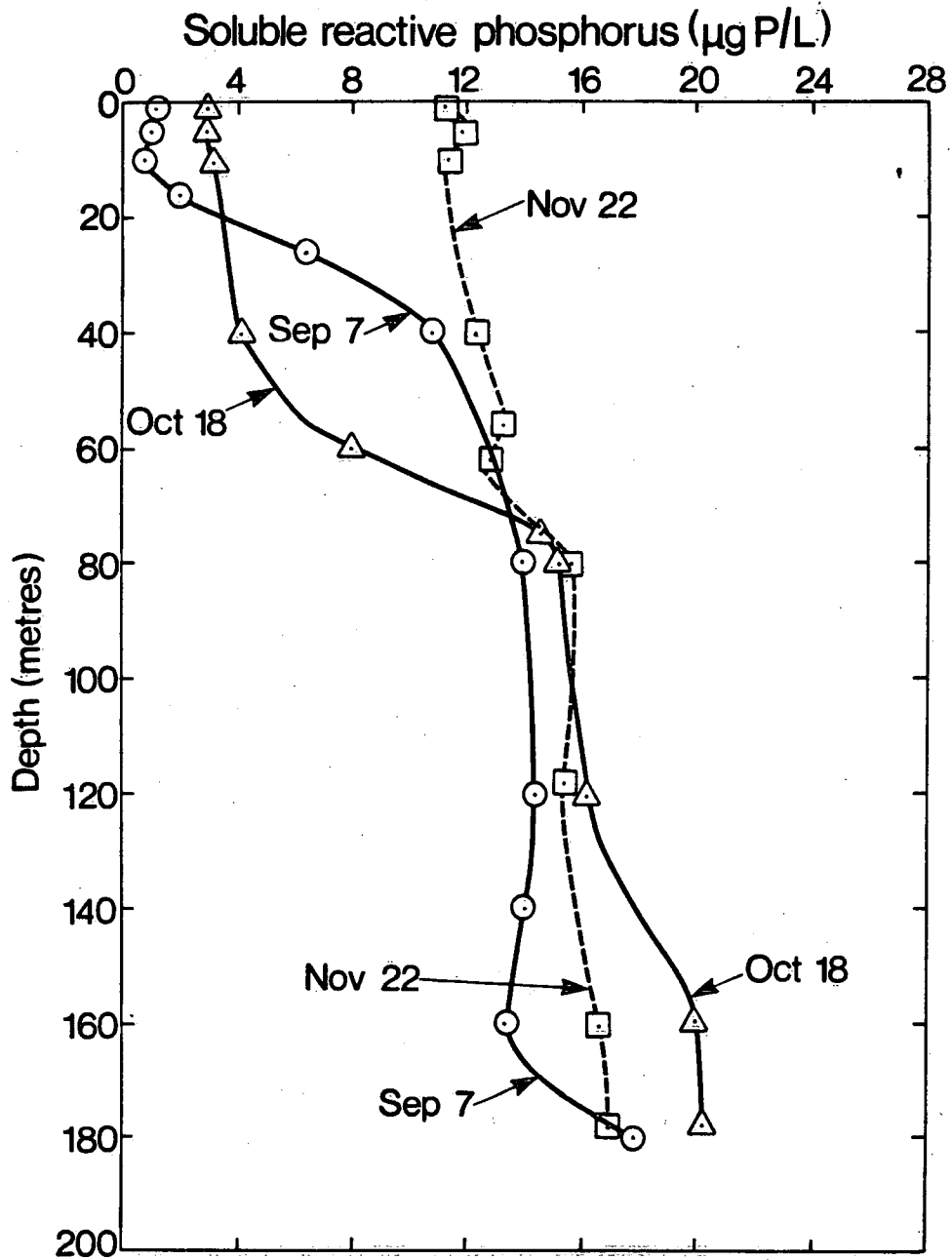
Lake Ontario, temperatures versus depth at 32 stations, September 5 to 11, 1972, vessel 'Martin Karlsen.'

Figure 3.



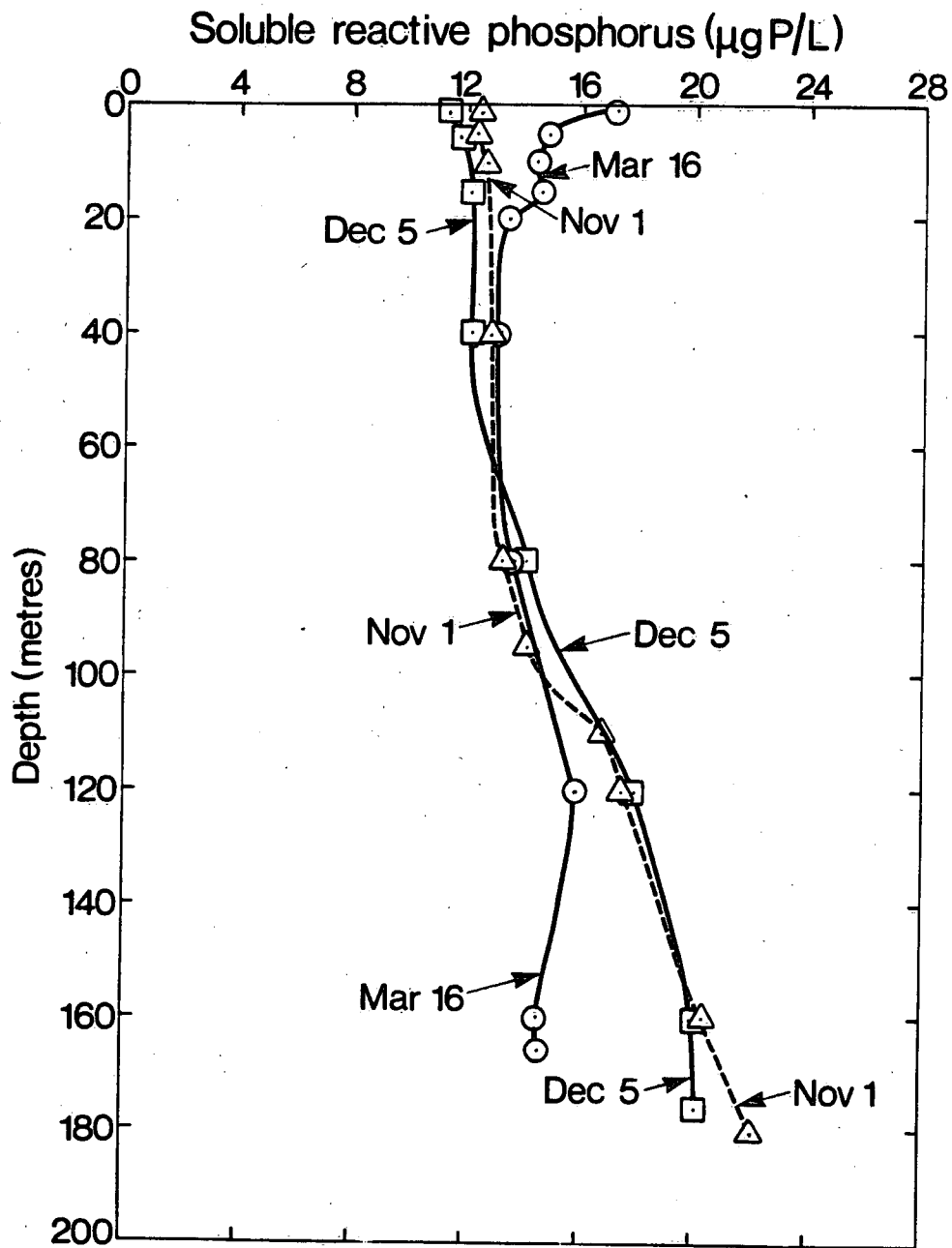
Lake Ontario: soluble reactive phosphorus at a mid-lake station in 1972 (cruises of the "Martin Karlsen").

Figure 4.



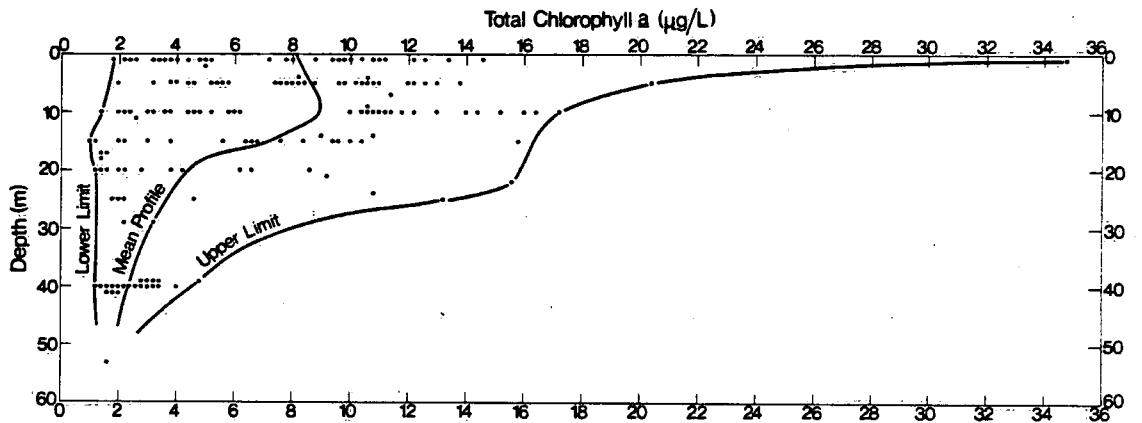
Lake Ontario: soluble reactive phosphorus at a mid-lake station in late 1972 (cruises of the "Martin Karlsen").

Figure 5.



Lake Ontario: soluble reactive phosphorus at a mid-lake station in 1973 (cruises of the "Martin Karlsen").

Figure 6.



Lake Ontario, total chlorophyll a versus depth at 32 stations, July 17 to 21, 1972 cruise of the 'Martin Karlsen.'

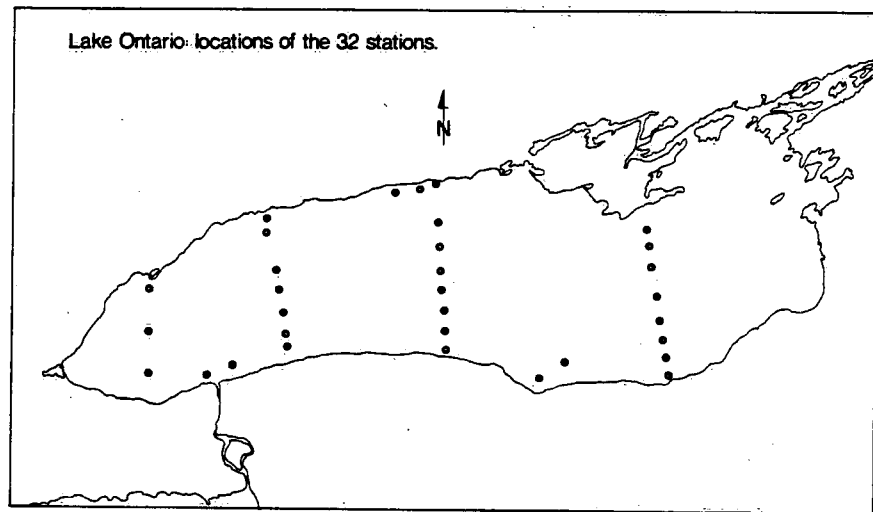


Figure 7.

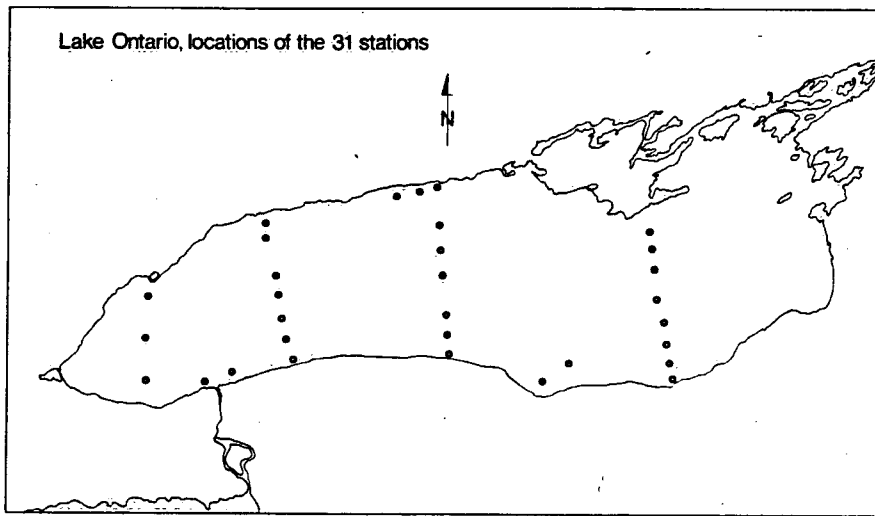
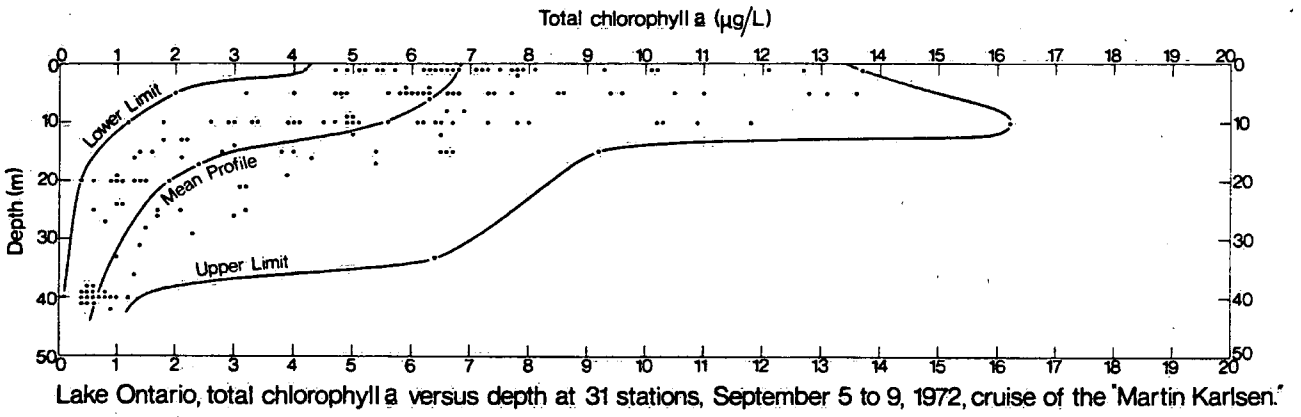
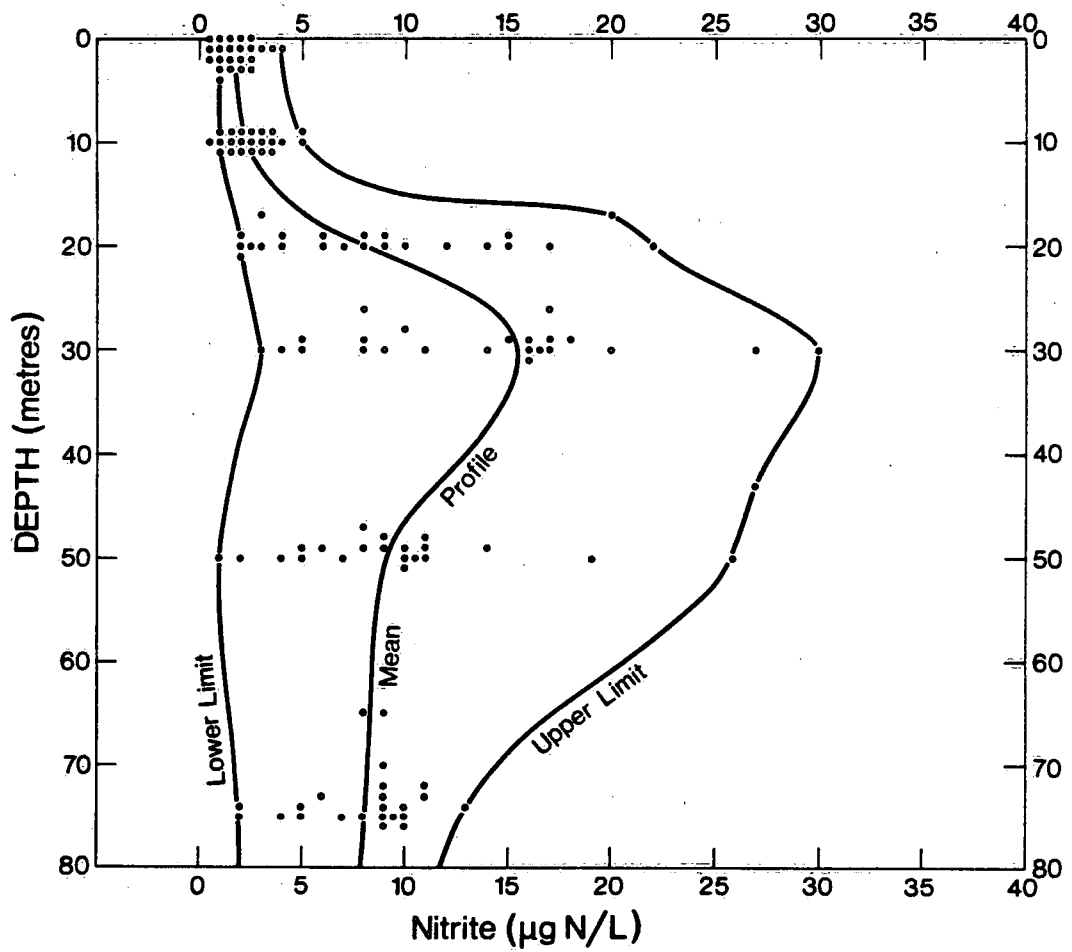
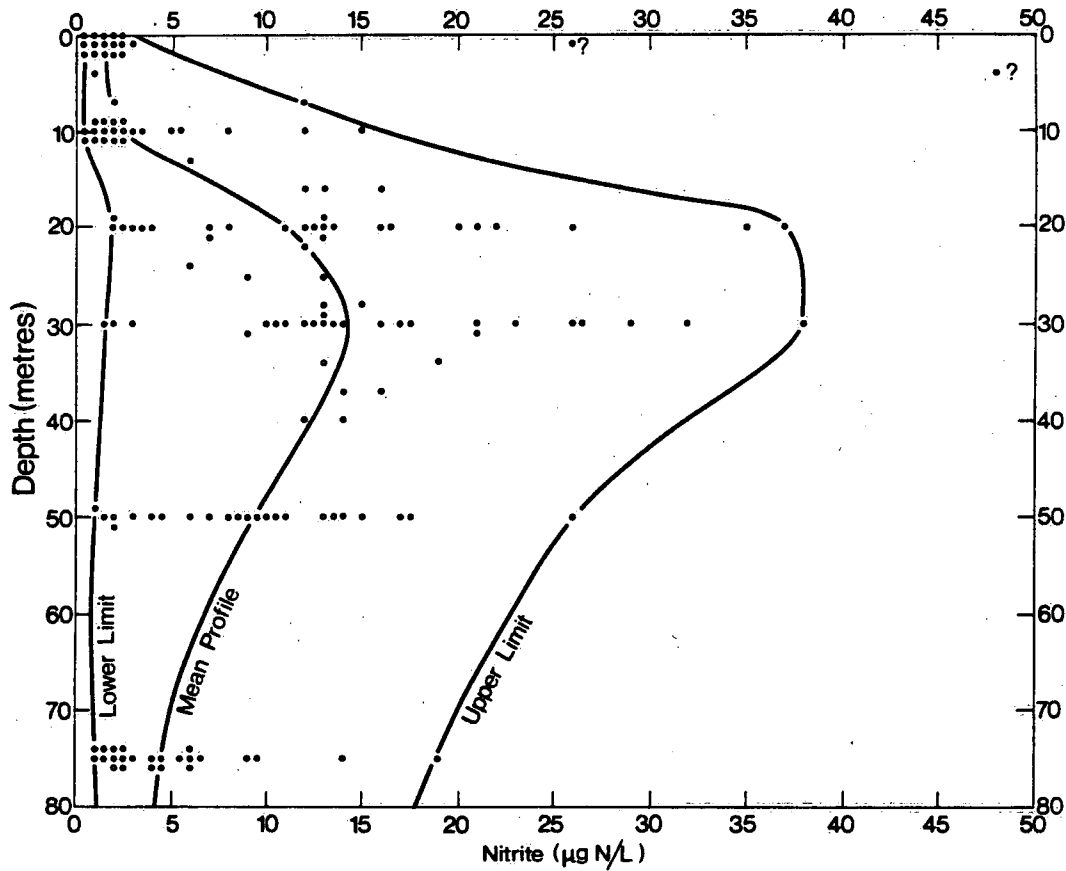


Figure 8.



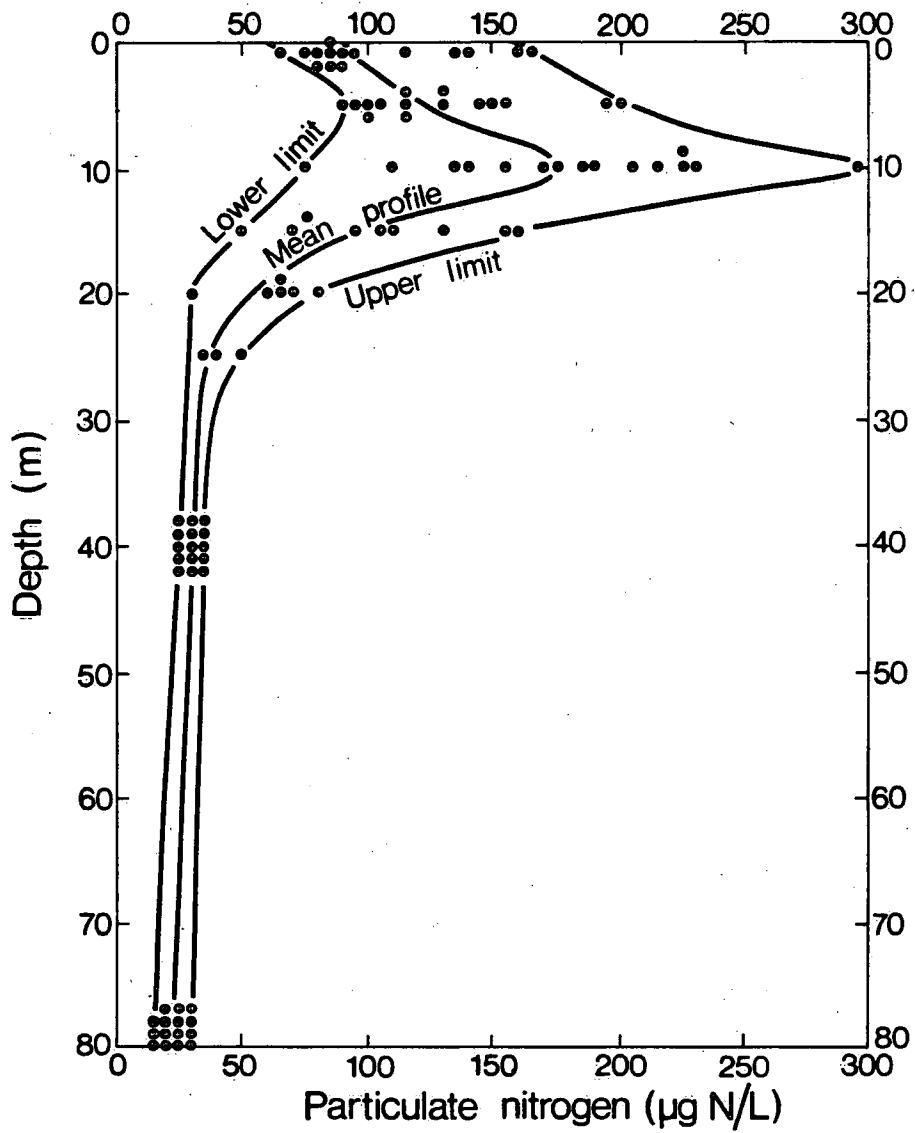
Lake Ontario, nitrite versus depth, cruise of the Brandal, August 15 to 19, 1966, offshore stations with soundings >100 m

Figure 9.



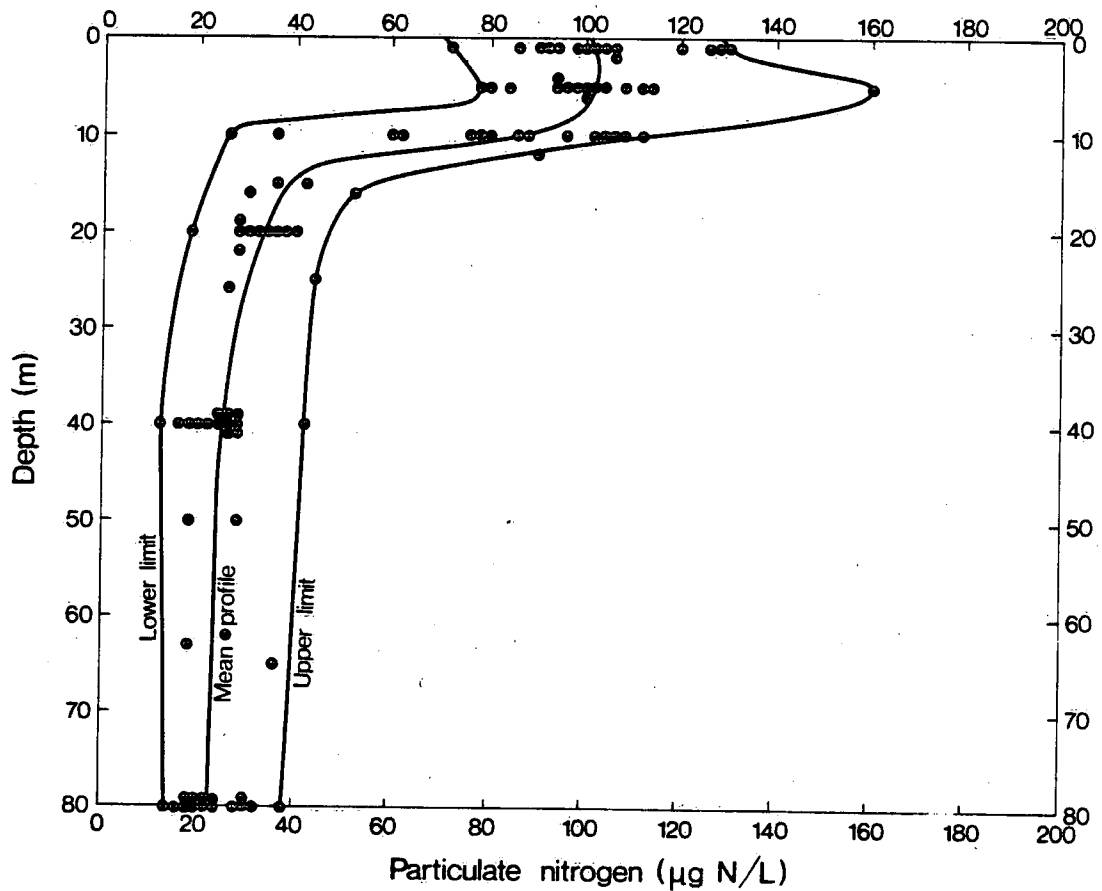
Lake Ontario, nitrite versus depth, cruise of the Theron, August 6 to 8, 1967, offshore stations with soundings >100m.

Figure 10.



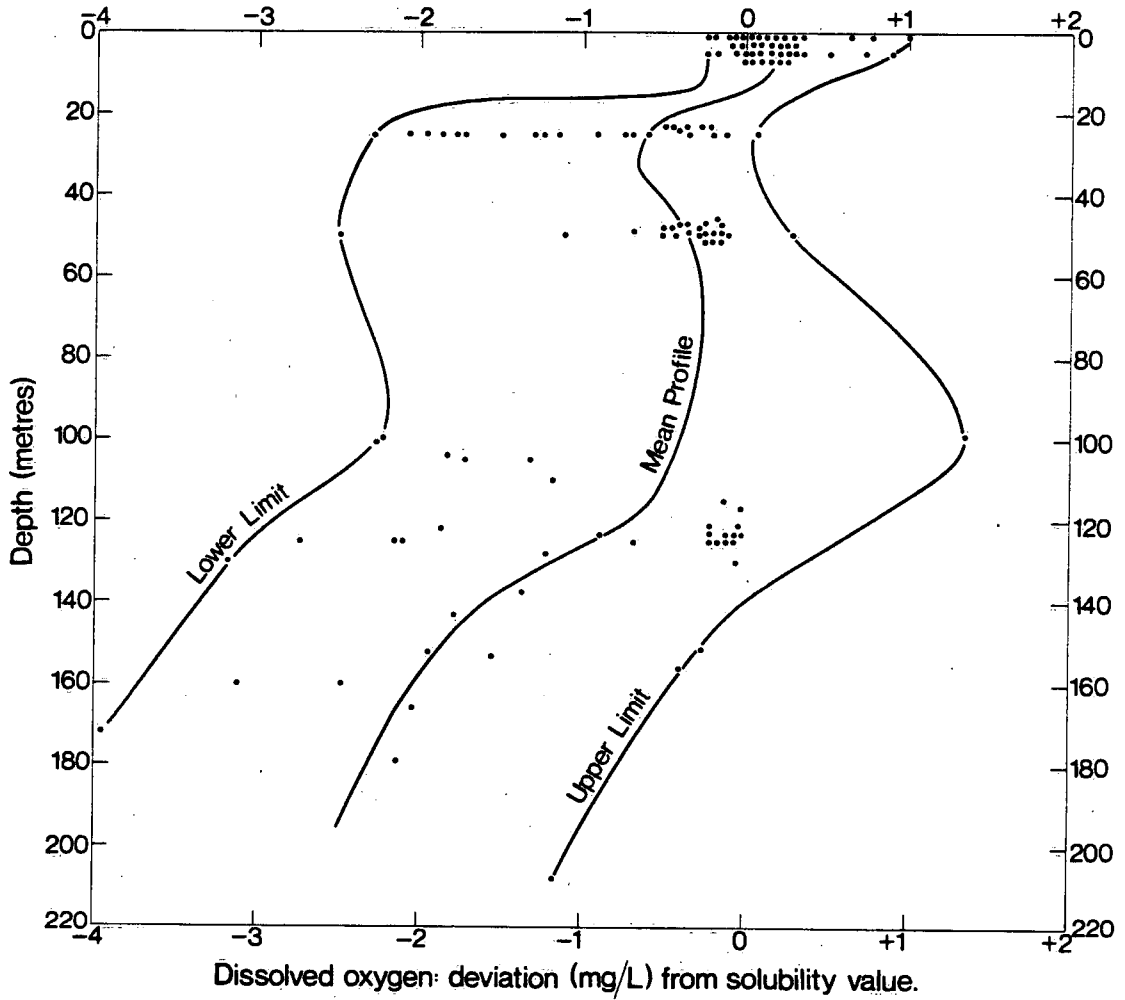
Lake Ontario, particulate nitrogen at offshore stations (soundings >100m), July 17 to 21, 1972, cruise of the Martin Karlsen.

Figure 11.



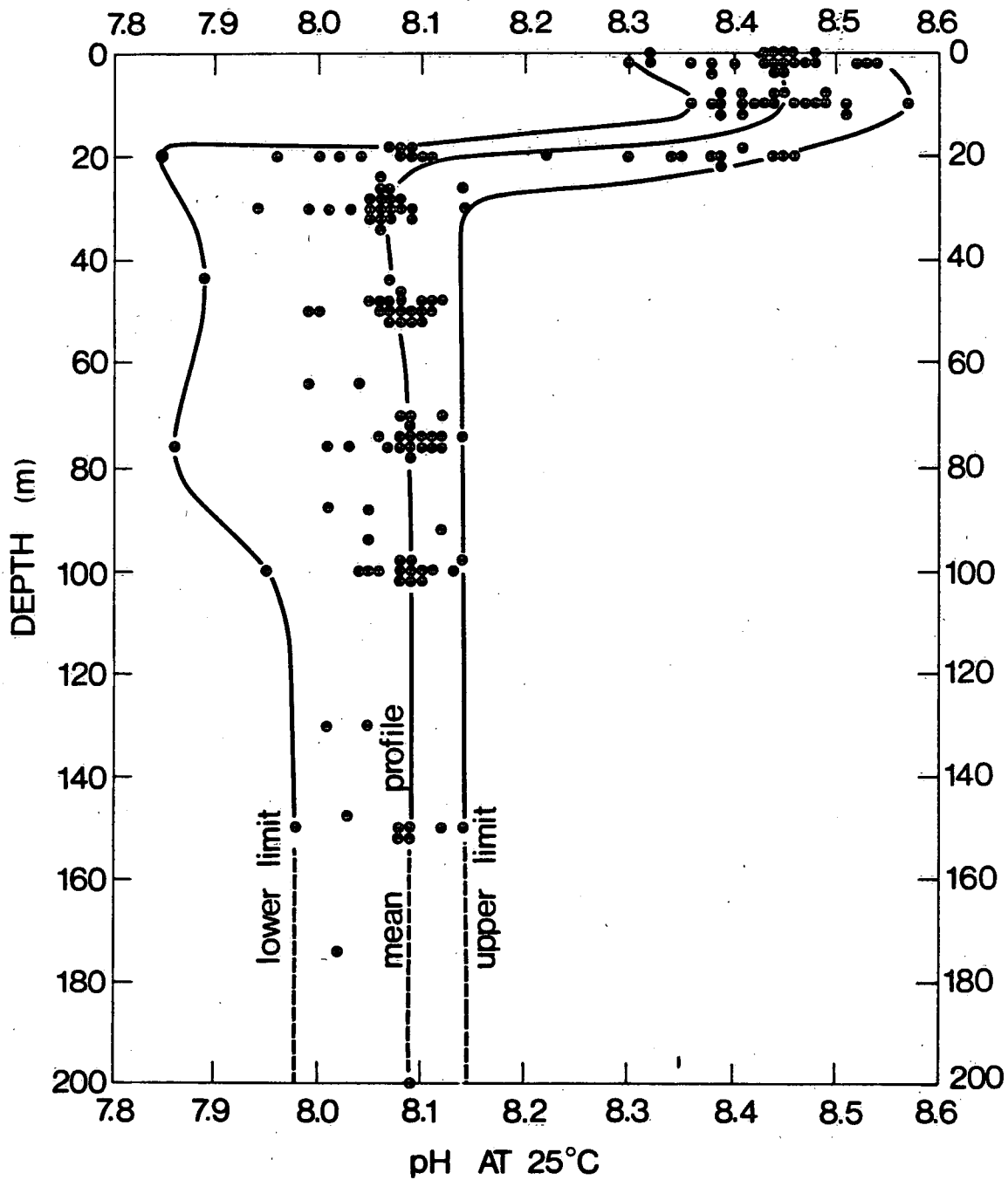
Lake Ontario, particulate nitrogen at offshore stations (soundings > 100m), September 5 to 9, 1972, cruise of the Martin Karlsen.

Figure 12:



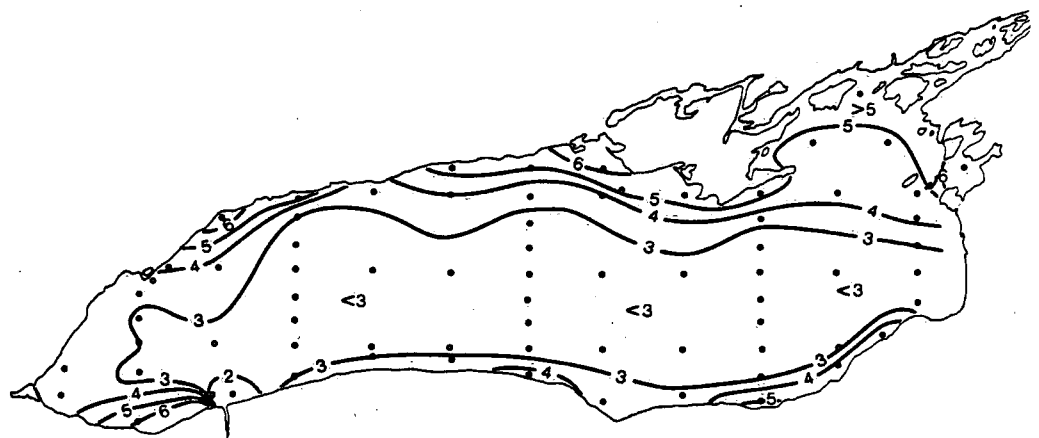
Lake Ontario, dissolved oxygen, deviations (mg/L) from solubility values, versus depth, at 24 offshore stations with soundings >100 m, September 15 to 19, 1970, vessel "Martin Karlsen".

Figure 13.



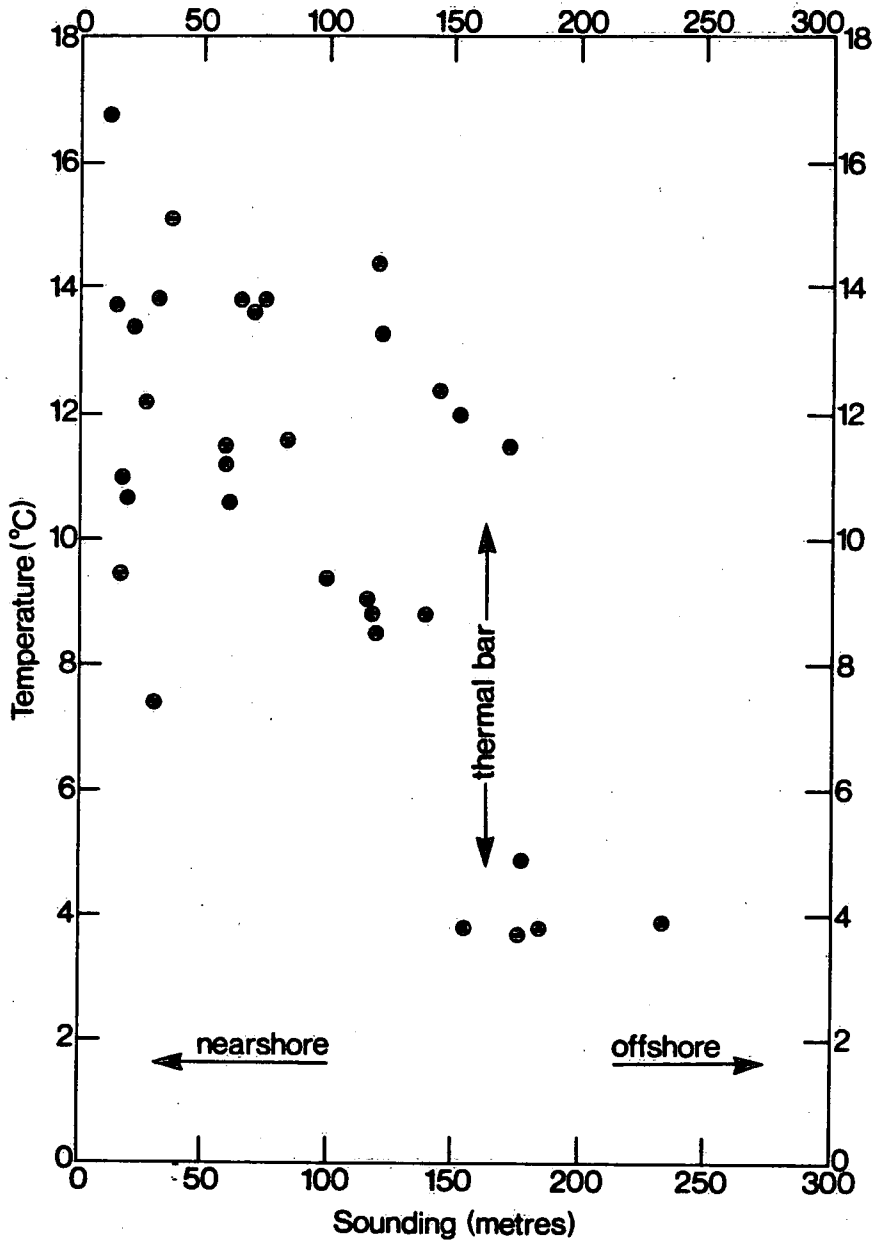
Lake Ontario, pH measured at 25°C, vs depth, at offshore stations with soundings >100m, September 13 to 16, 1966, cruise of the vessel Brandal.

Figure 14.



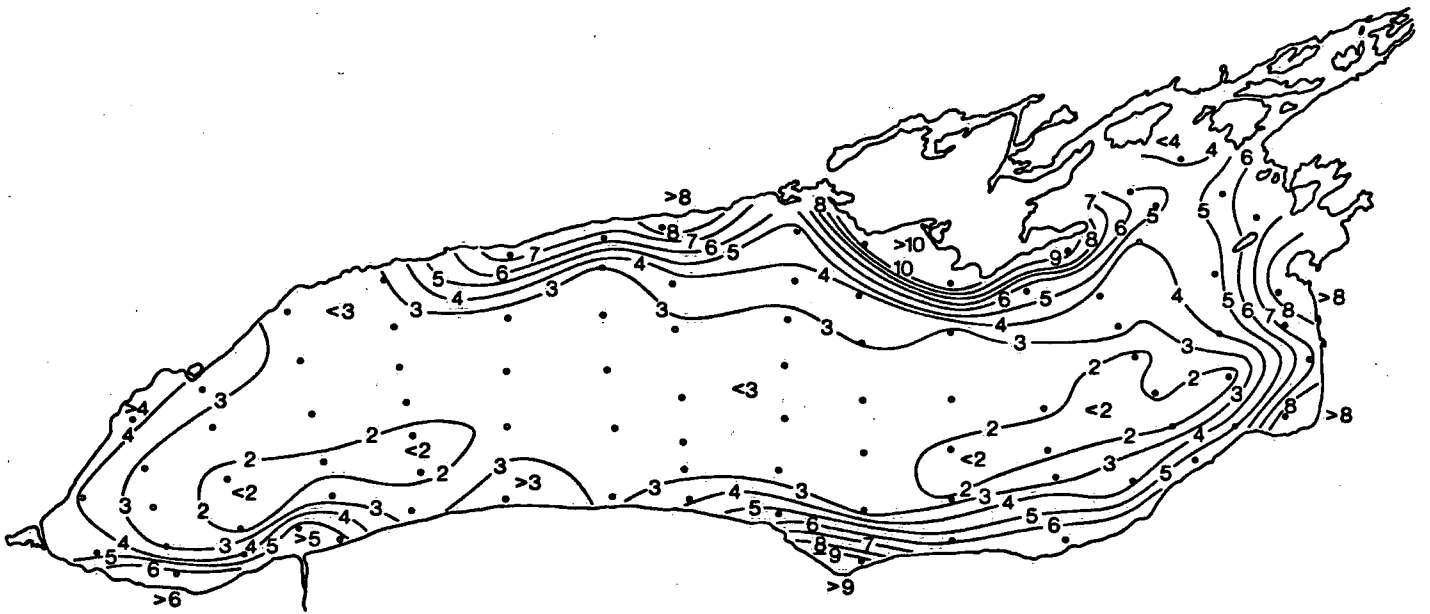
Lake Ontario, temperatures ($^{\circ}\text{C}$) at a depth of 1m,
April 29 to May 3, 1968, cruise of the "Theron".

Figure 15.



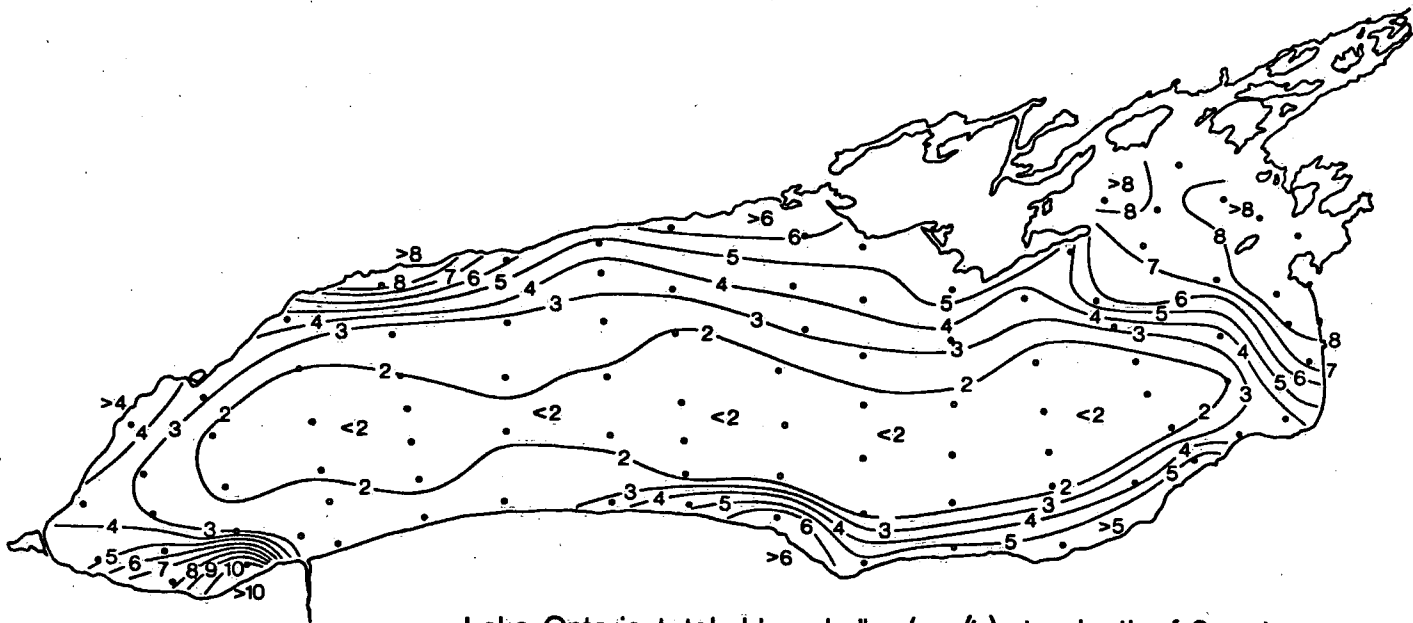
Lake Ontario, temperature at 1 m depth, versus the sounding at the same station, June 19 to 23, 1972, cruise of the Martin Karlsen.

Figure 16.



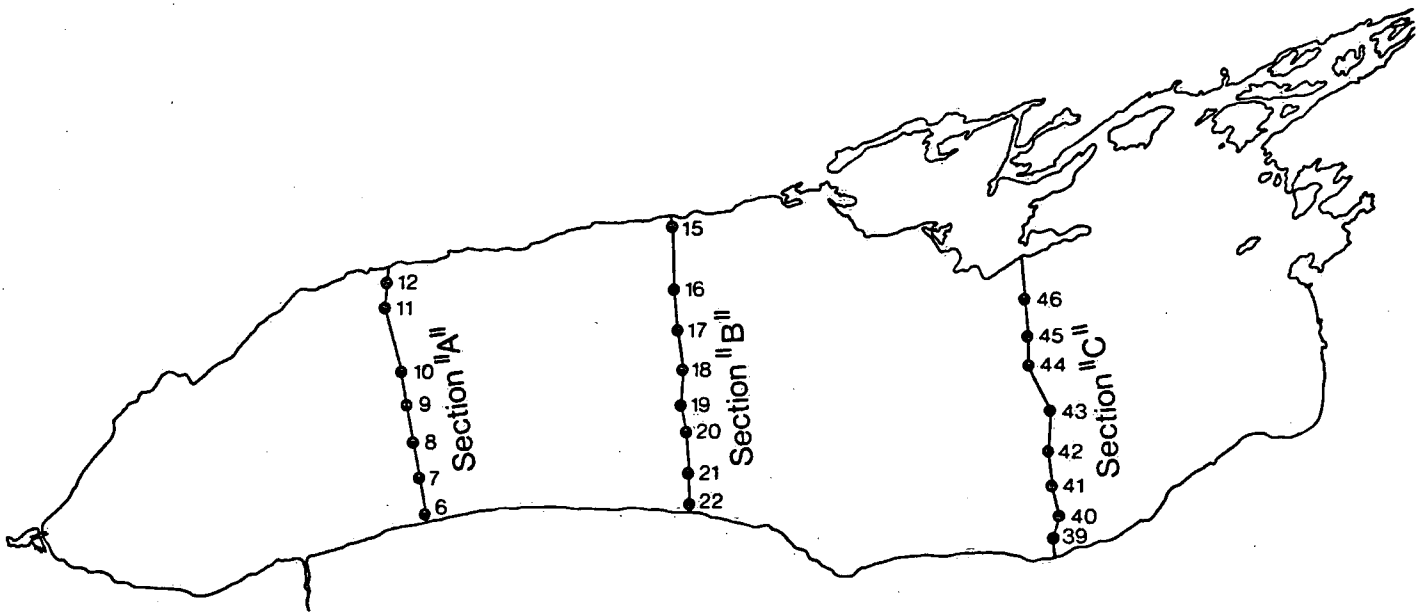
Lake Ontario, total chlorophyll *a* ($\mu\text{g/L}$) at a depth of 0 metres, April 4 to 8, 1972, Limnos and Porte Dauphine.

Figure 17.



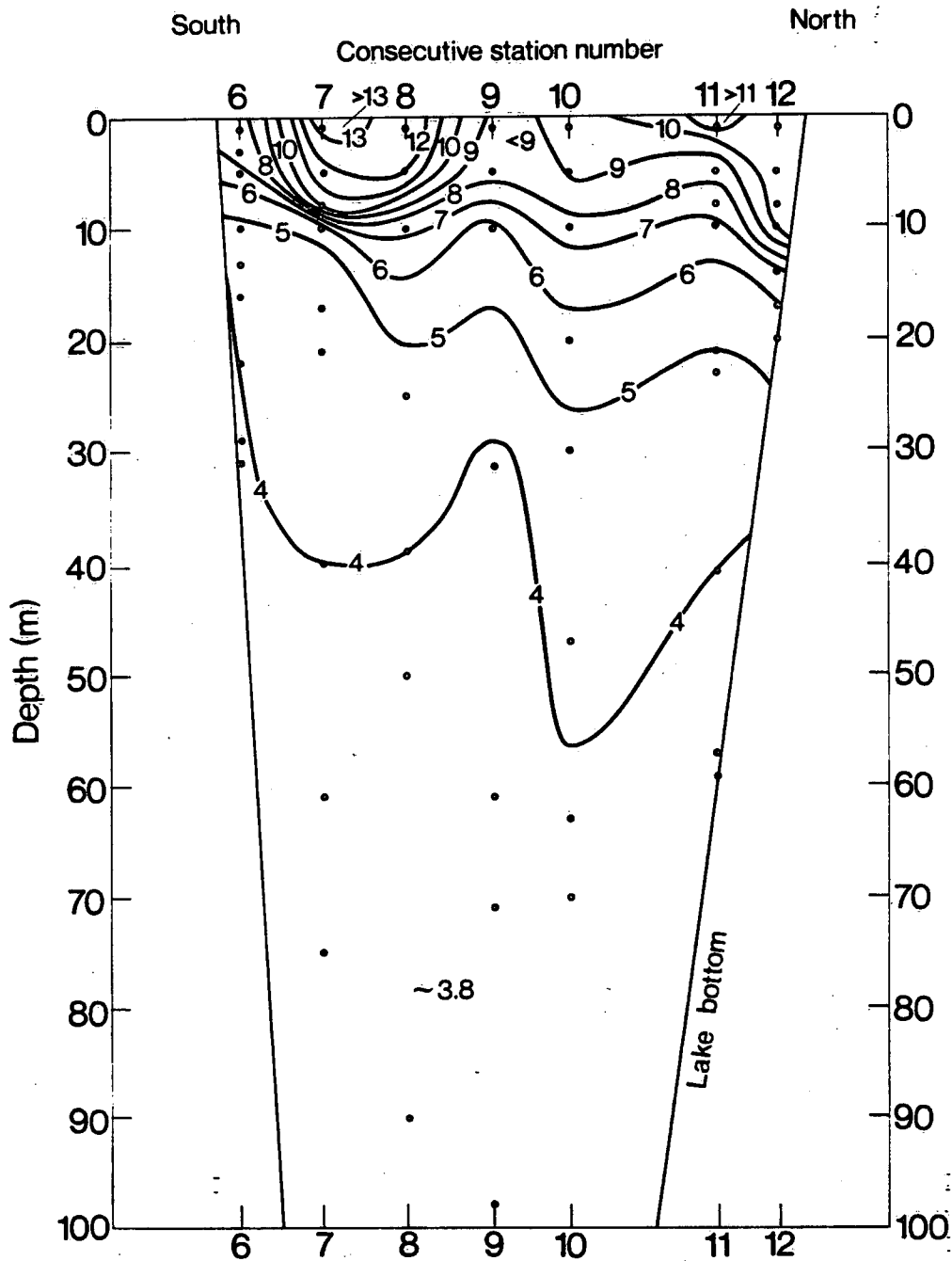
Lake Ontario, total chlorophyll a ($\mu\text{g/L}$) at a depth of 0 metres, May 1 to 3, 1972, Limnos and Porte Dauphine.

Figure 18.



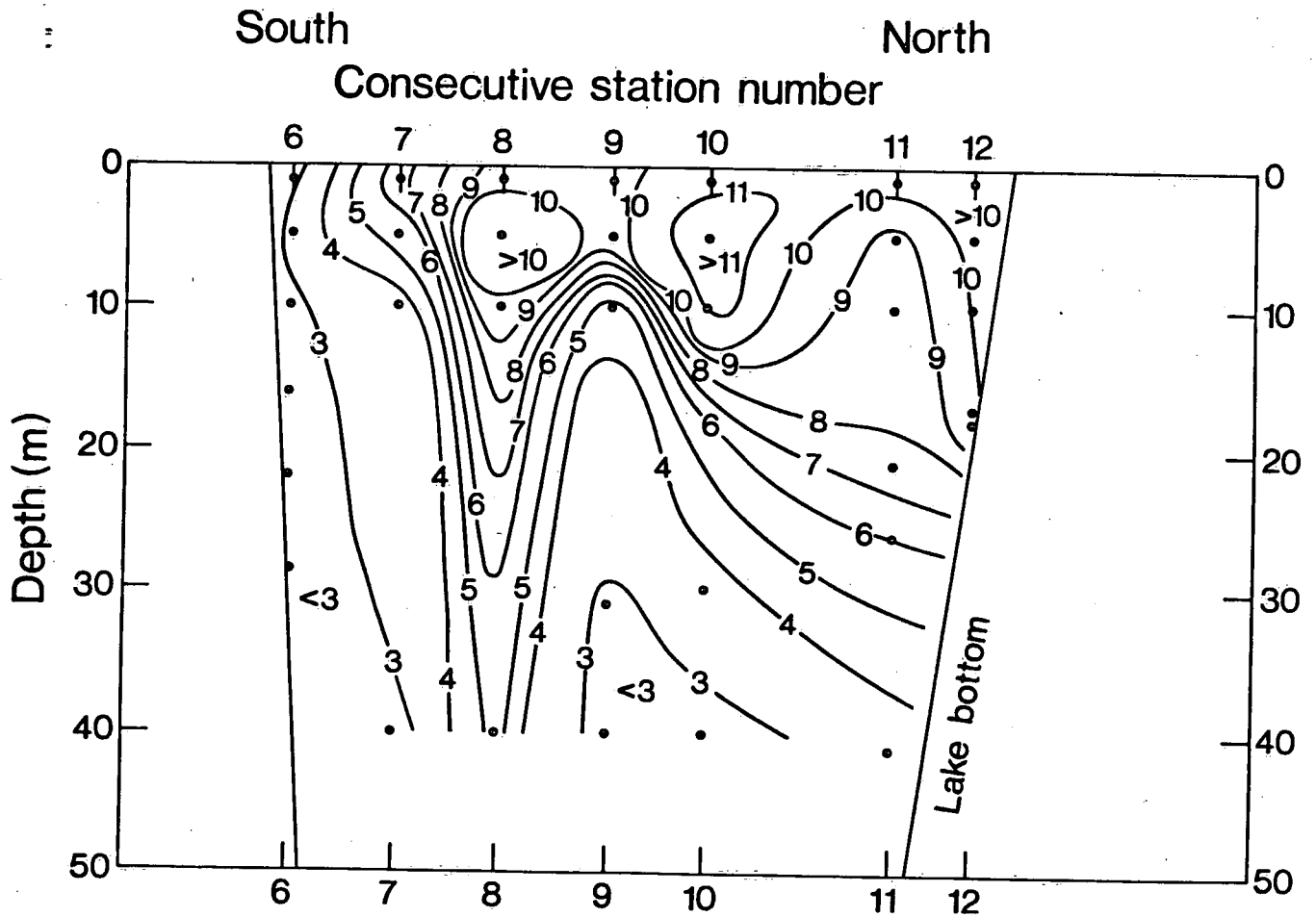
Lake Ontario, June 20 to 23, 1972, cruise of the "Martin Karlsen": locations of the 3 transverse sections, and consecutive station numbers.

Figure 19.



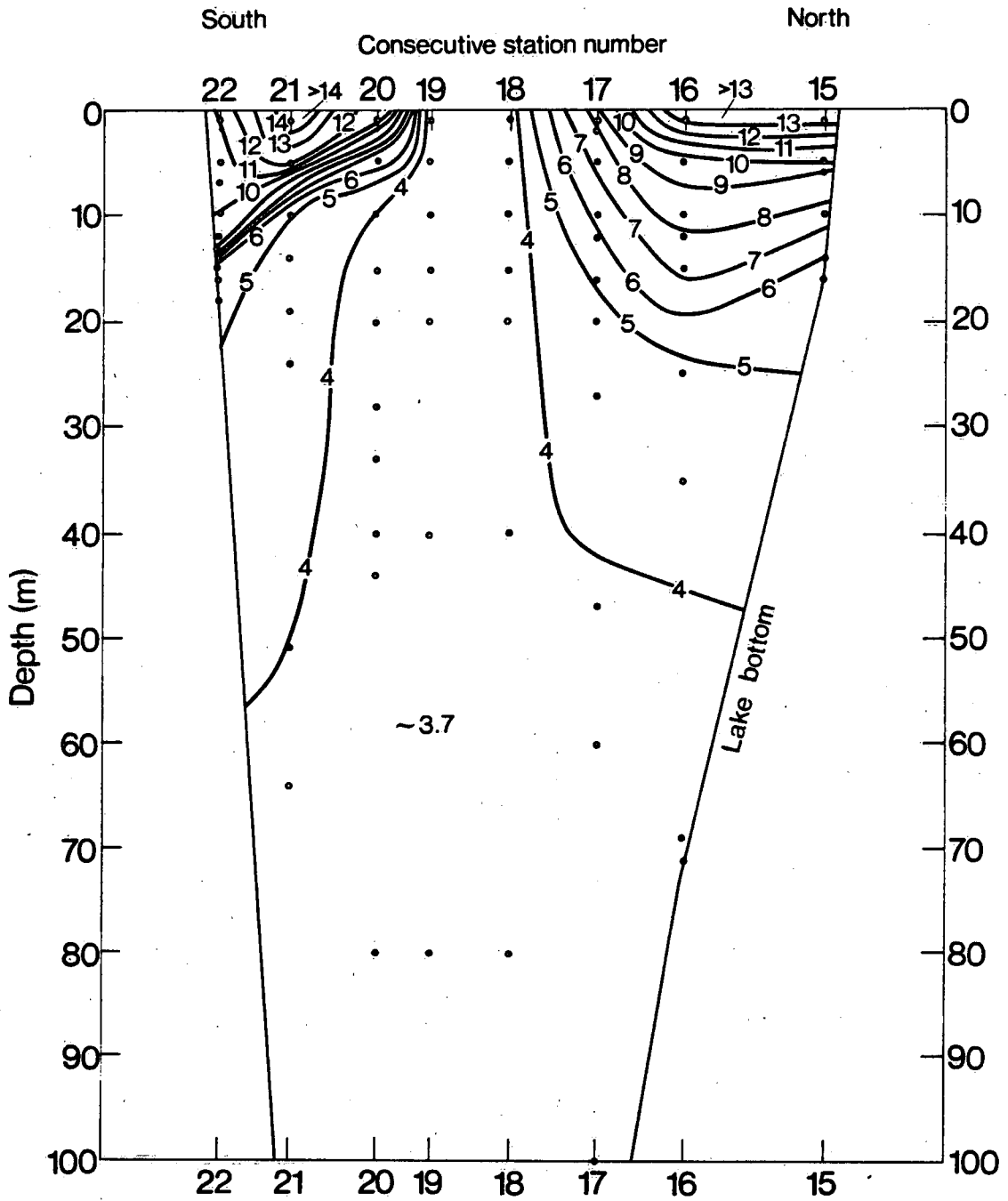
Lake Ontario, temperatures ($^{\circ}\text{C}$) in transverse section "A", June 20, 1972, vessel "Martin Karlsen".

Figure 20.



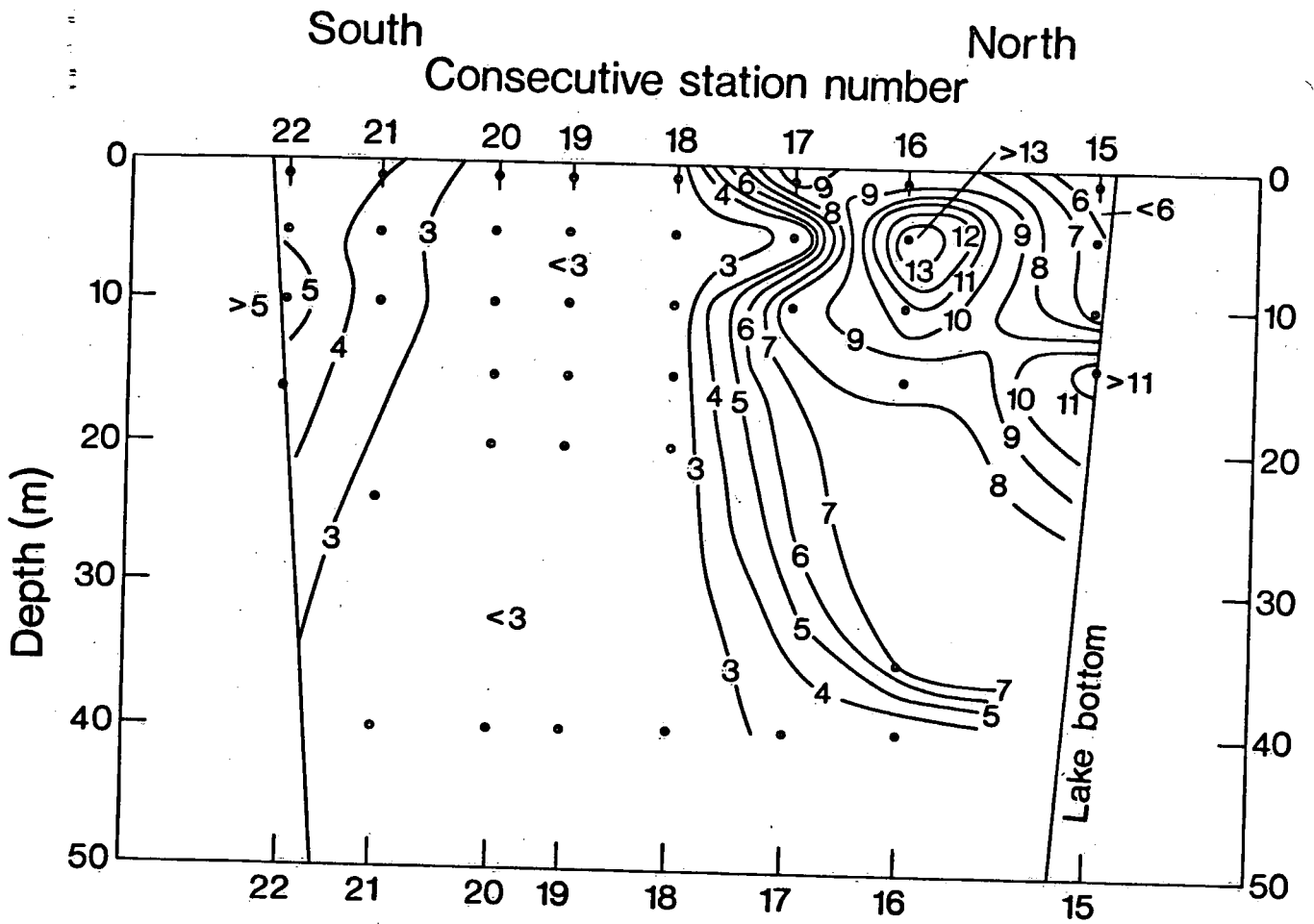
Lake Ontario, total chlorophyll *a* (µg/L) in transverse section "A", June 20, 1972, vessel "Martin Karlsen".

Figure 21.



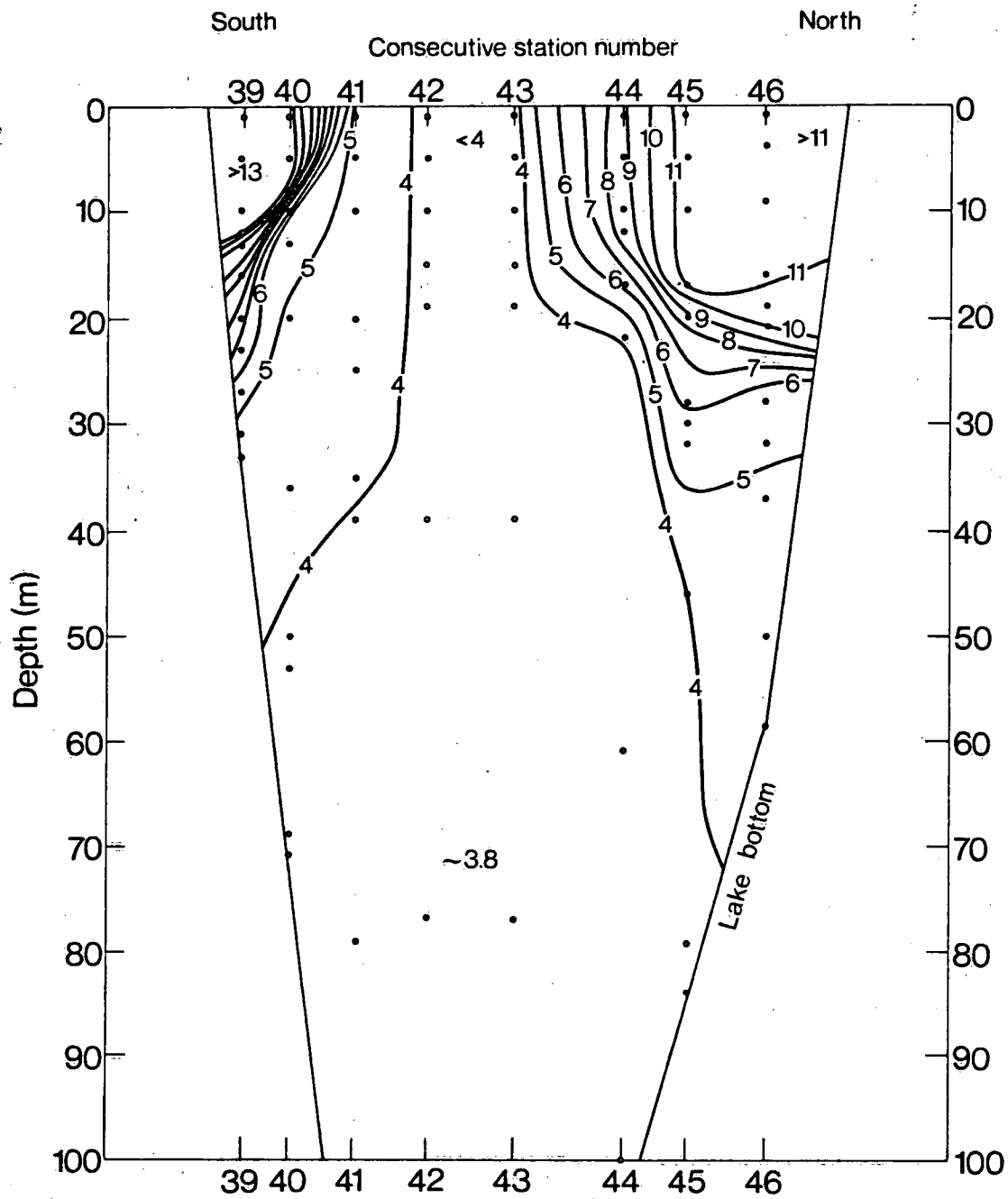
Lake Ontario, temperatures ($^{\circ}\text{C}$) in transverse section "B",
 June 20 & 21, 1972, vessel "Martin Karlsen".

Figure 22.



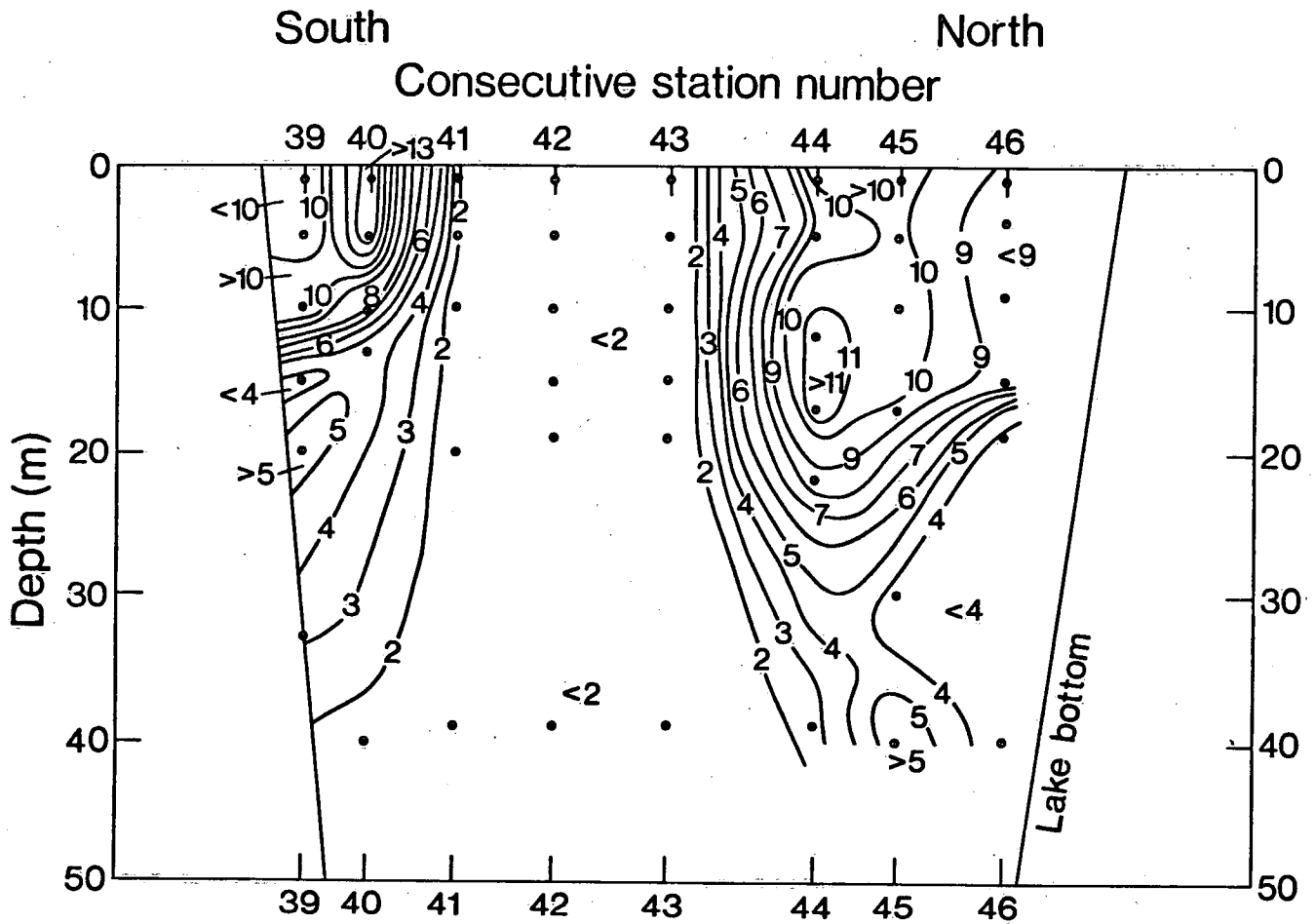
Lake Ontario, total chlorophyll *a* (µg/L) in transverse section "B", June 20 & 21, 1972, vessel "Martin Karlsen".

Figure 23.



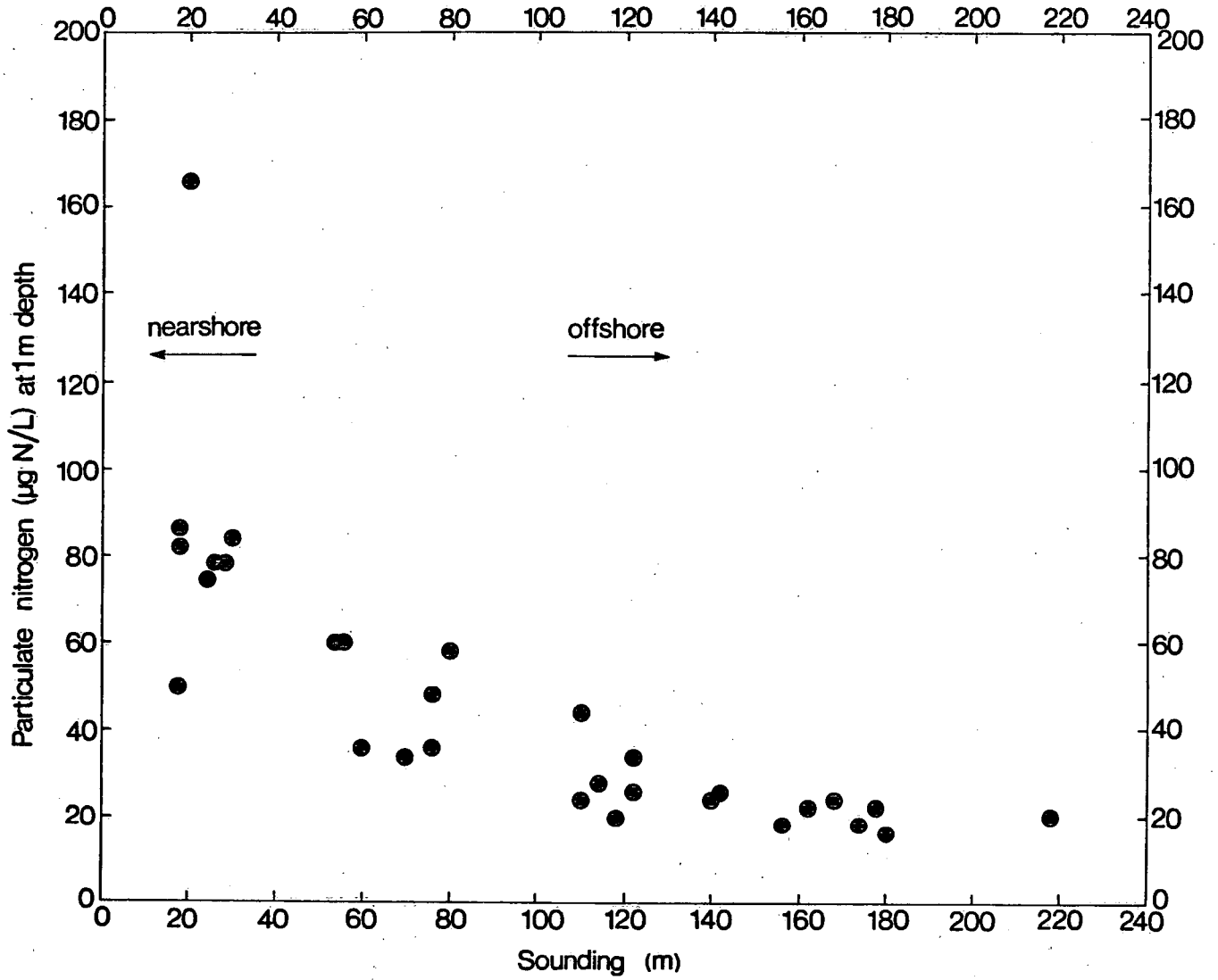
Lake Ontario, temperatures ($^{\circ}\text{C}$) in transverse section "C",
 June 22 & 23, 1972, vessel "Martin Karlsen".

Figure 24.



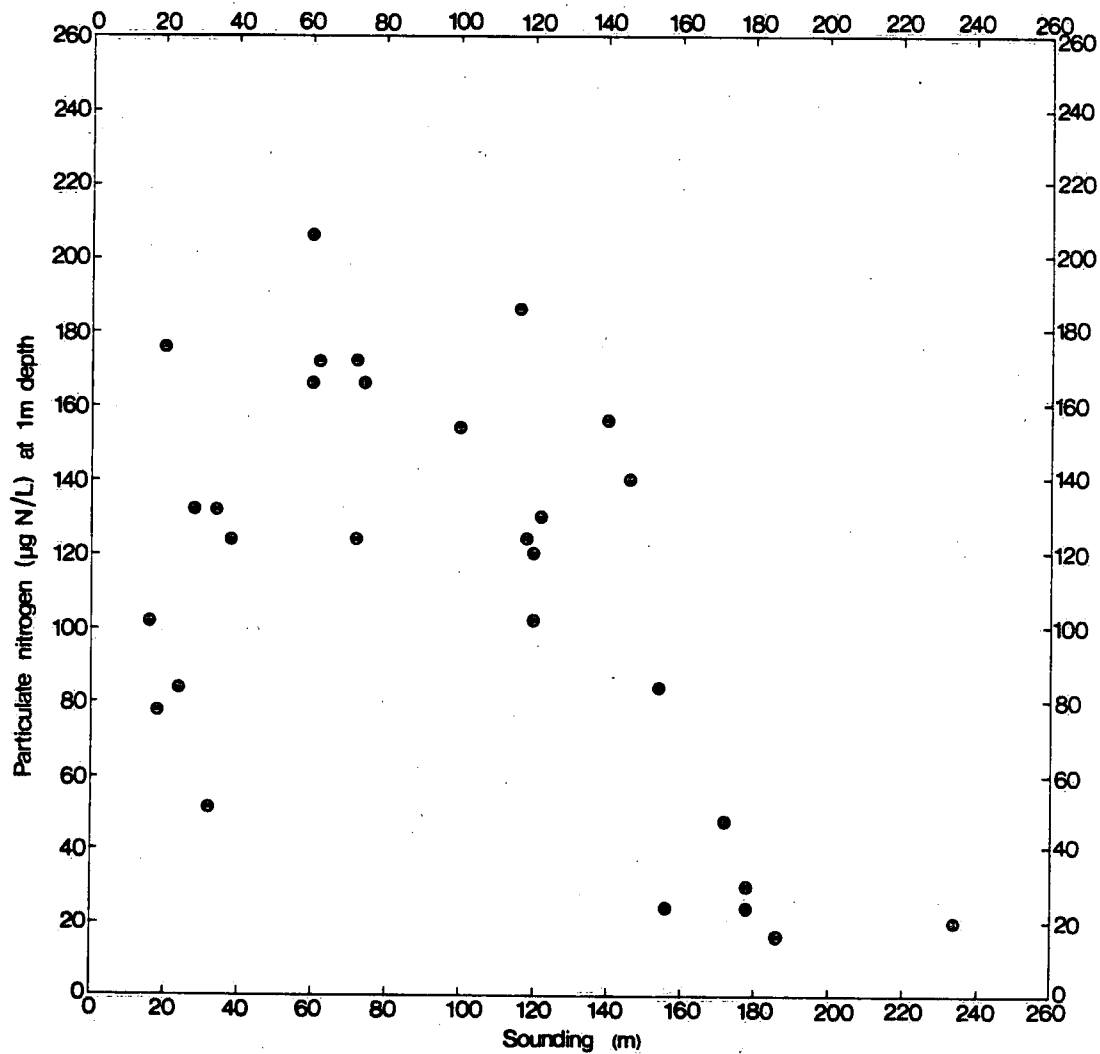
Lake Ontario, total chlorophyll *a* (µg/L) in transverse section "C", June 22 & 23, 1972, vessel "Martin Karlsen".

Figure 25.



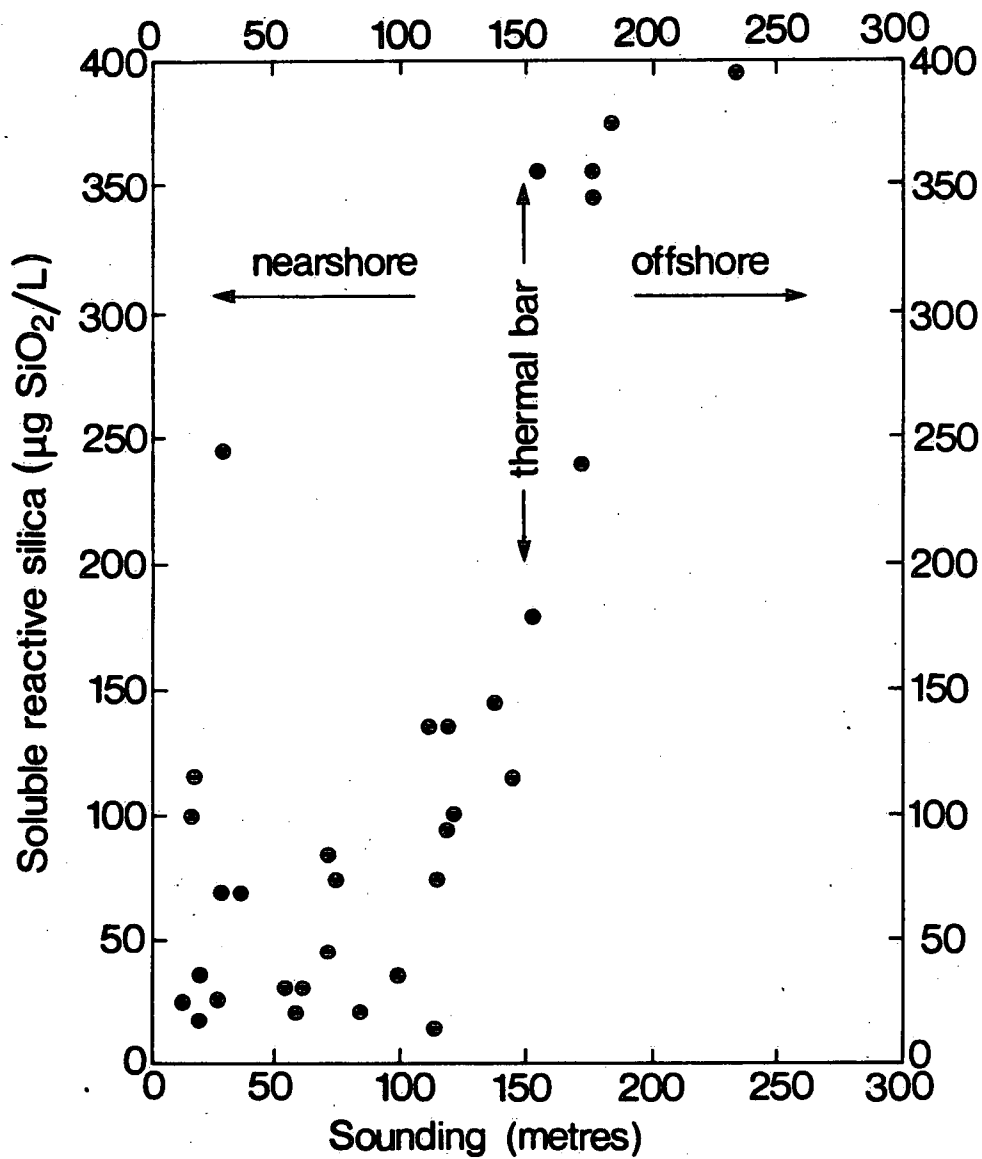
Lake Ontario, particulate nitrogen at 1 m depth, vs the sounding at the same station, May 23 to 29, 1972, cruise of the Martin Karlsen.

Figure 26.



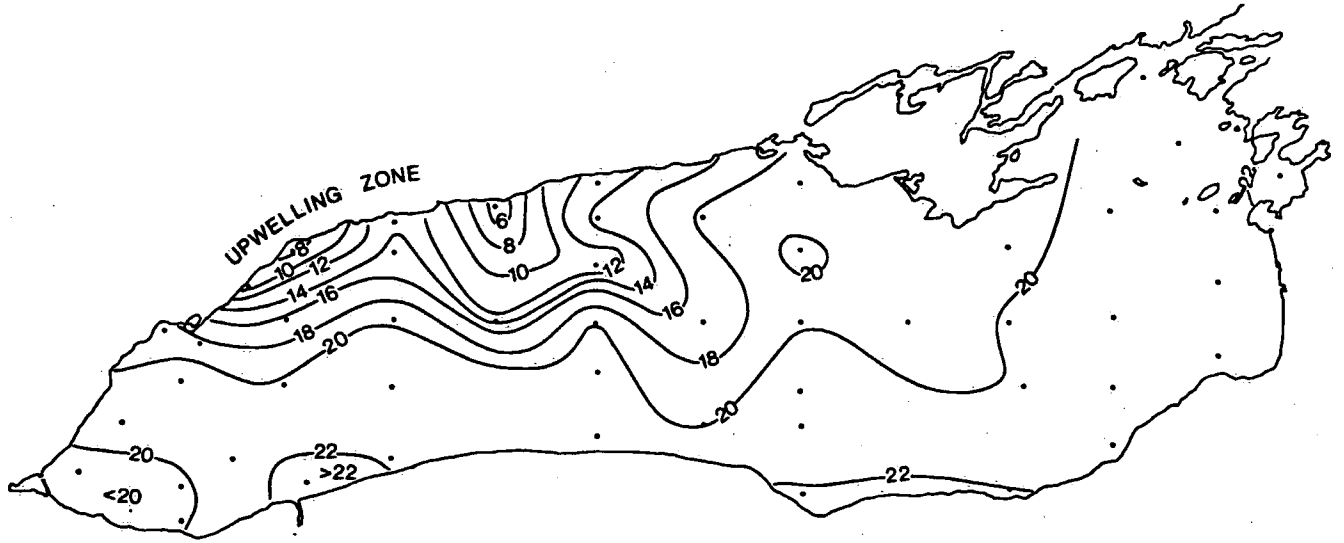
Lake Ontario, particulate nitrogen at 1m depth, vs the sounding at the same station, June 19 to 23, 1972, cruise of the Martin Karlsen.

Figure 27.



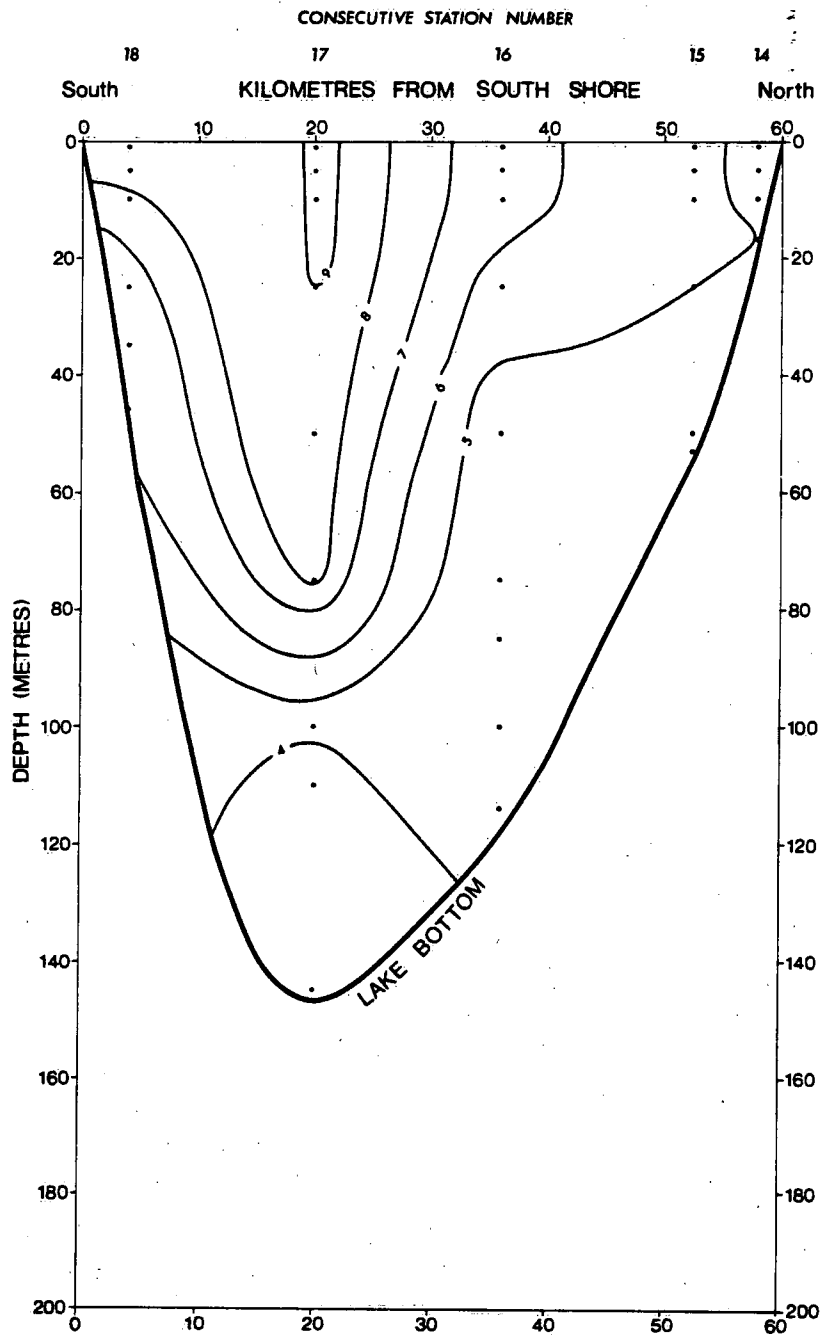
Lake Ontario, soluble reactive silica at 1m depth vs the sounding at the same station, June 19 to 23, 1972, cruise of the Martin Karlsen.

Figure 28.



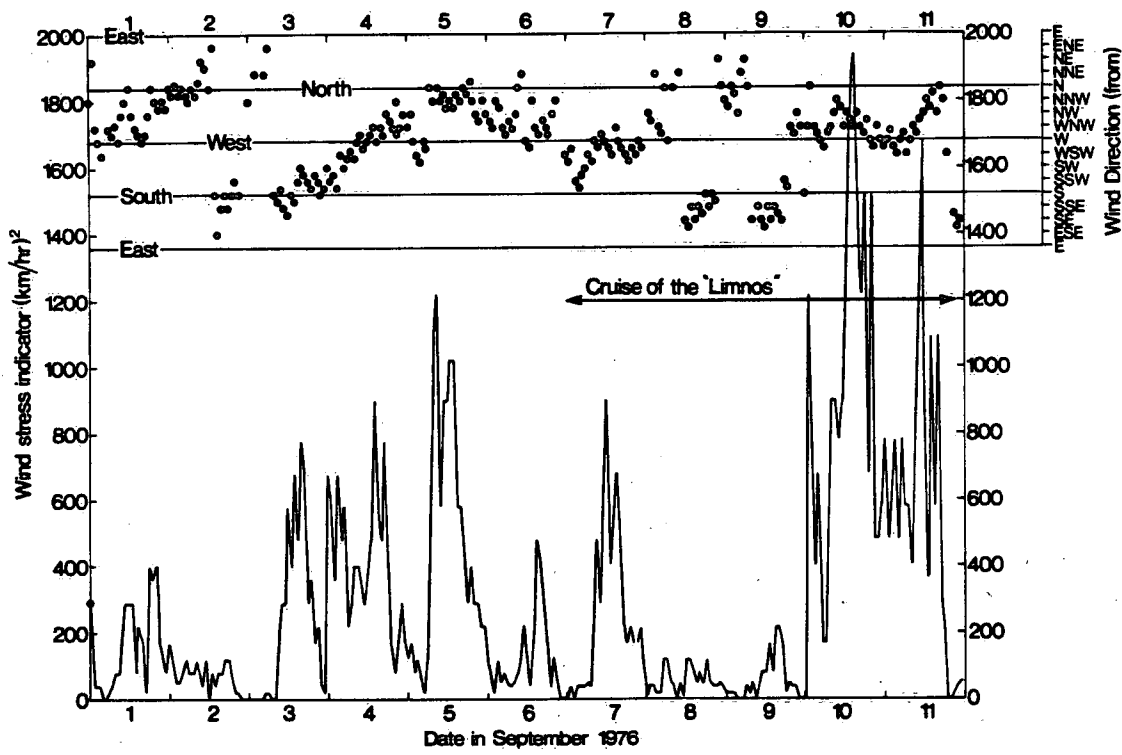
Lake Ontario, temperatures (°C) at a depth of 1 metre, August 9 to 13, 1971, cruise of the "Martin Karlsen".

Figure 29.



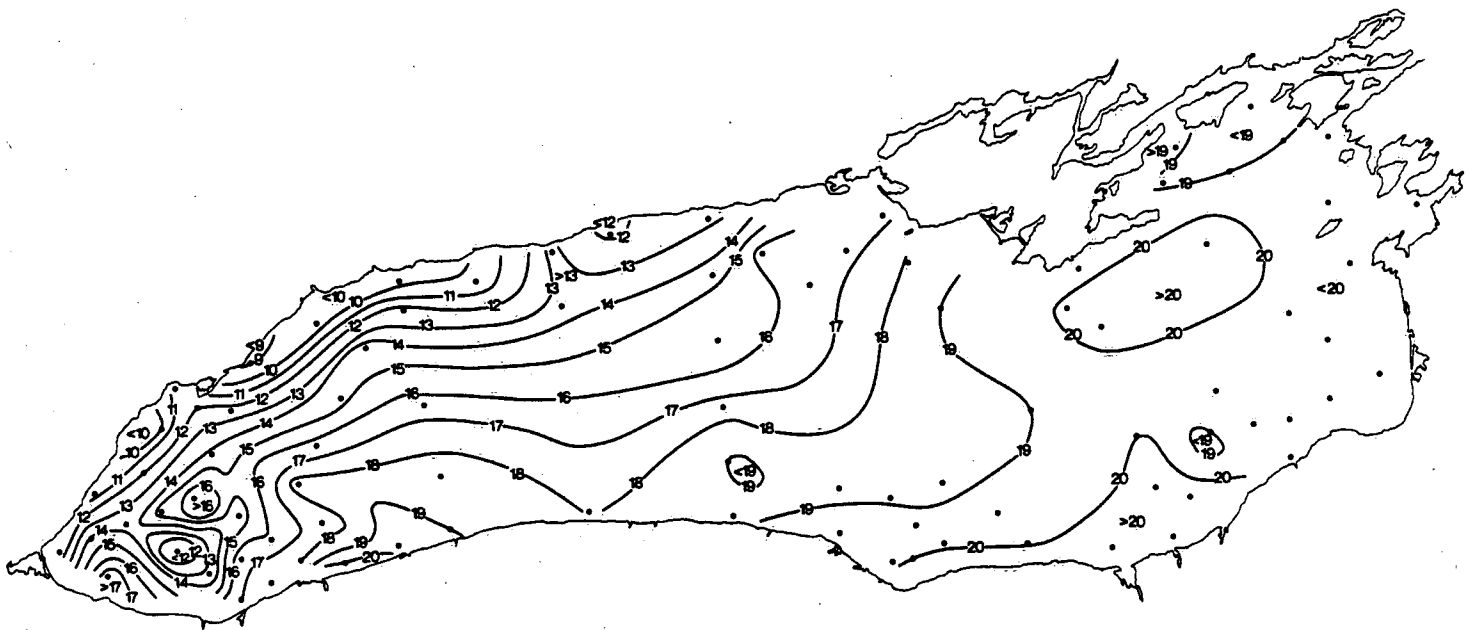
LAKE ONTARIO: NOVEMBER 16, 1971, CRUISE OF THE MARTIN KARLSEN. TEMPERATURE ($^{\circ}\text{C}$) IN A TRANSVERSE SECTION FROM OSHAWA SOUTHWARD.

Figure 30.



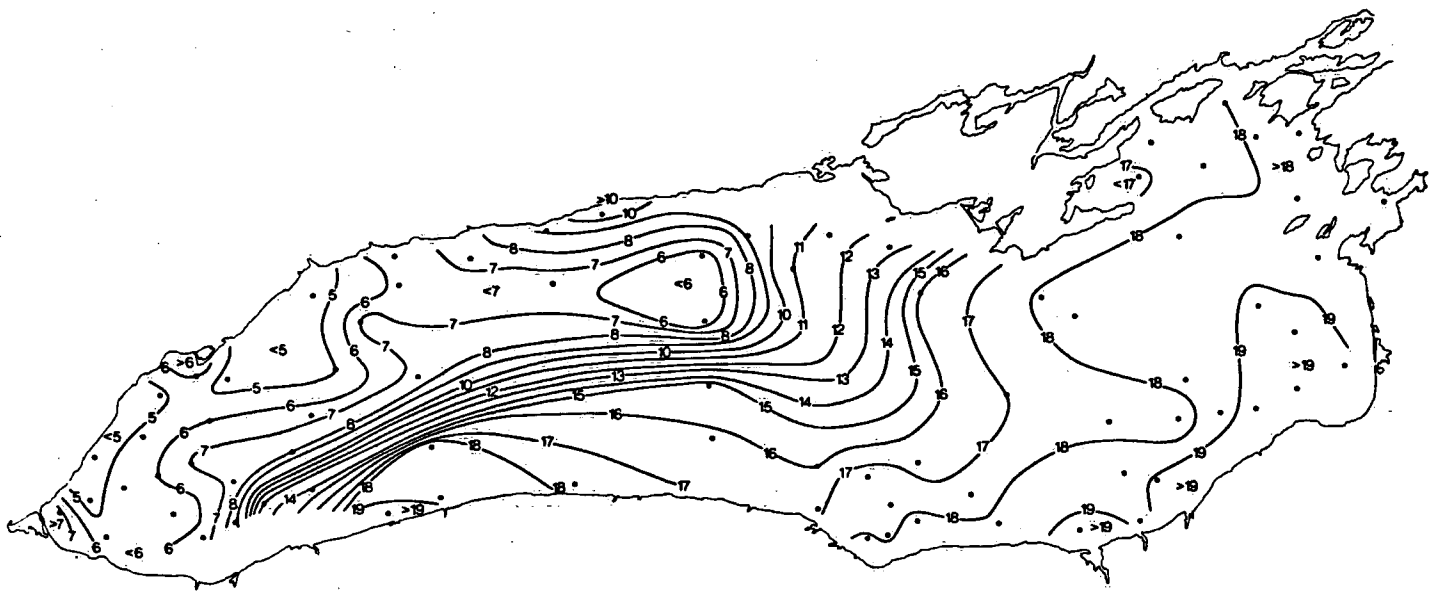
Lake Ontario: winds at Toronto International Airport, September 1 to 11, 1976

Figure 31.



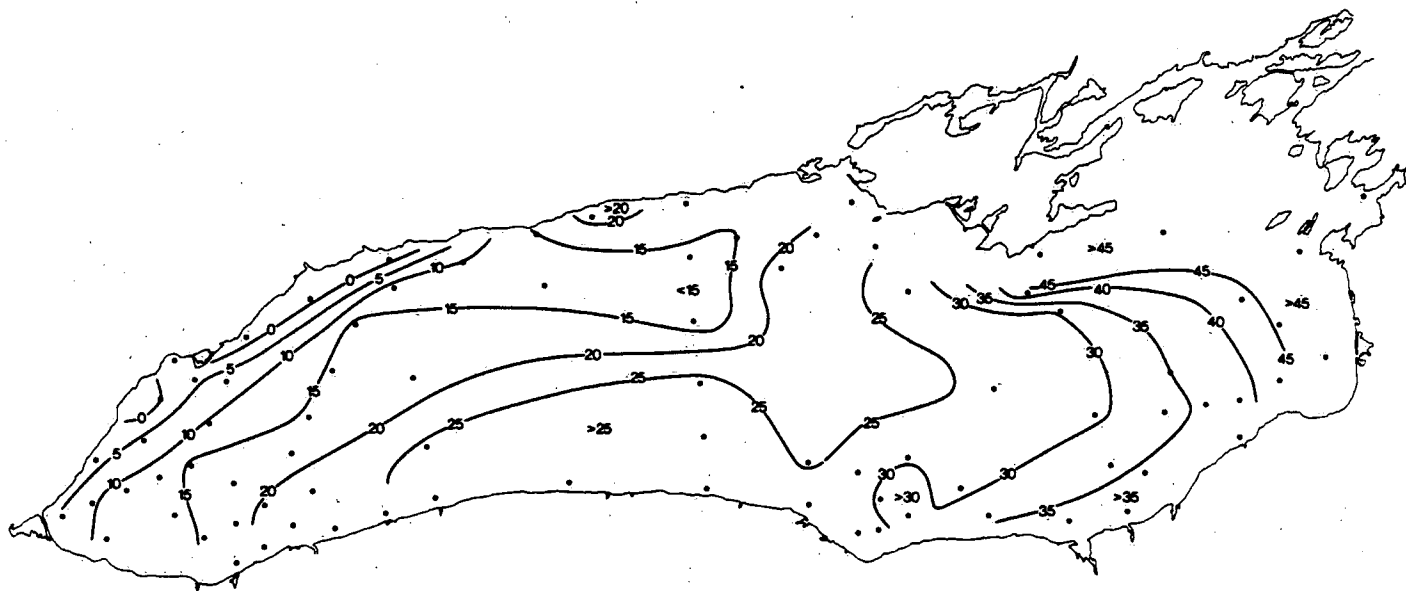
Lake Ontario: Temperature ($^{\circ}\text{C}$) at a depth of 0 metres
September 7 to 11, 1976
Cruise of the 'Limnos'

Figure 32.



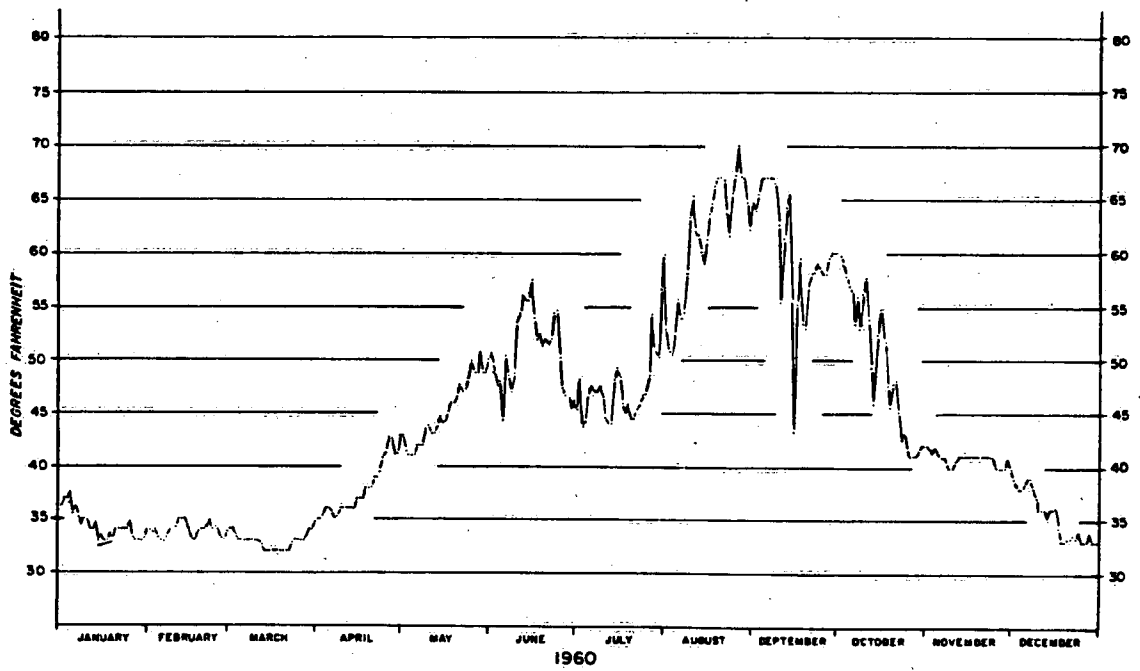
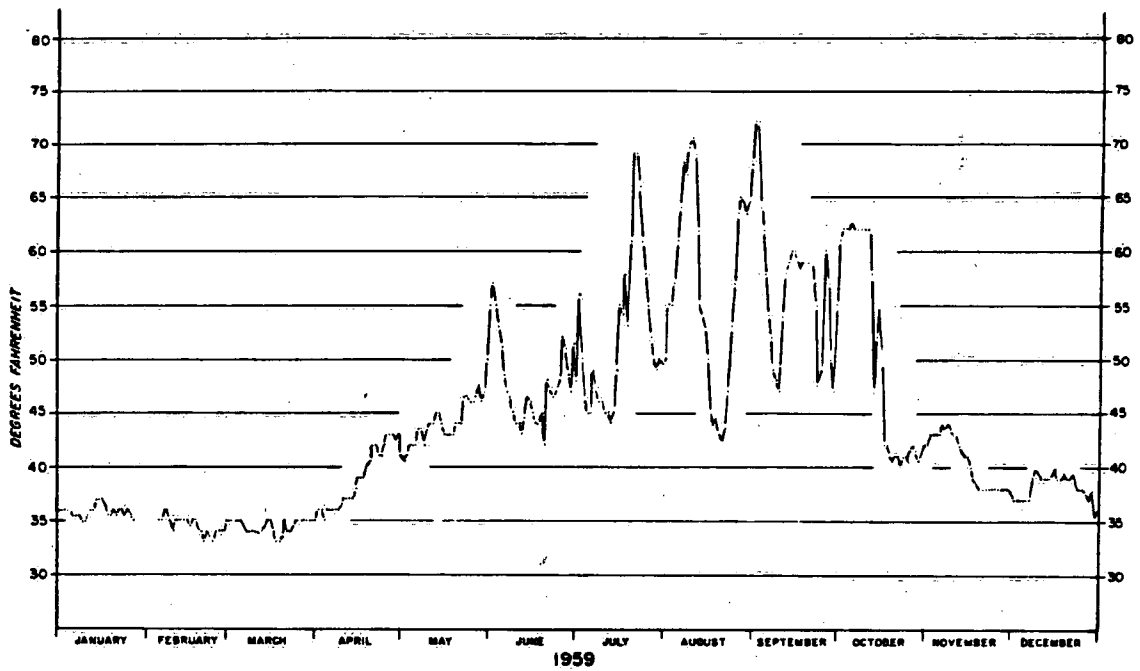
Lake Ontario: Temperature ($^{\circ}\text{C}$) at a depth of 20 metres.
September 7 to 11, 1976
Cruise of the 'Limnos'

Figure 33.



Lake Ontario, Temperature:
Depth (m) of the 10°C isothermal surface.
September 7 to 11, 1976
Cruise of the *Limnos*

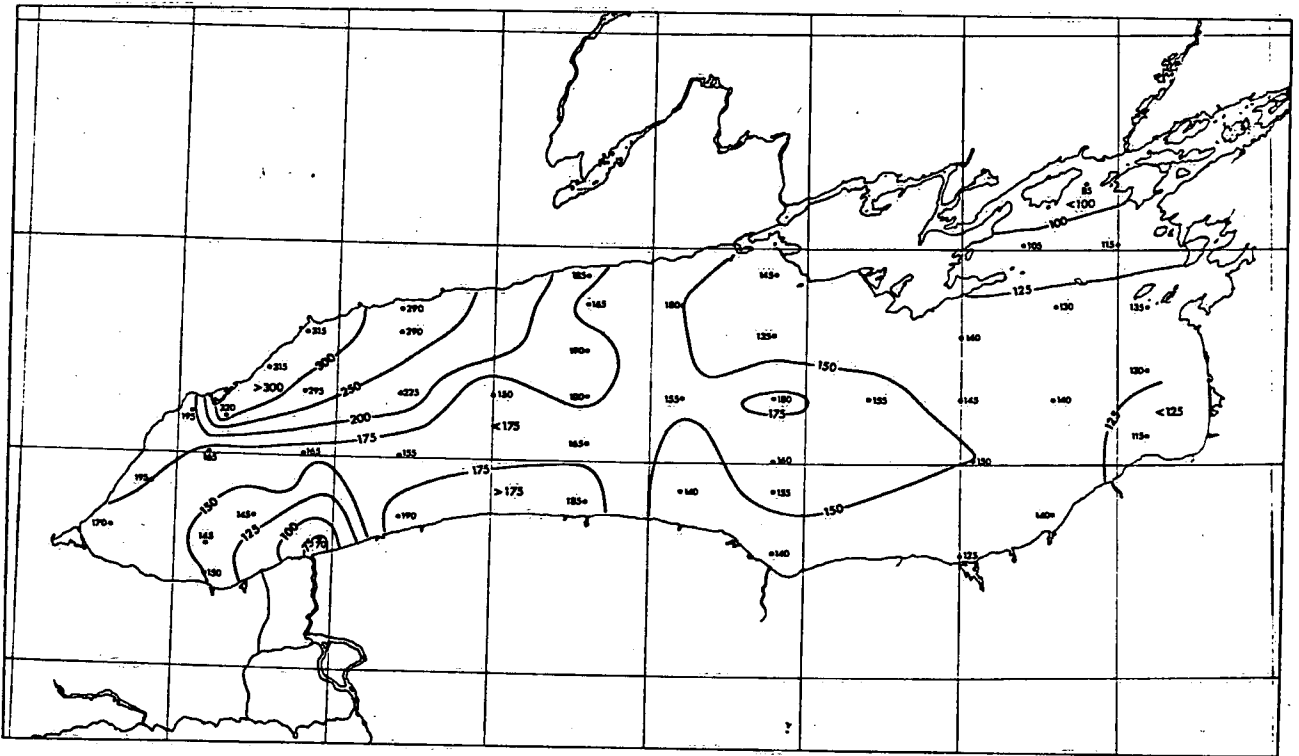
Figure 34.



Average daily water temperatures at Hamilton intakes, 1959 and 1960.

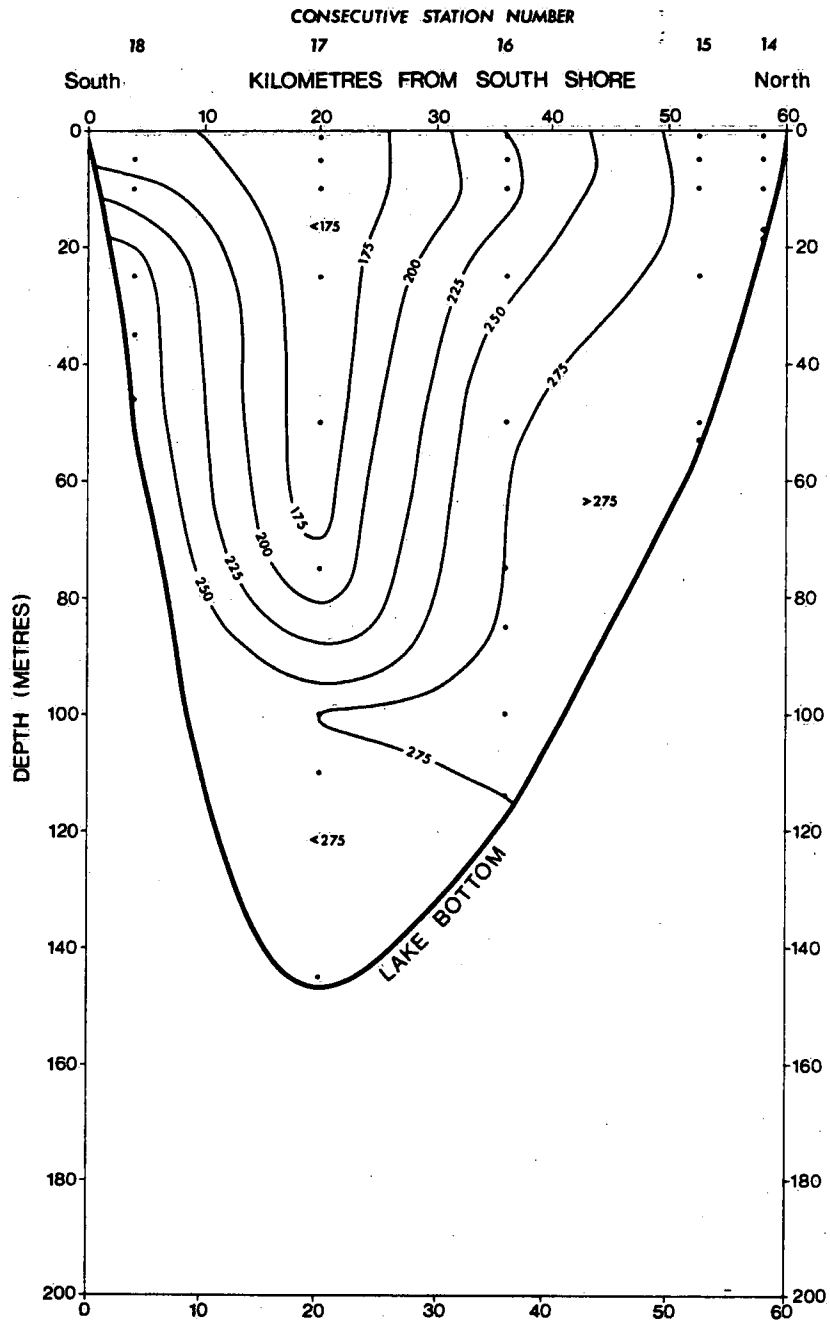
From: Matheson and Anderson, 1965.

Figure 35.



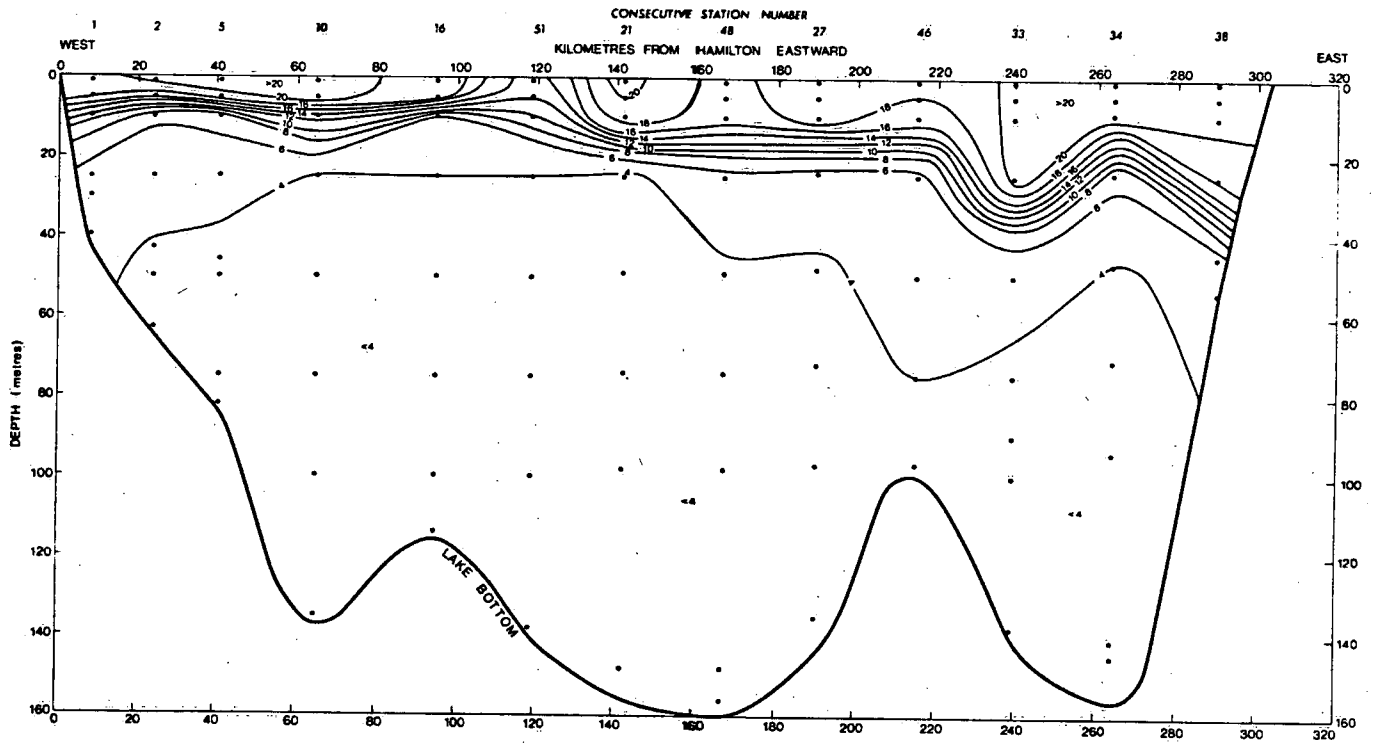
Lake Ontario, nitrate + nitrite ($\mu\text{g N/L}$) at a depth of 1 metre, November 15 to 19, 1971, cruise of the "Martin Karlsen".

Figure 36.



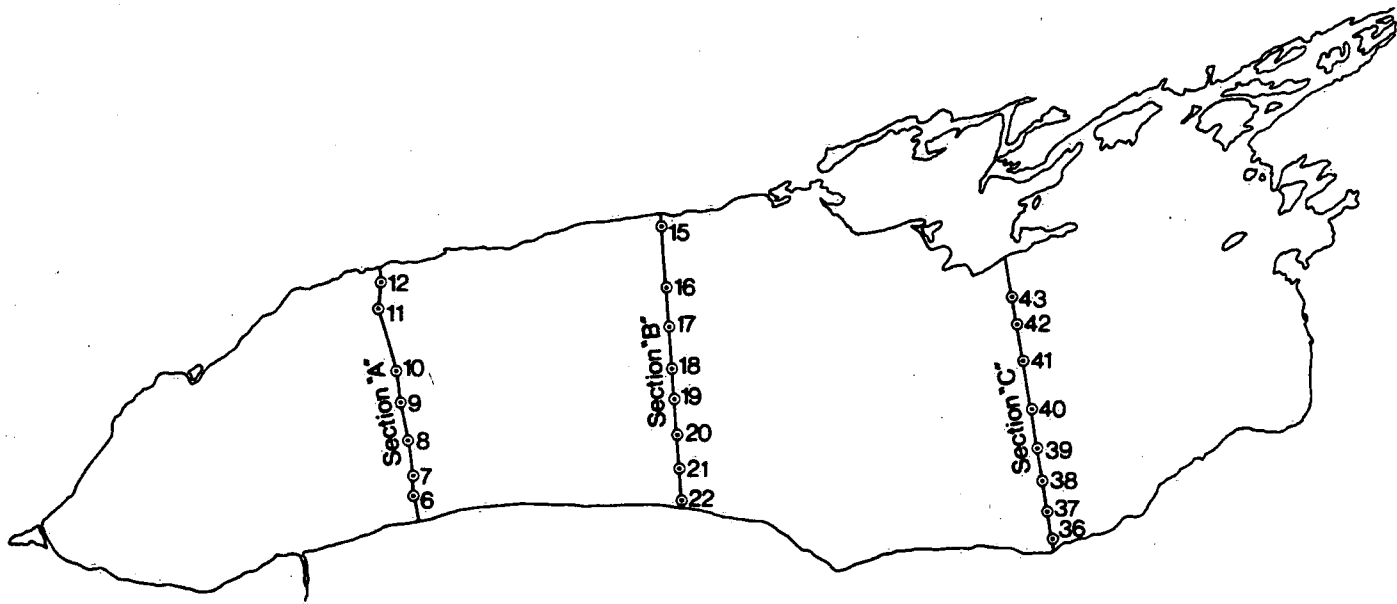
Lake Ontario, nitrate + nitrite ($\mu\text{g N/L}$) in a transverse section from Oshawa southward, November 16, 1971, cruise of the "Martin Karlsen".

Figure 37.



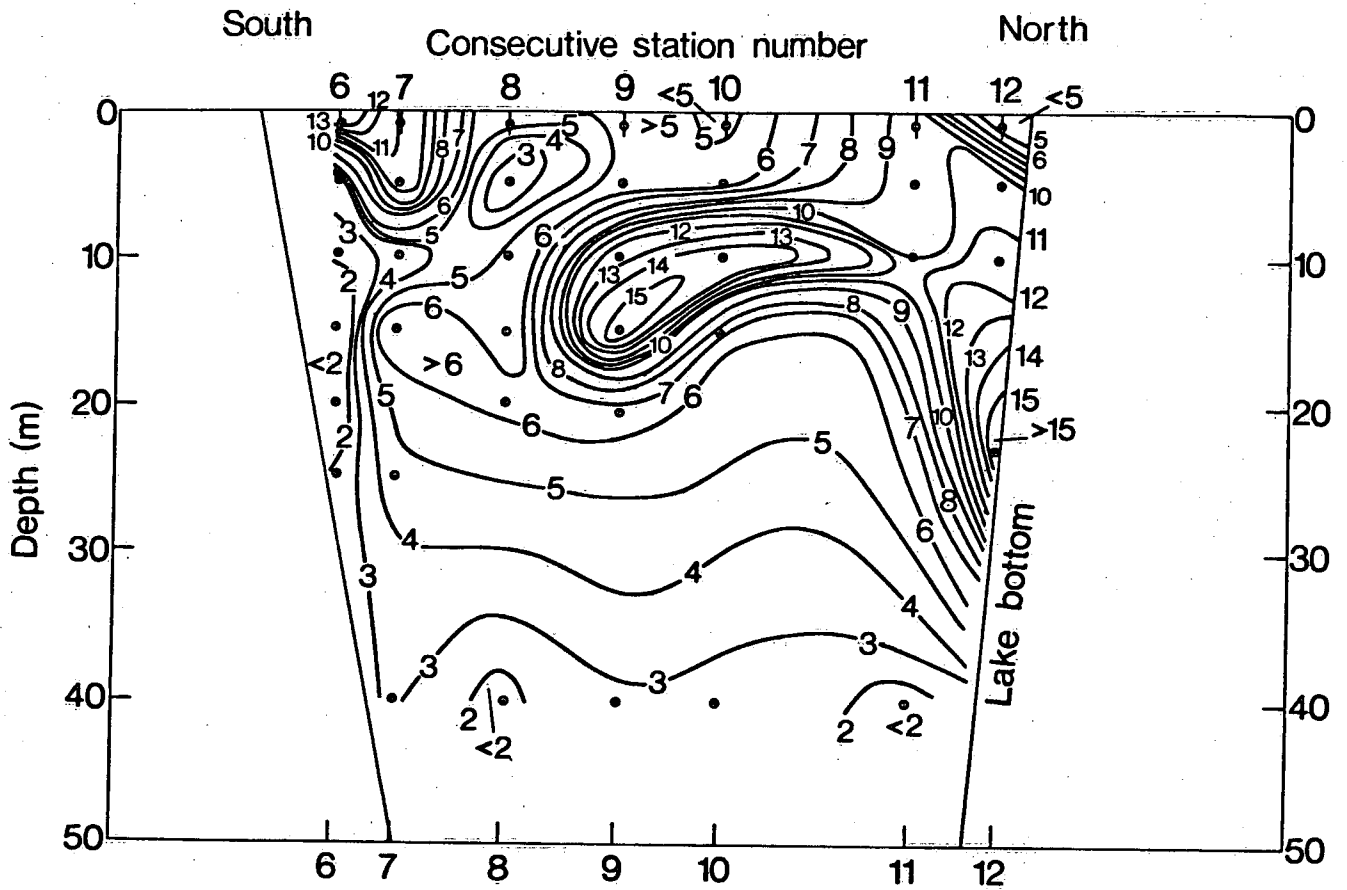
LAKE ONTARIO, AUGUST 9 TO 13, 1971. CRUISE OF THE 'MARTIN KARLSEN'. TEMPERATURE IN A LONGITUDINAL SECTION FROM HAMILTON, EASTWARD. UNITS ARE °C

Figure 3B.



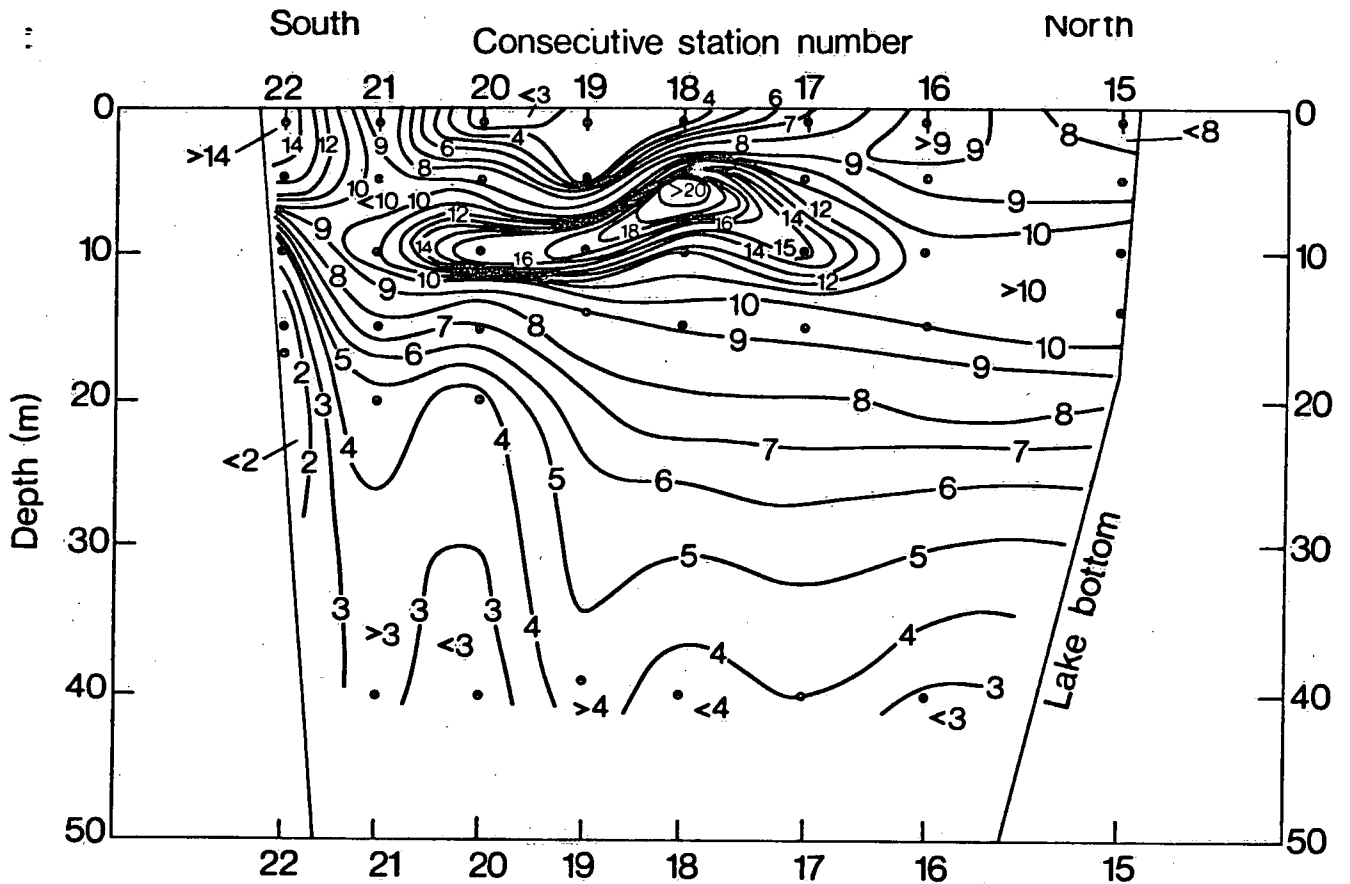
Lake Ontario, July 18 to 21, 1972, cruise of the "Martin Karlsen": locations of the three transverse sections, and consecutive station numbers.

Figure 39.



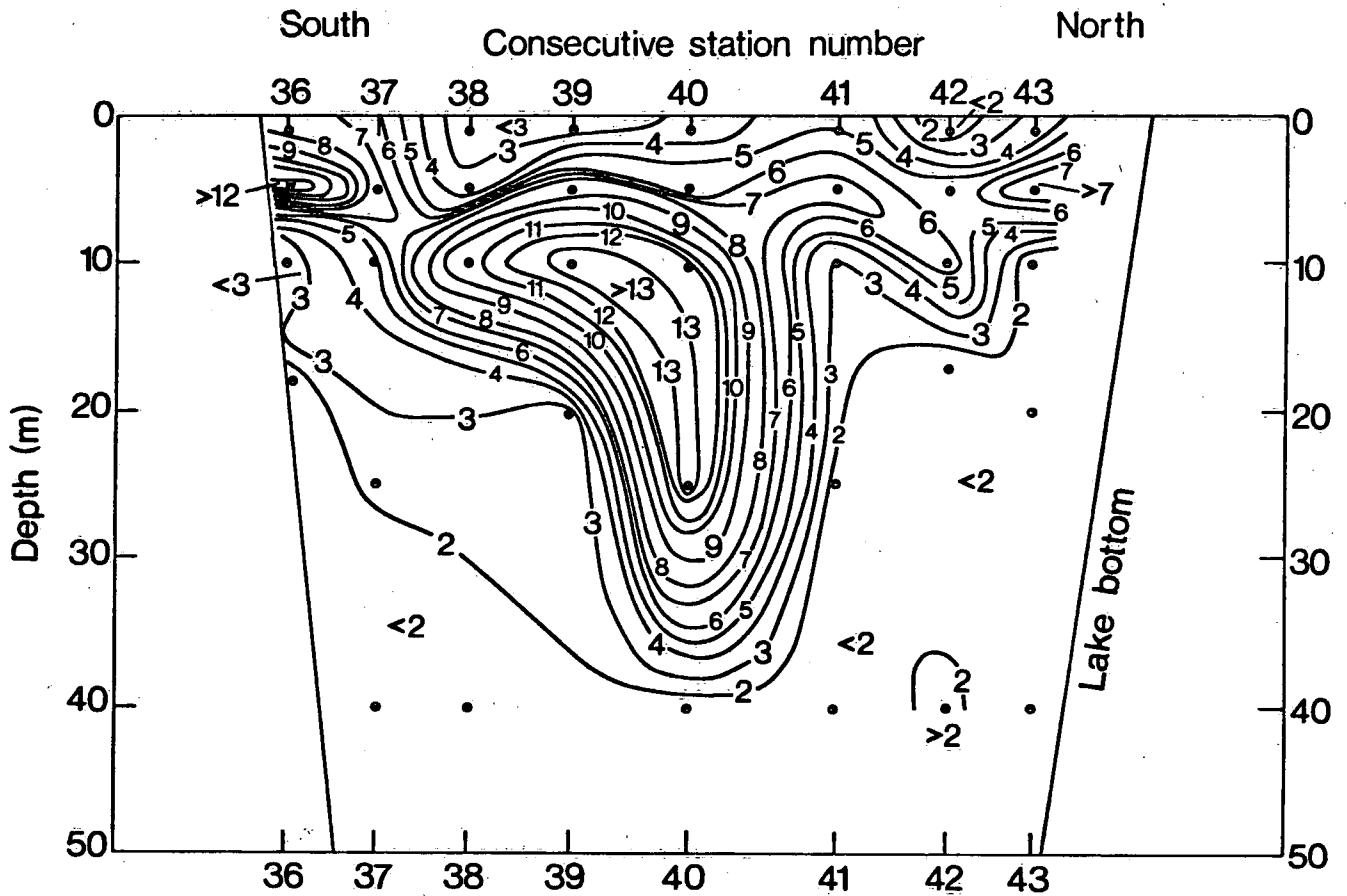
Lake Ontario, total chlorophyll *a* ($\mu\text{g/L}$) in transverse section "A", July 18, 1972, vessel "Martin Karlsen".

Figure 40.



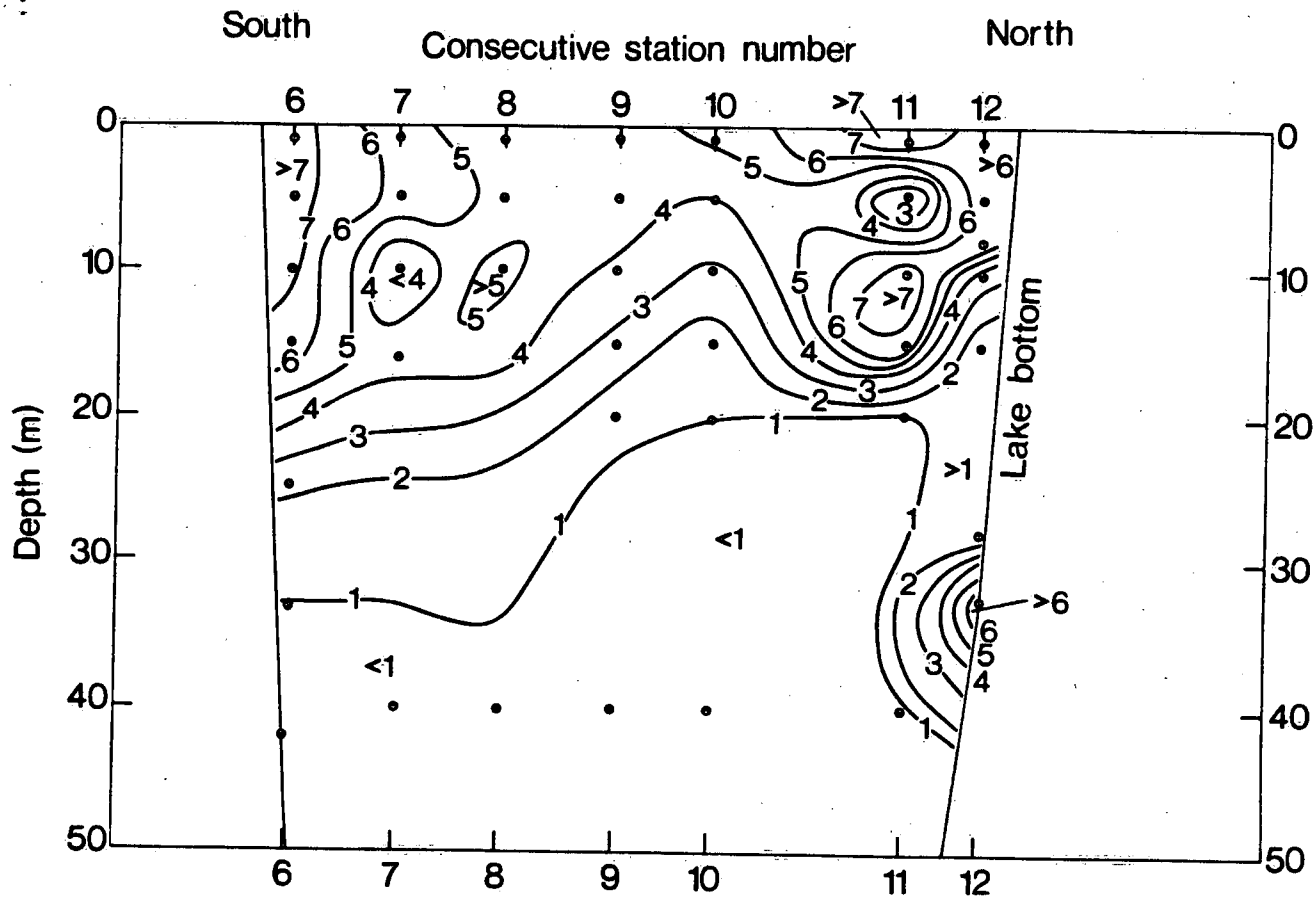
Lake Ontario, total chlorophyll *a* (µg/L) in transverse section "B", July 18 & 19, 1972, vessel "Martin Karlsen".

Figure 41.



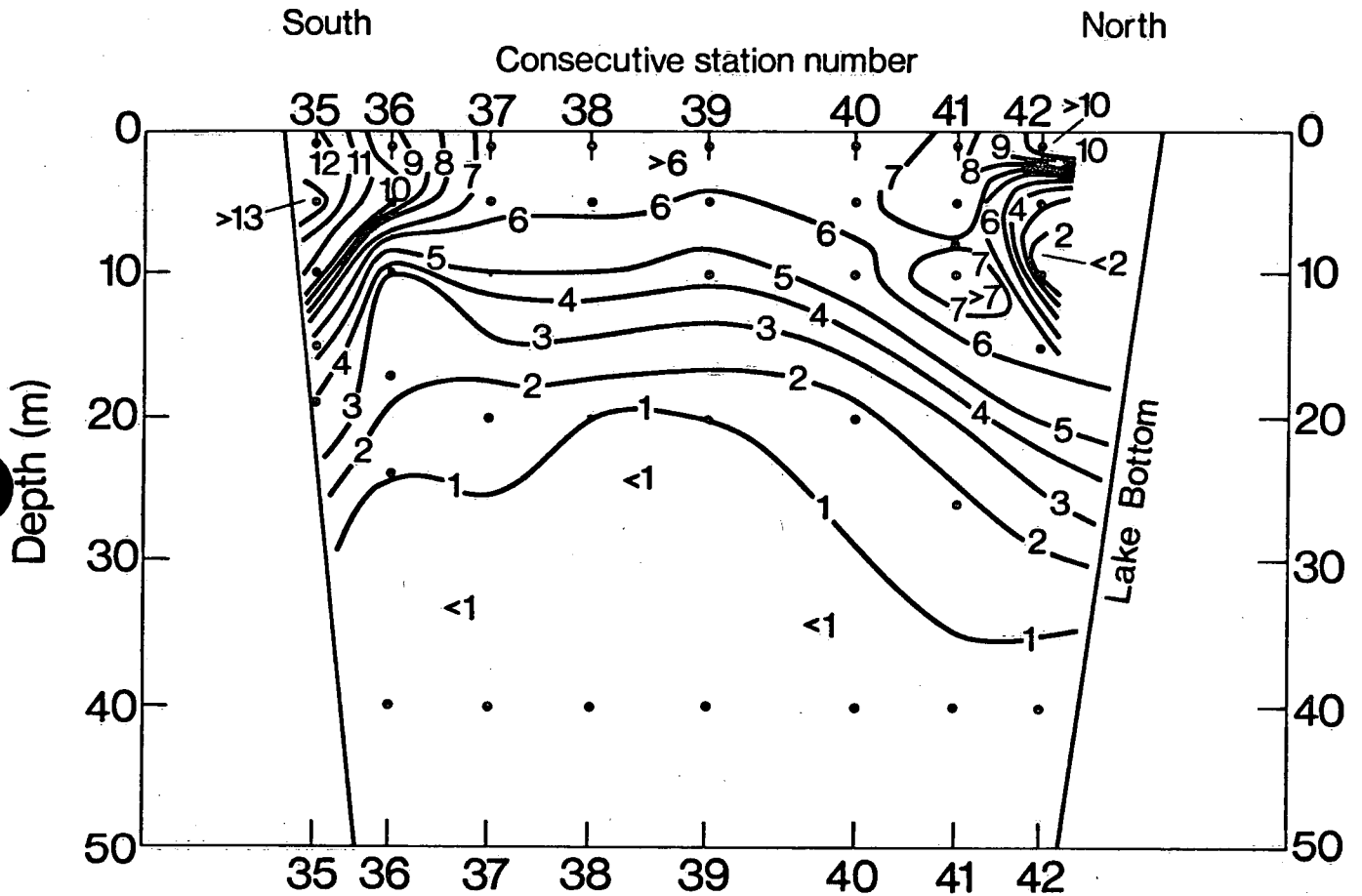
Lake Ontario, total chlorophyll *a* (µg/L) in transverse section "C", July 20 & 21, 1972, vessel "Martin Karlsen".

Figure 42.



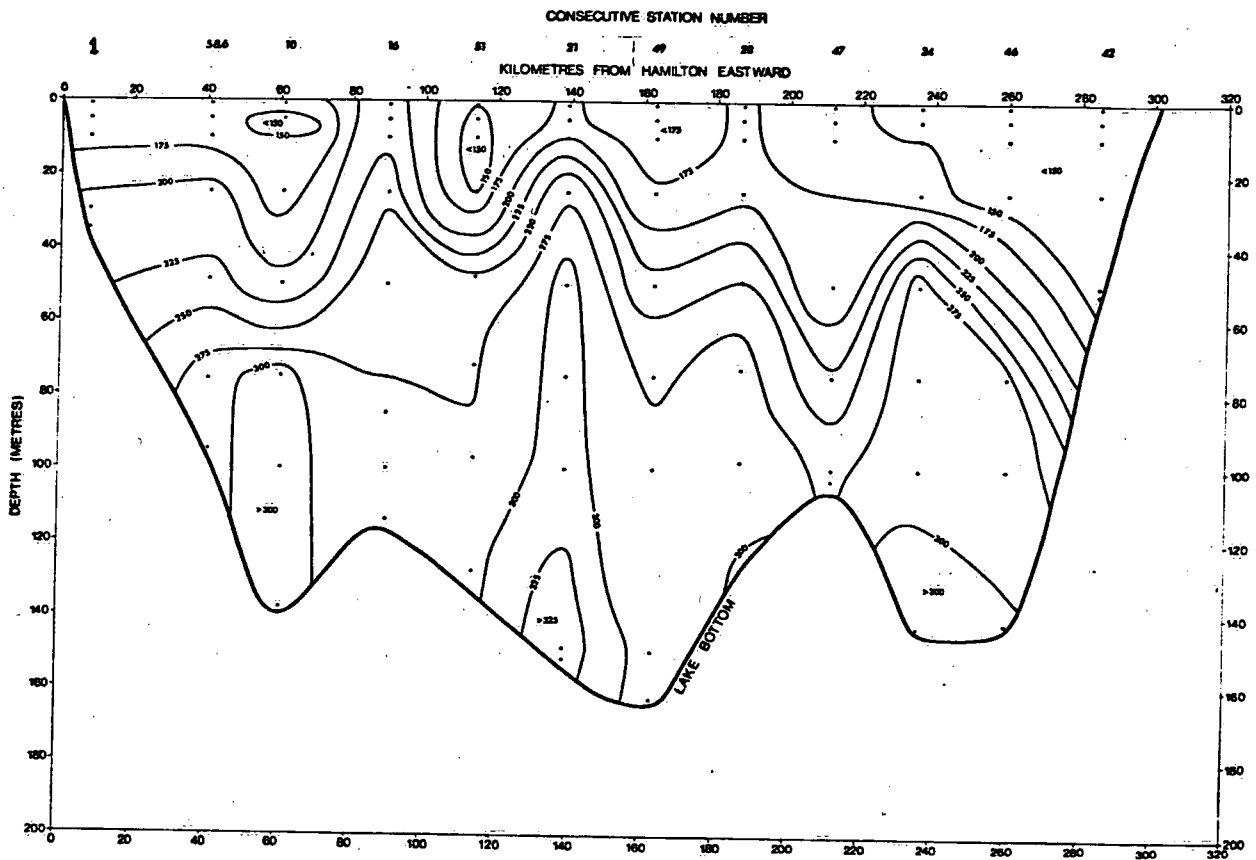
Lake Ontario, total chlorophyll *a* (µg/L) in transverse section "A",
 September 6, 1972, vessel "Martin Karlsen".

Figure 43.



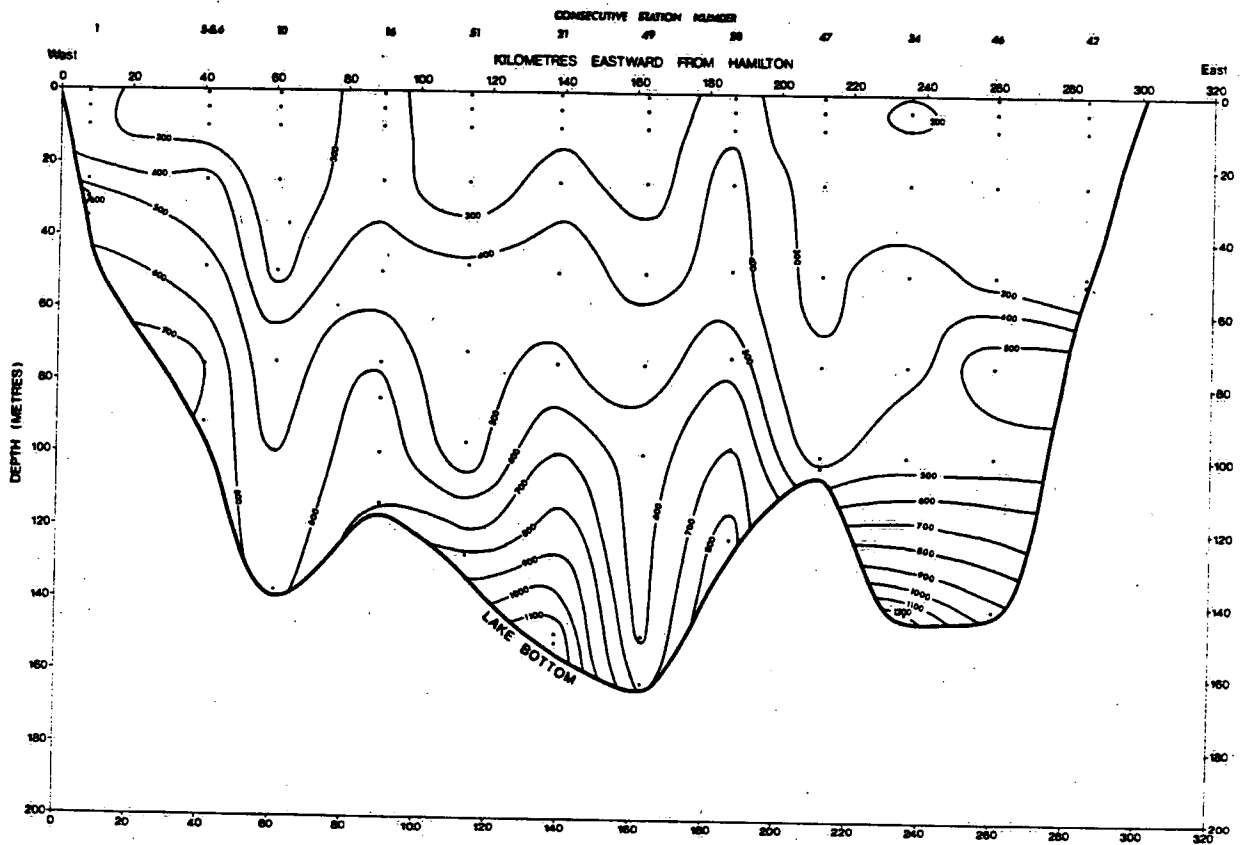
Lake Ontario, total chlorophyll *a* ($\mu\text{g/L}$) in transverse section "C",
 September 8 & 9, 1972, vessel "Martin Karlsen".

Figure 45.



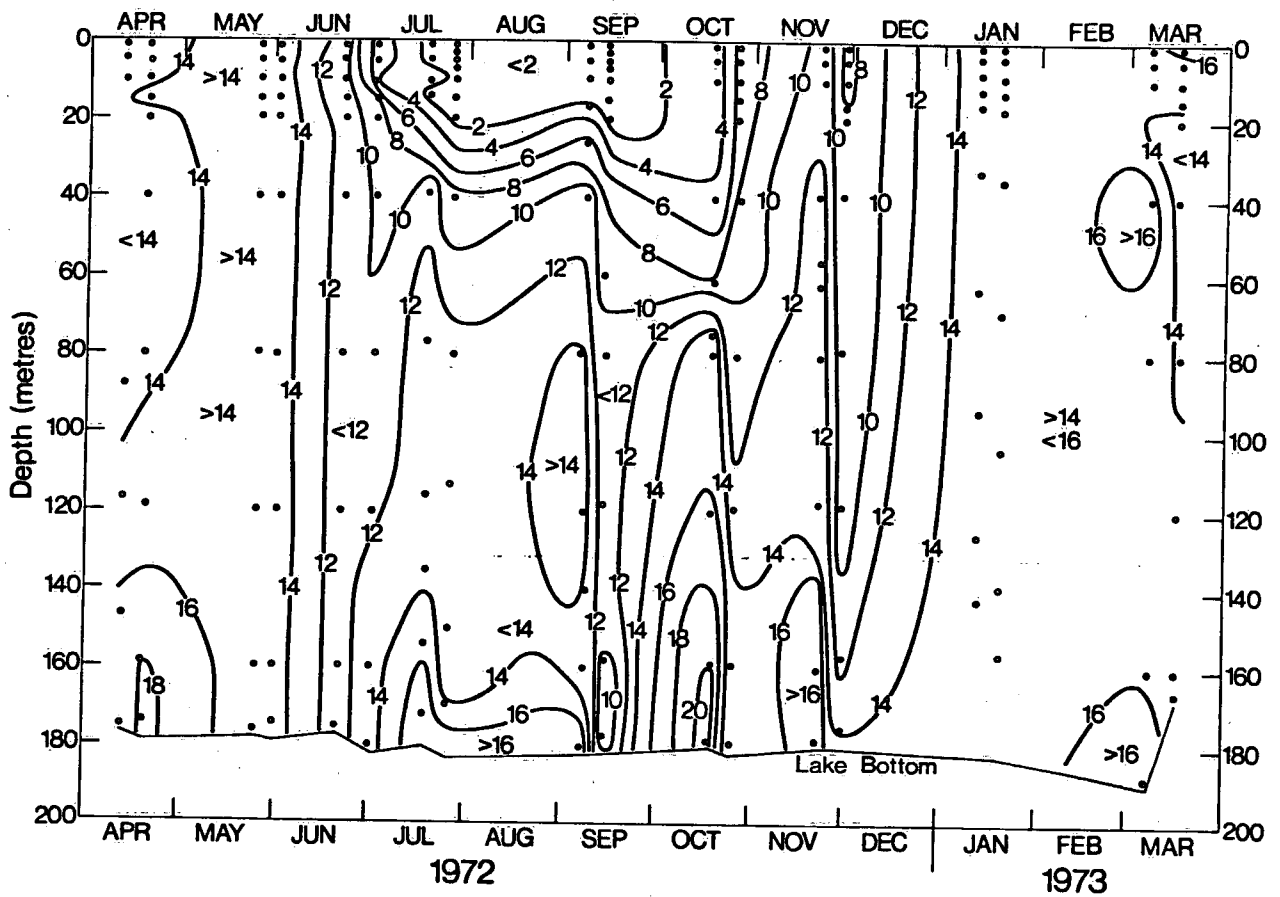
Lake Ontario, nitrate + nitrite ($\mu\text{g N/L}$) in a longitudinal section from Hamilton eastward, November 15 to 19, 1971, cruise of the "Martin Karlsen".

Figure 46.



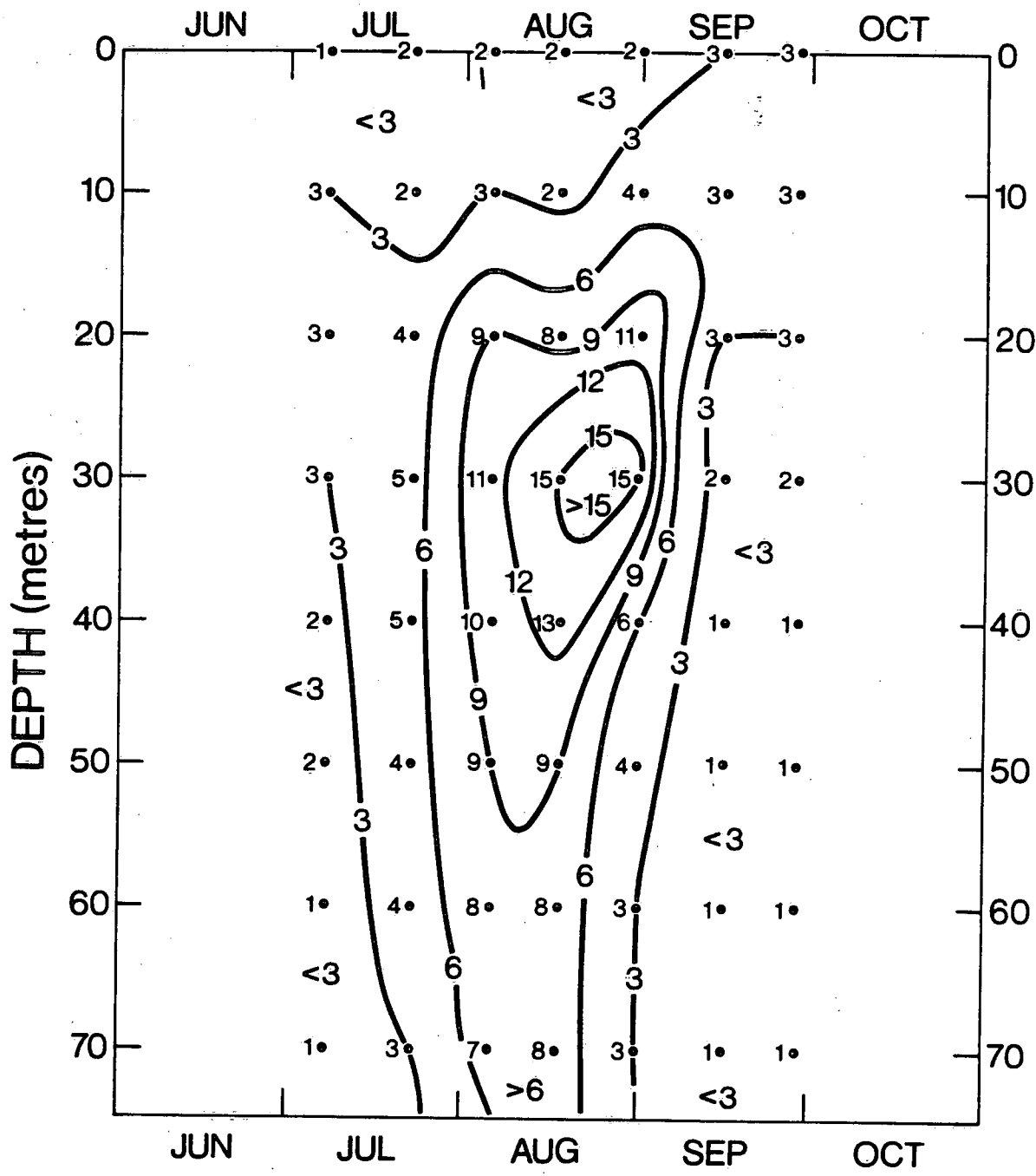
Lake Ontario, soluble reactive silica ($\mu\text{g SiO}_2/\text{L}$)
 in a longitudinal section from Hamilton eastward,
 November 15 to 19, 1971, cruise of the Martin Karlsen".
 Vertical exaggeration x 1000.

Figure 47.



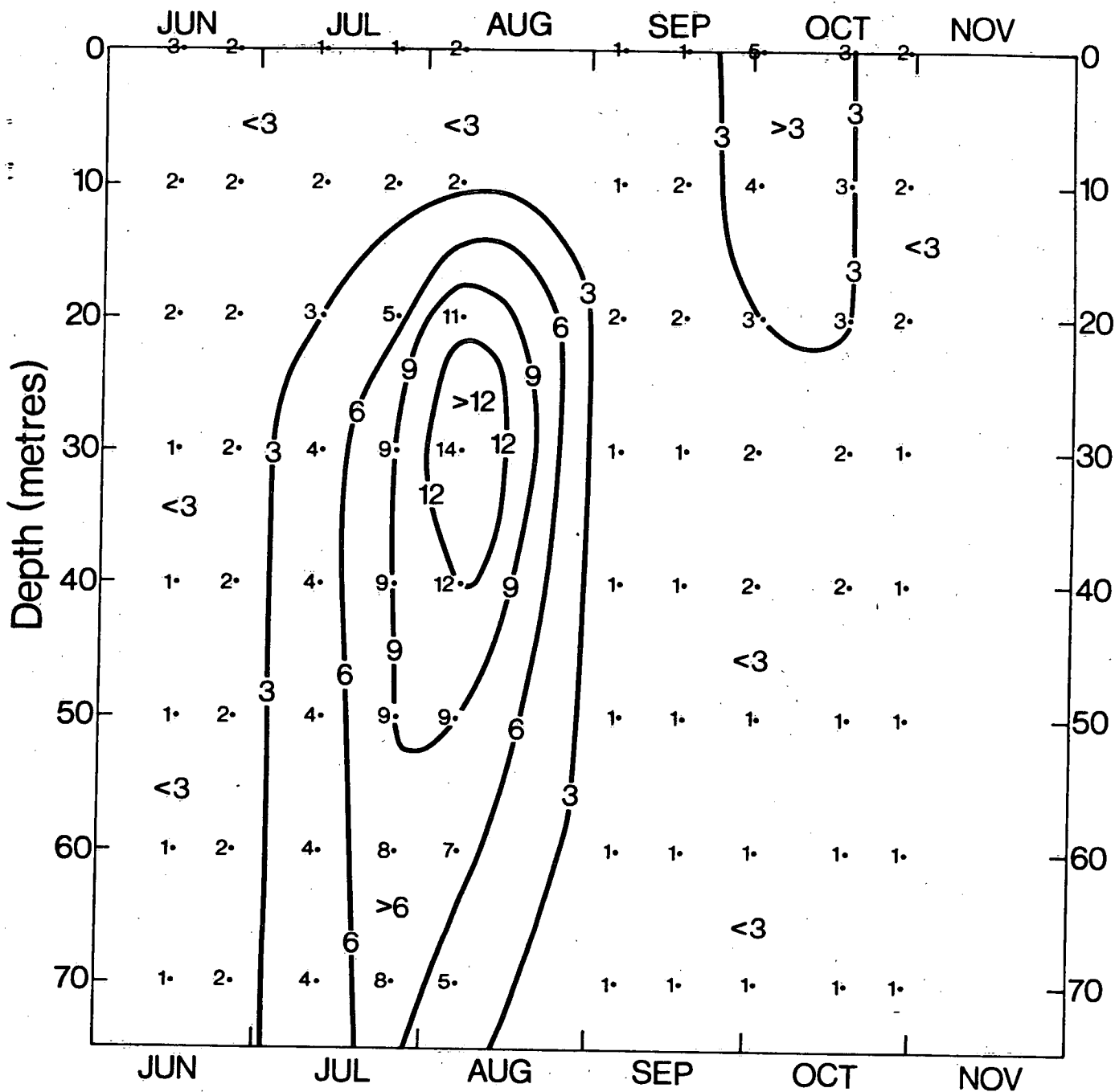
Lake Ontario: Soluble reactive phosphorus ($\mu\text{gP/L}$) versus time and depth at a mid-lake station (P-19) observed on cruises of the "Martin Karlsen" during 1972 and early 1973.

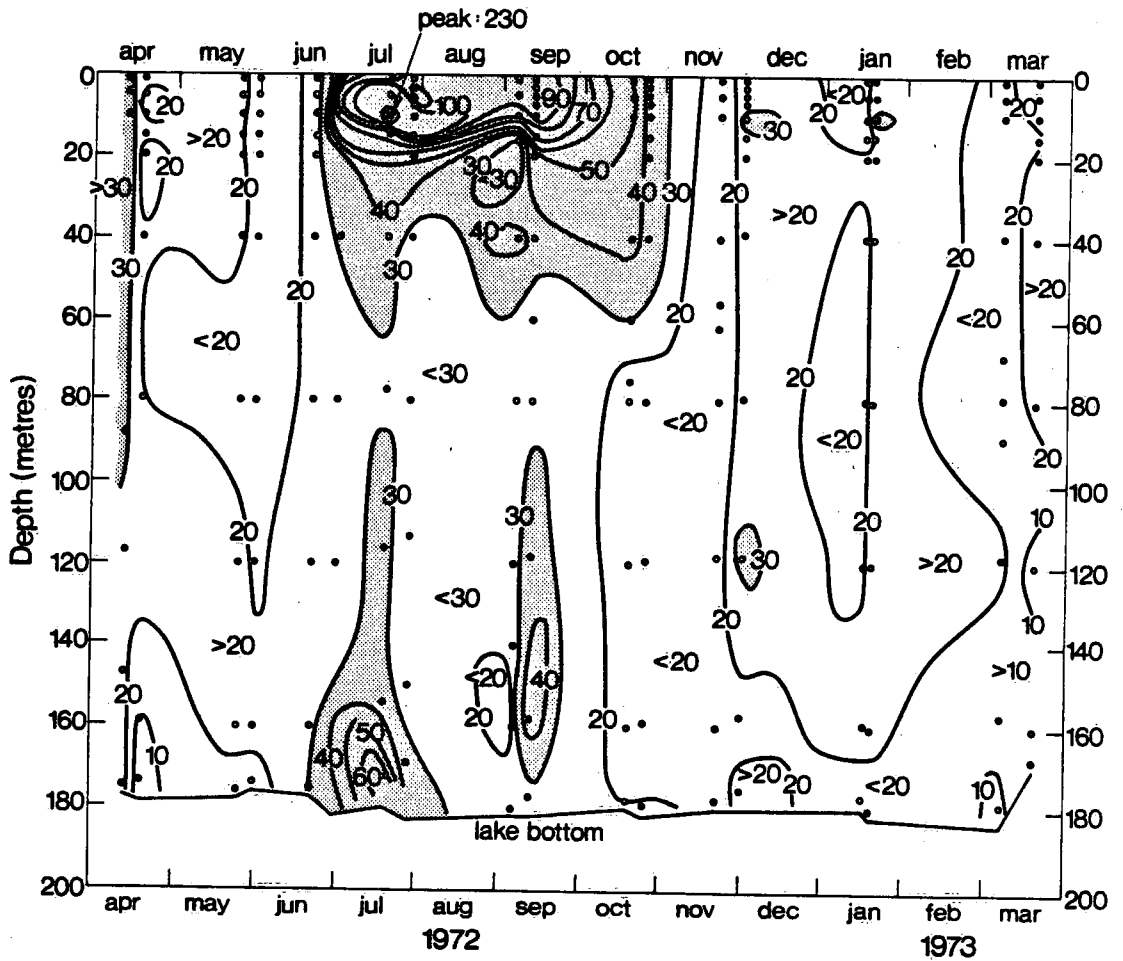
Figure 48.



Lake Ontario, nitrite ($\mu\text{g N/L}$) versus time and depth: mean values for the offshore area (soundings $>100\text{ m}$) observed on cruises of the vessel Brandal during 1966.

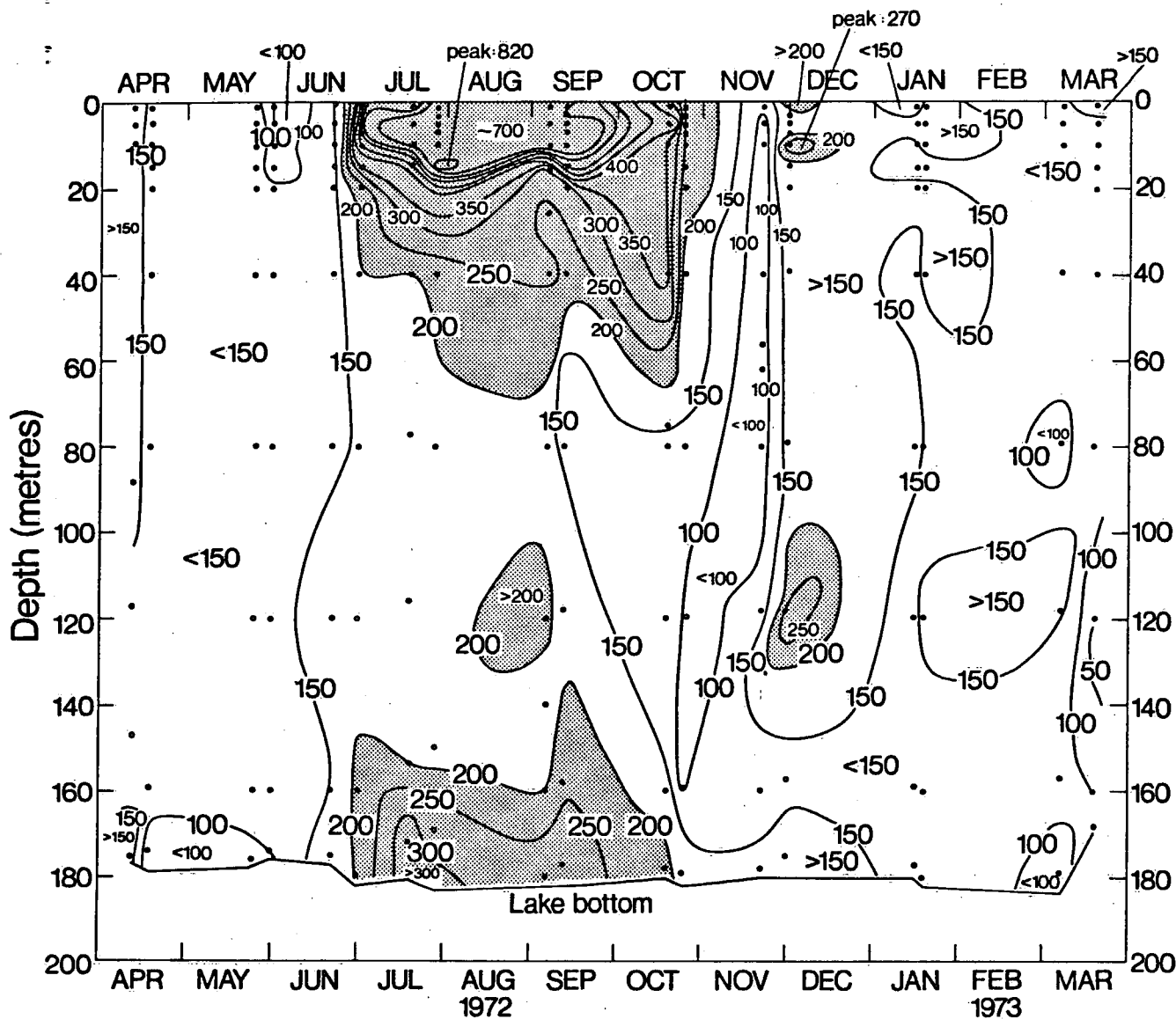
Figure 49.





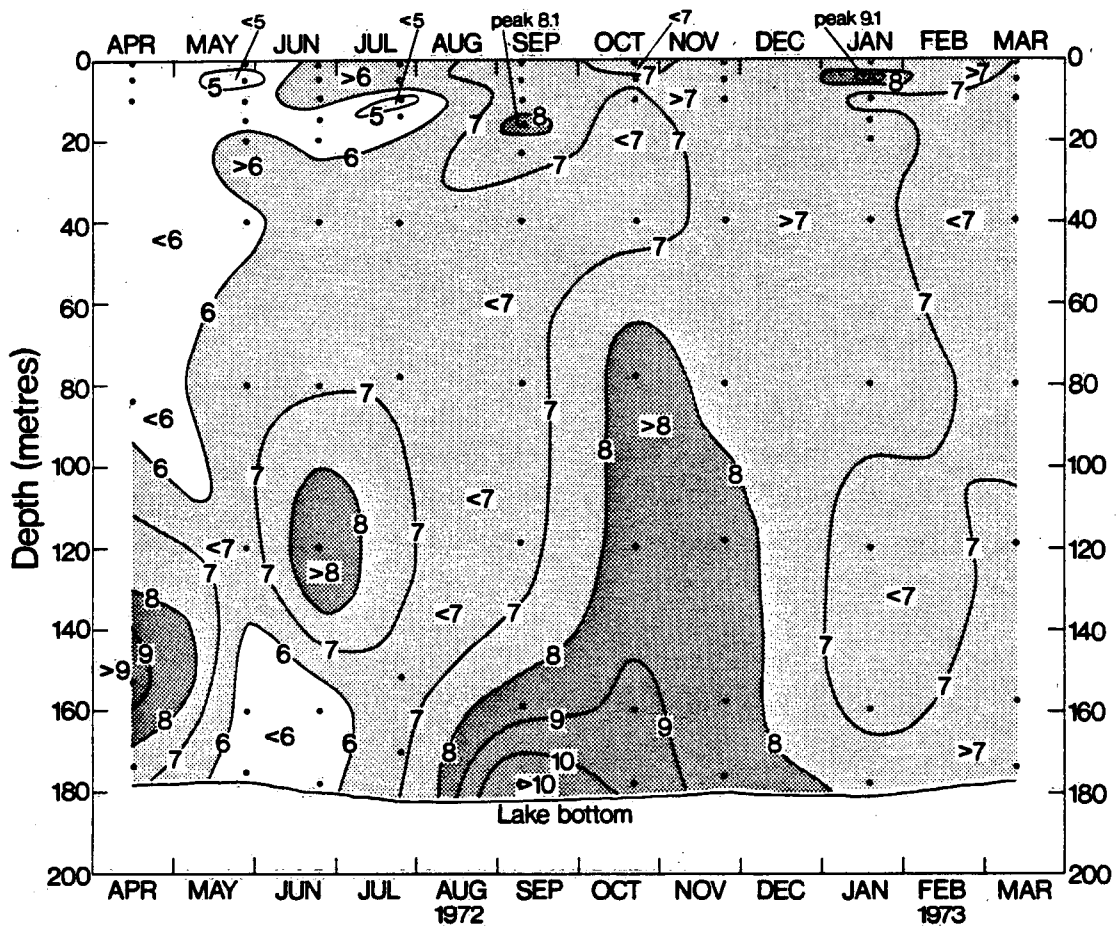
Lake Ontario: particulate nitrogen ($\mu\text{g N/L}$) at mid-lake station P-19, CCIW vessel "Martin Karlsen," 1972 and early 1973. Contour interval is $10 \mu\text{g/L}$, except in the high patch. Areas >30 are shaded.

Figure 51.



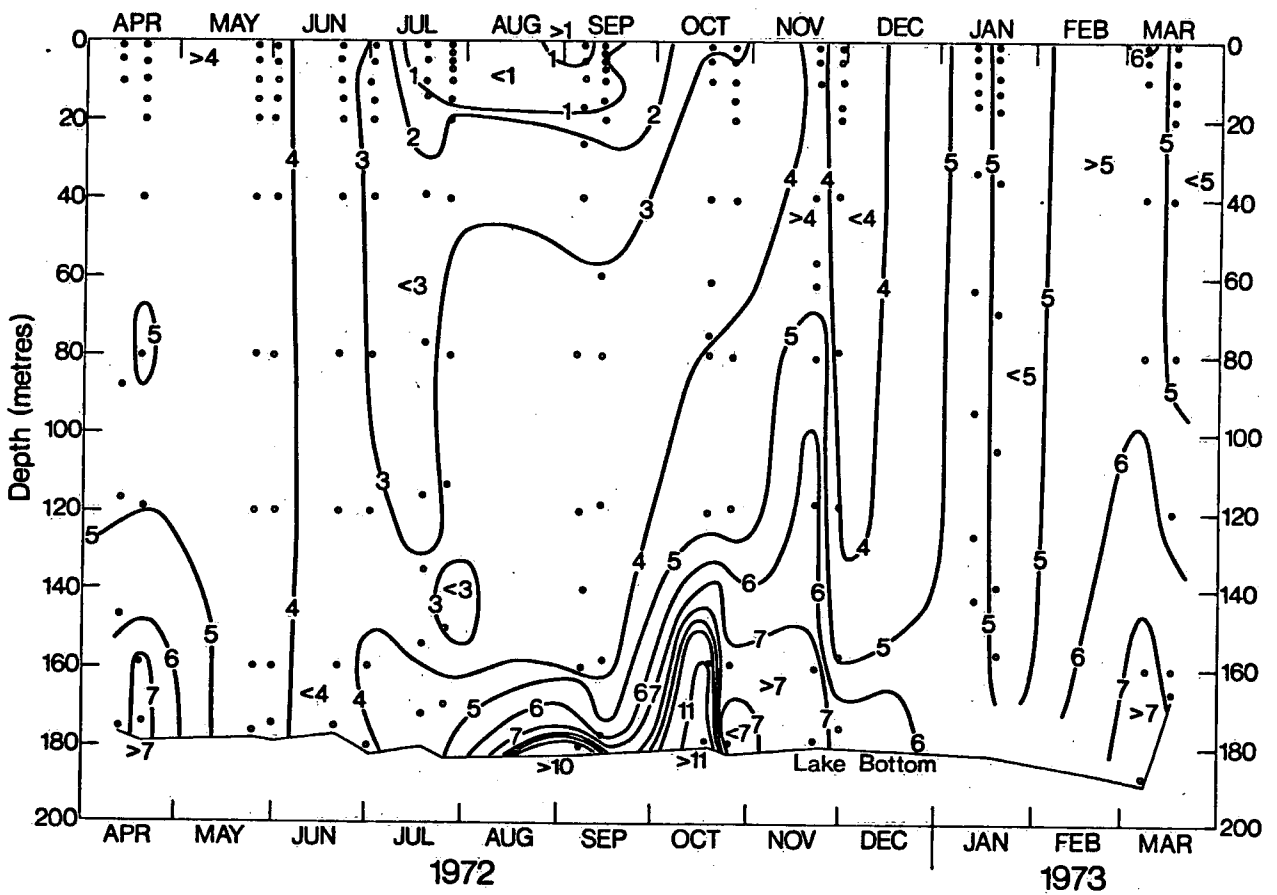
Lake Ontario: particulate organic carbon ($\mu\text{g C/L}$) at mid-lake station P-19, vessel "Martin Karlsen" 1972 and early 1973. Contour interval is 50 $\mu\text{g/L}$, except in high patch. Areas >200 are shaded

Figure 52.



Lake Ontario: particulate organic carbon/nitrogen ratio by weight, at mid-lake station P-19, vessel 'Martin Karlsen', 1972 and early 1973.

Figure 53.



Lake Ontario: soluble reactive silica vs time and depth at a mid-lake station (P-19) observed on cruises of the 'Martin Karlsen' during 1972 and early 1973. Units are hundreds of micrograms SiO₂ per litre. Contour interval is 100 micrograms per litre.

Figure 54.

LAKE ONTARIO: DISSOLVED OXYGEN VERSUS TIME AND DEPTH AT STATION P-19 (a mid-lake station), FROM CRUISES OF THE "MARTIN KARLSEN" DURING 1972 AND EARLY 1973. THE VALUES SHOWN ARE PERCENT SATURATION, OR PERCENT OF THE AIR-EQUILIBRIUM VALUE.

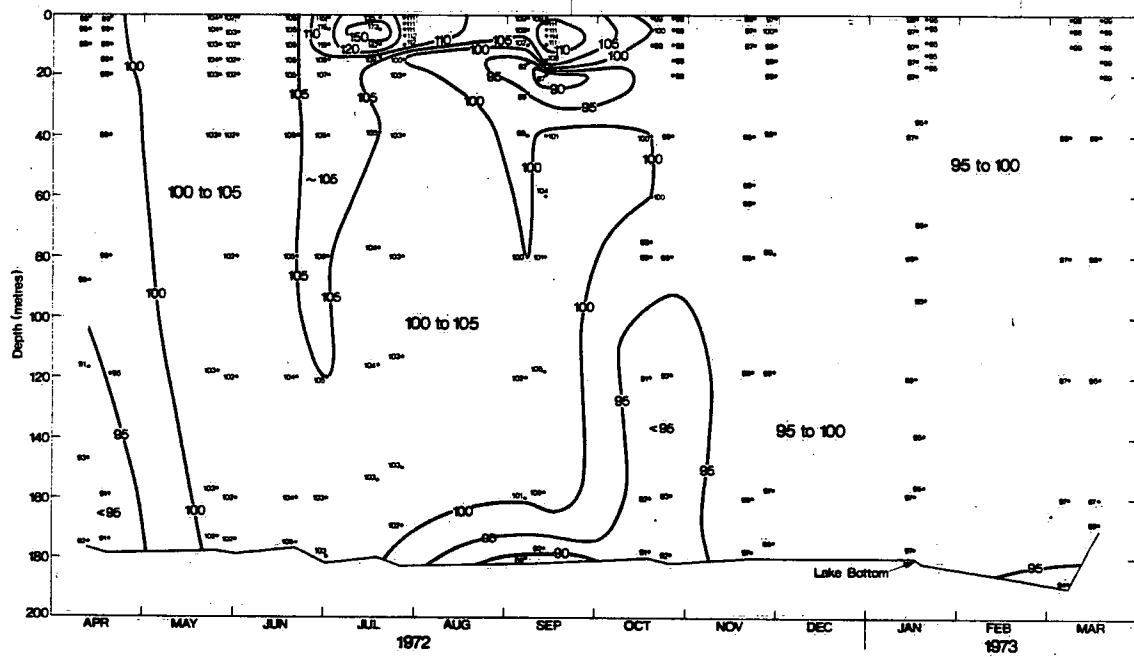
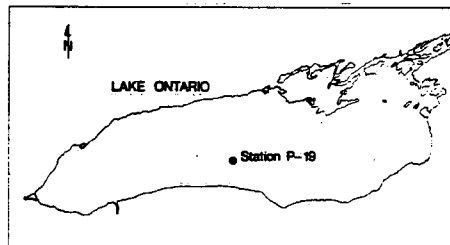
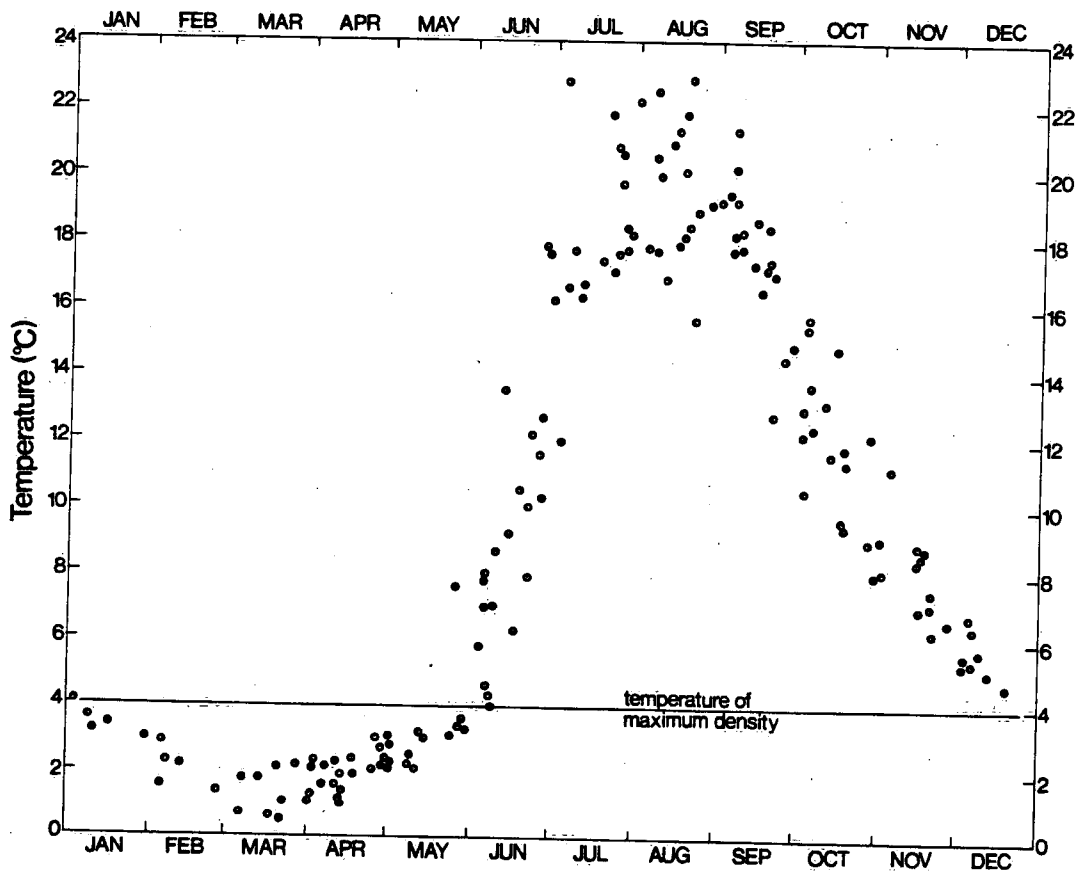
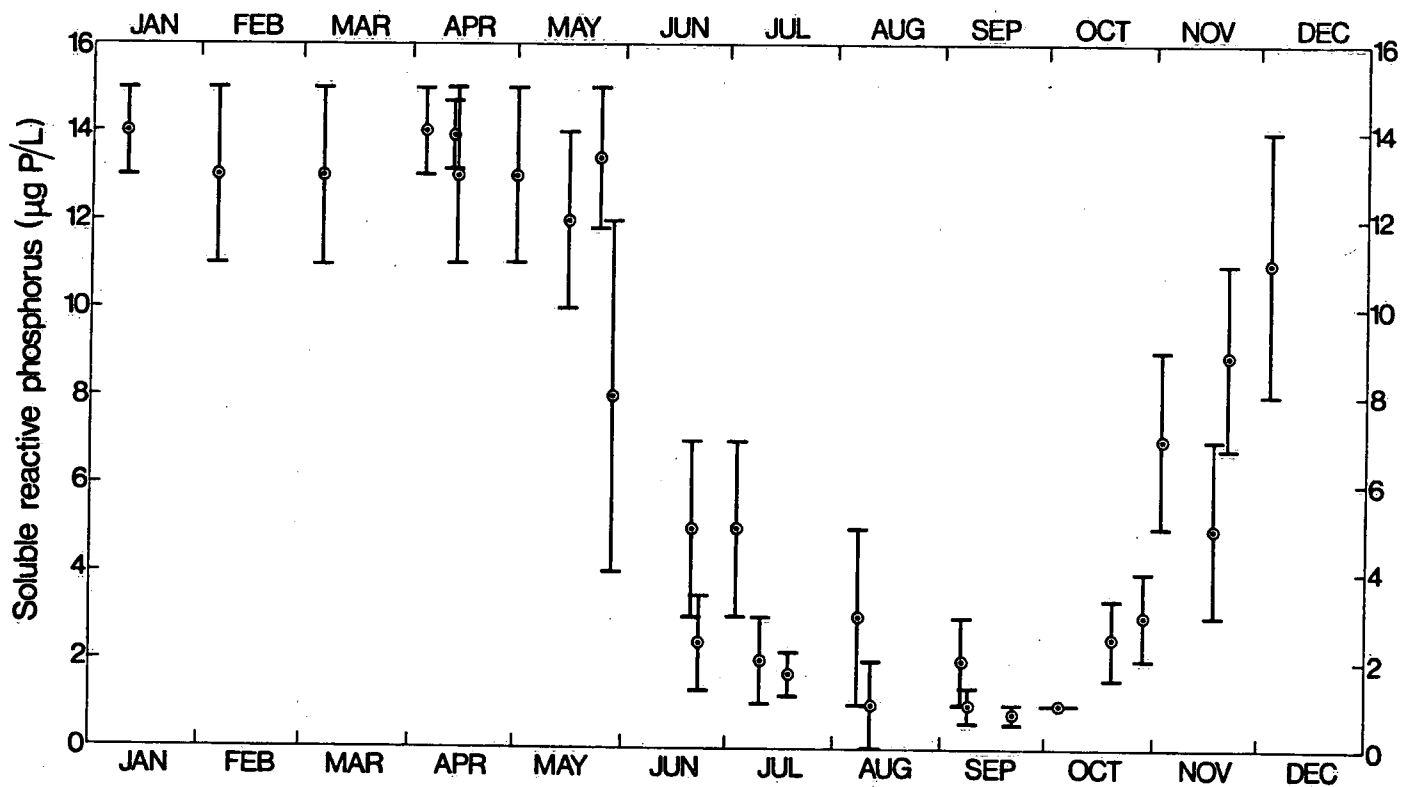


Figure 55.



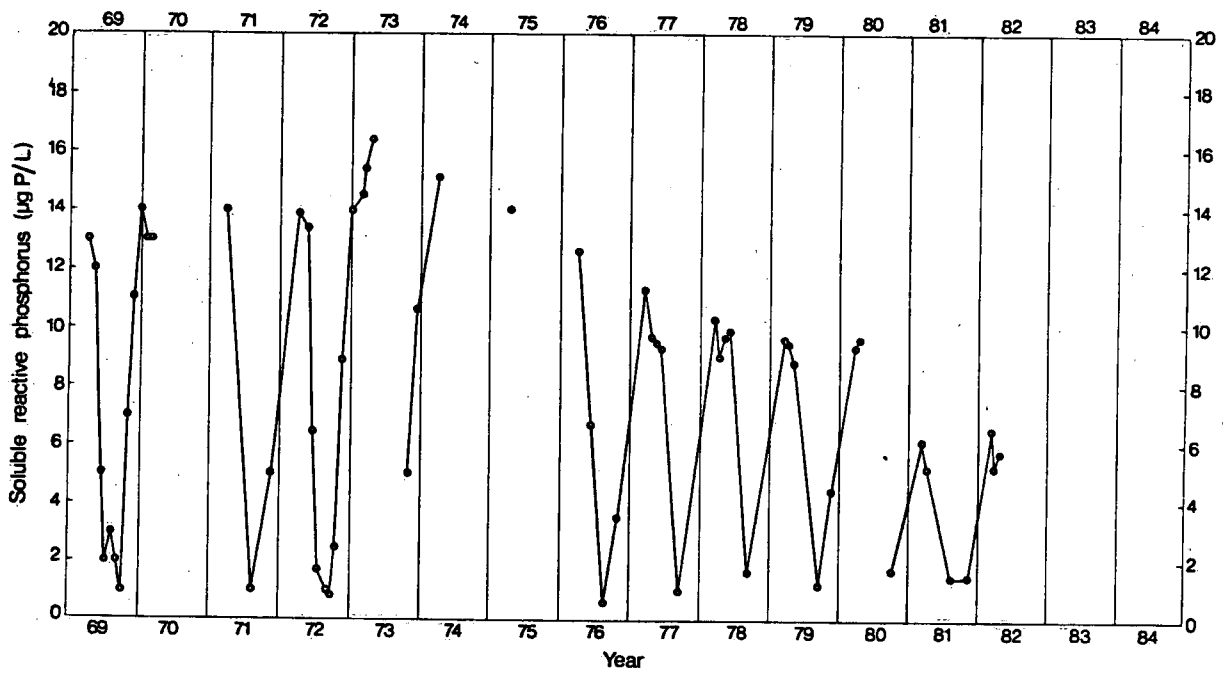
Lake Ontario, temperatures: seasonal cycle of cruise-mean surface temperatures (°C) in the offshore part (soundings >100m), data of CCIW, 1966 to 1979.

Figure 56.



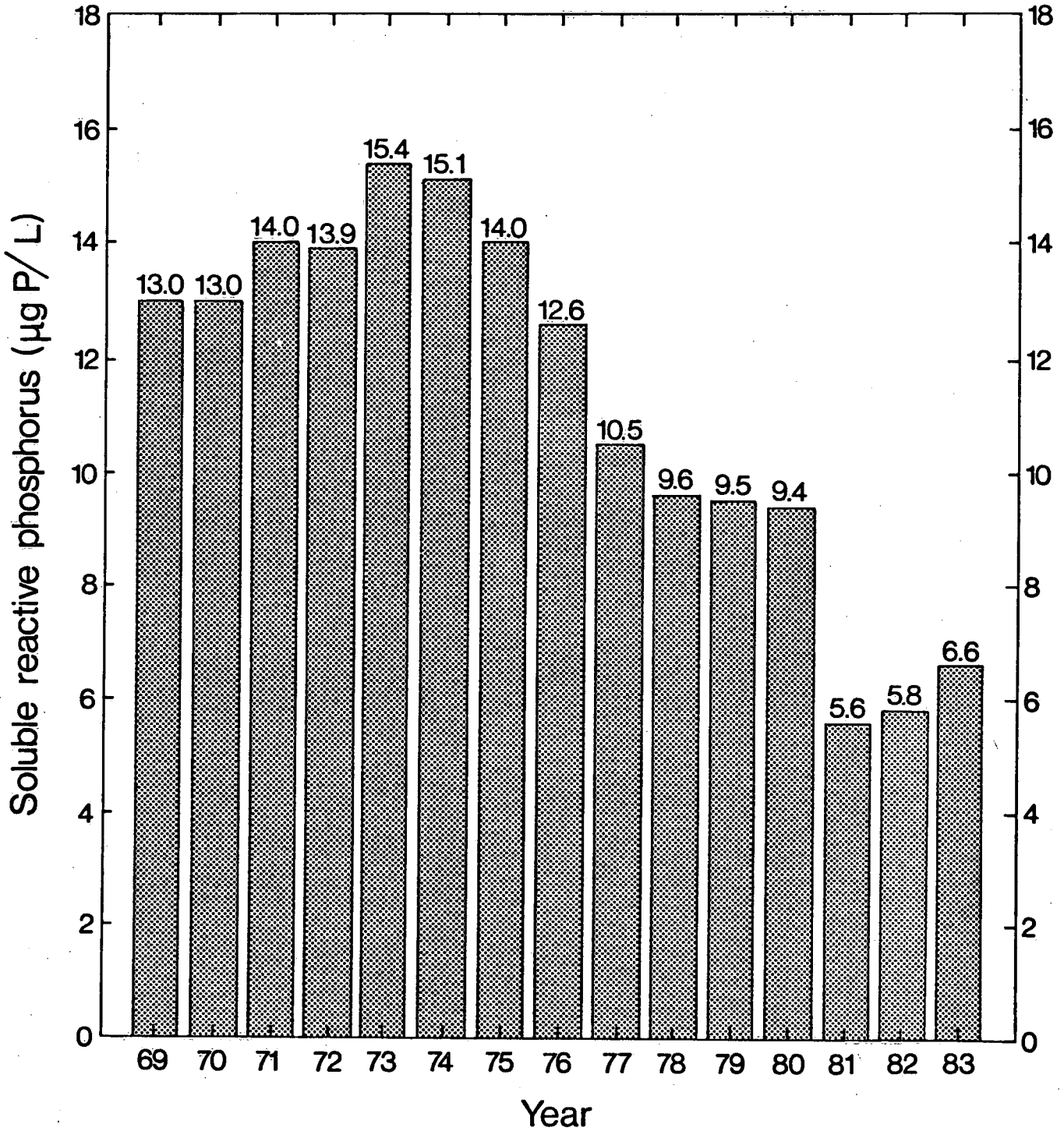
Lake Ontario, soluble reactive phosphorus, seasonal cycle in offshore surface waters, 1968 to 1972, observed on 27 cruises by CCIW vessels: samples from the upper 10 metres, at stations with soundings >100 metres. For each cruise the mean value and one standard deviation are shown.

Figure 57.



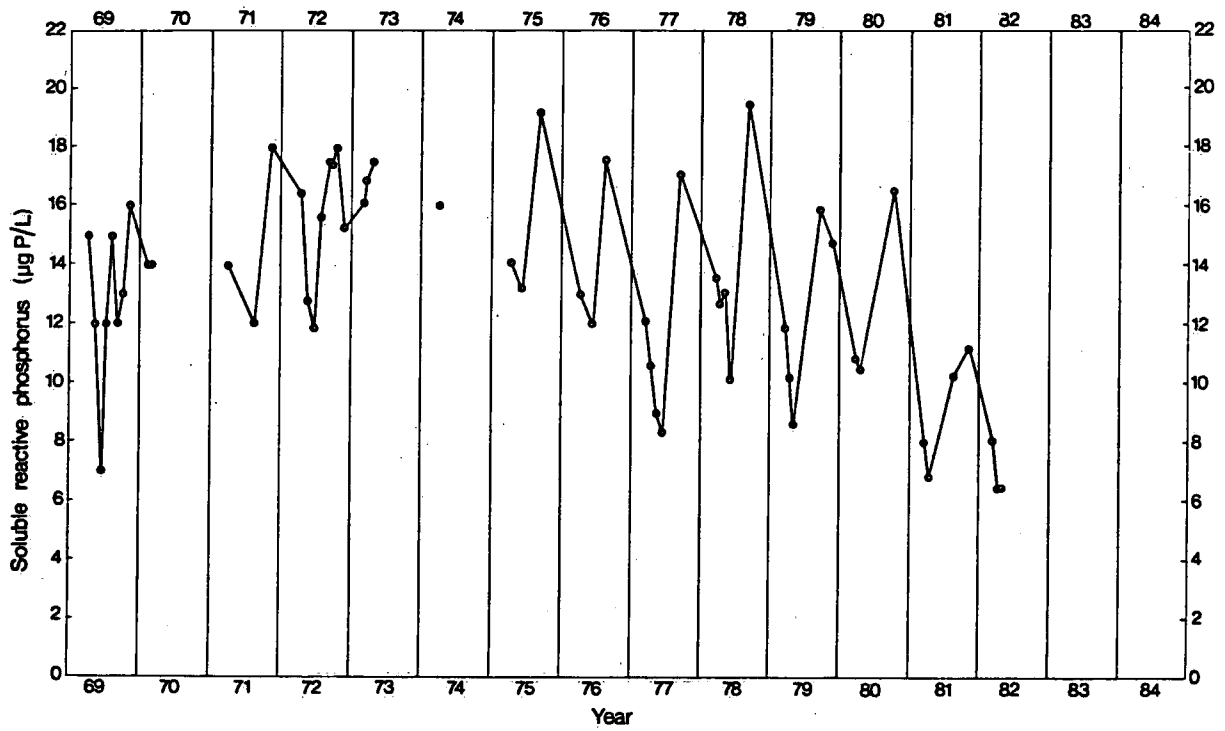
Lake Ontario: soluble reactive phosphorus, mean values in near - surface waters at offshore stations with soundings > 100m, on cruises of CCIW vessels, 1969 to 1982.

Figure 58.



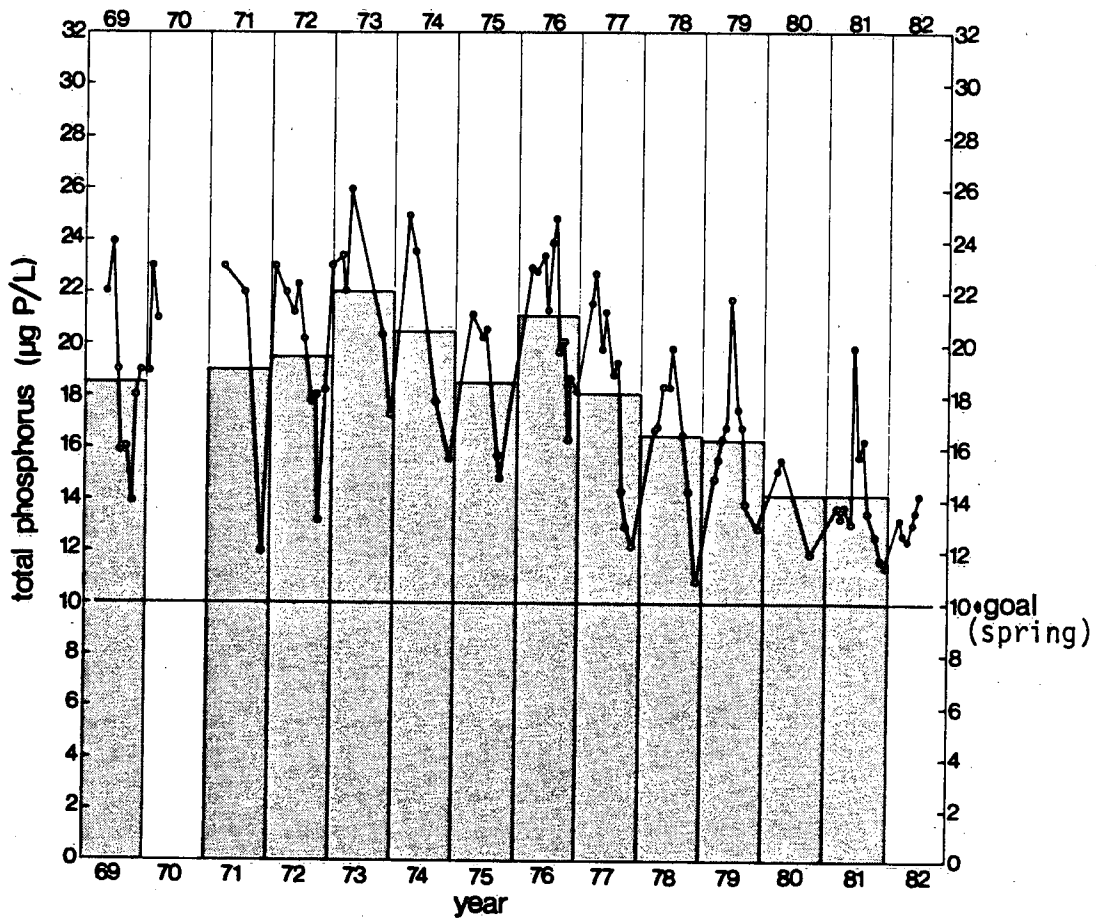
Lake Ontario, soluble reactive phosphorus in offshore, near-surface waters during March & April, 1969 to 1983. The goal is 6.0 µg P/L.

Figure S9.



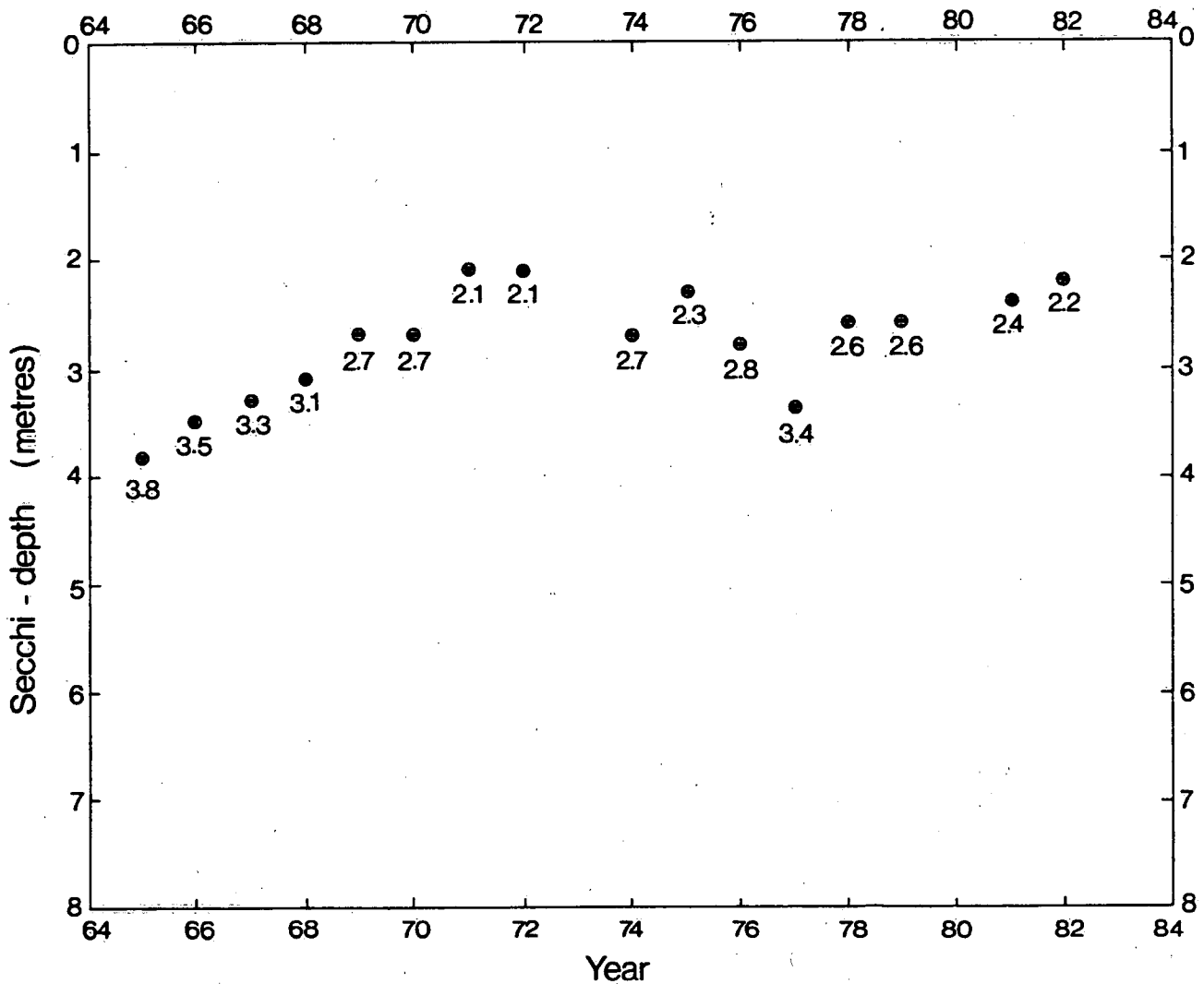
Lake Ontario: soluble reactive phosphorus, mean values in near-bottom waters at offshore stations with soundings >100m, on cruises of CCIW vessels, 1969 to 1982.

Figure 60.



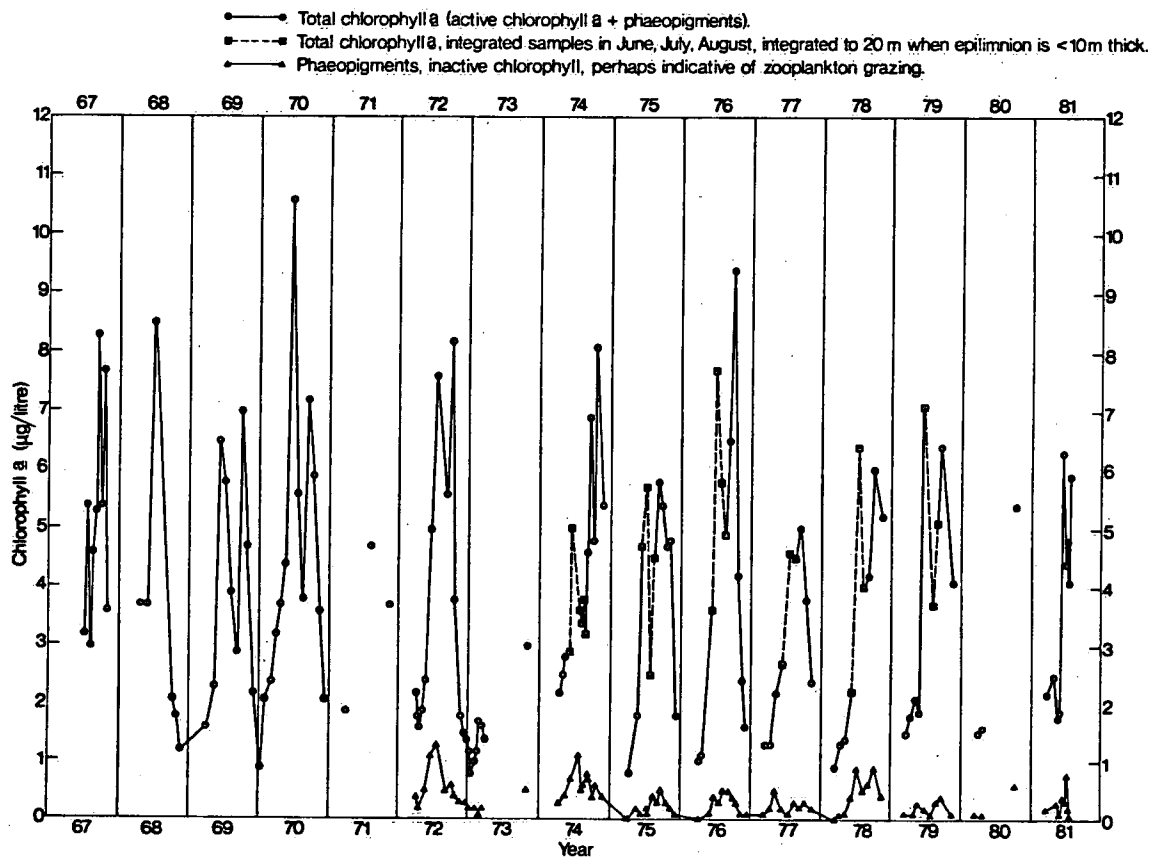
Lake Ontario: total phosphorus in near-surface waters at offshore stations having soundings >100m, 1969 to 1982. Dots are cruise-mean values; bars are unweighted annual mean values. Data of CCIW.

Figure 61.



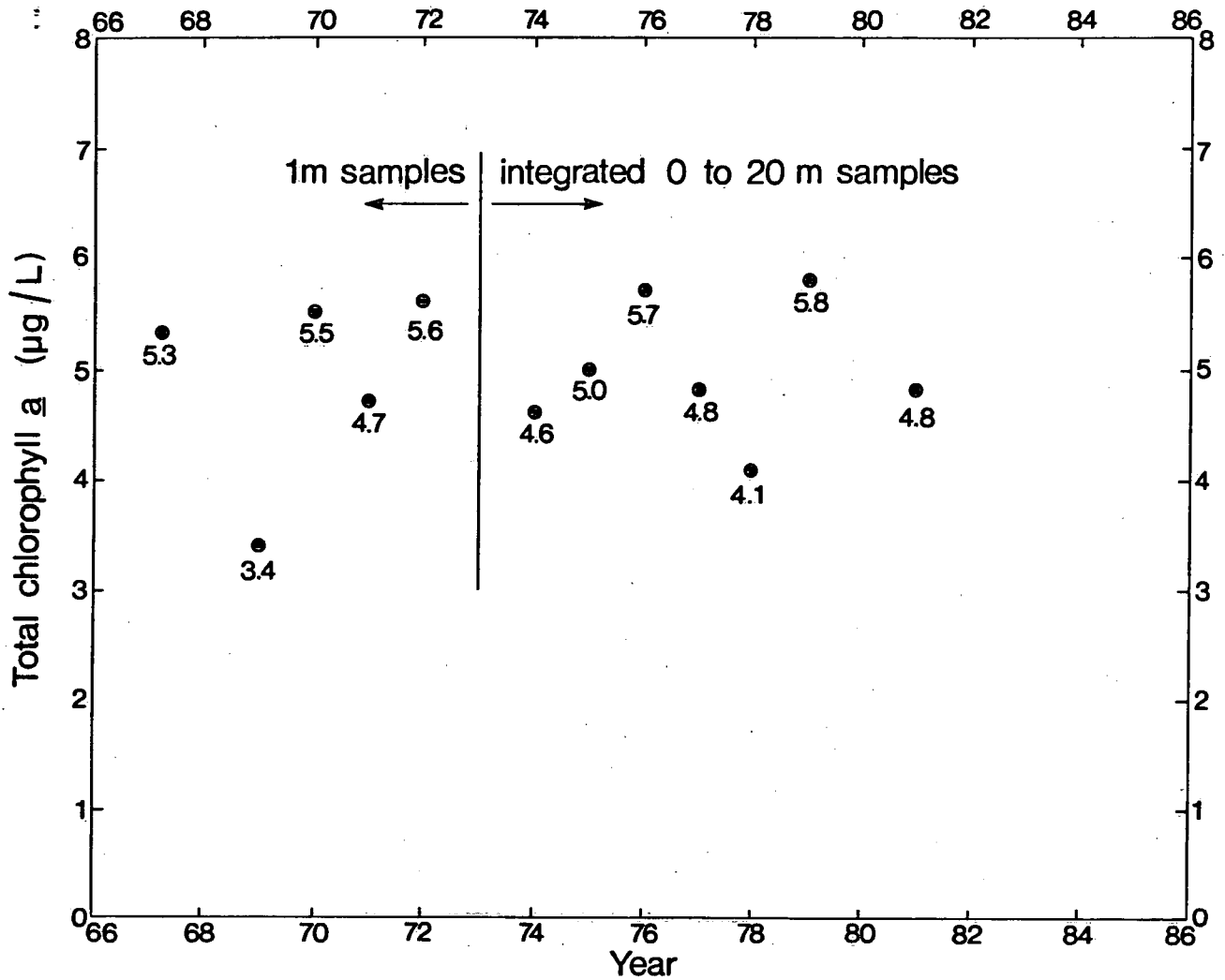
Lake Ontario: secchi - depth transparency, mean values for summer (July, August, and September), 1965 to 1982, in the offshore area where soundings > 100 m. Reciprocal values were used in the calculations of summer - means.

Figure 62.



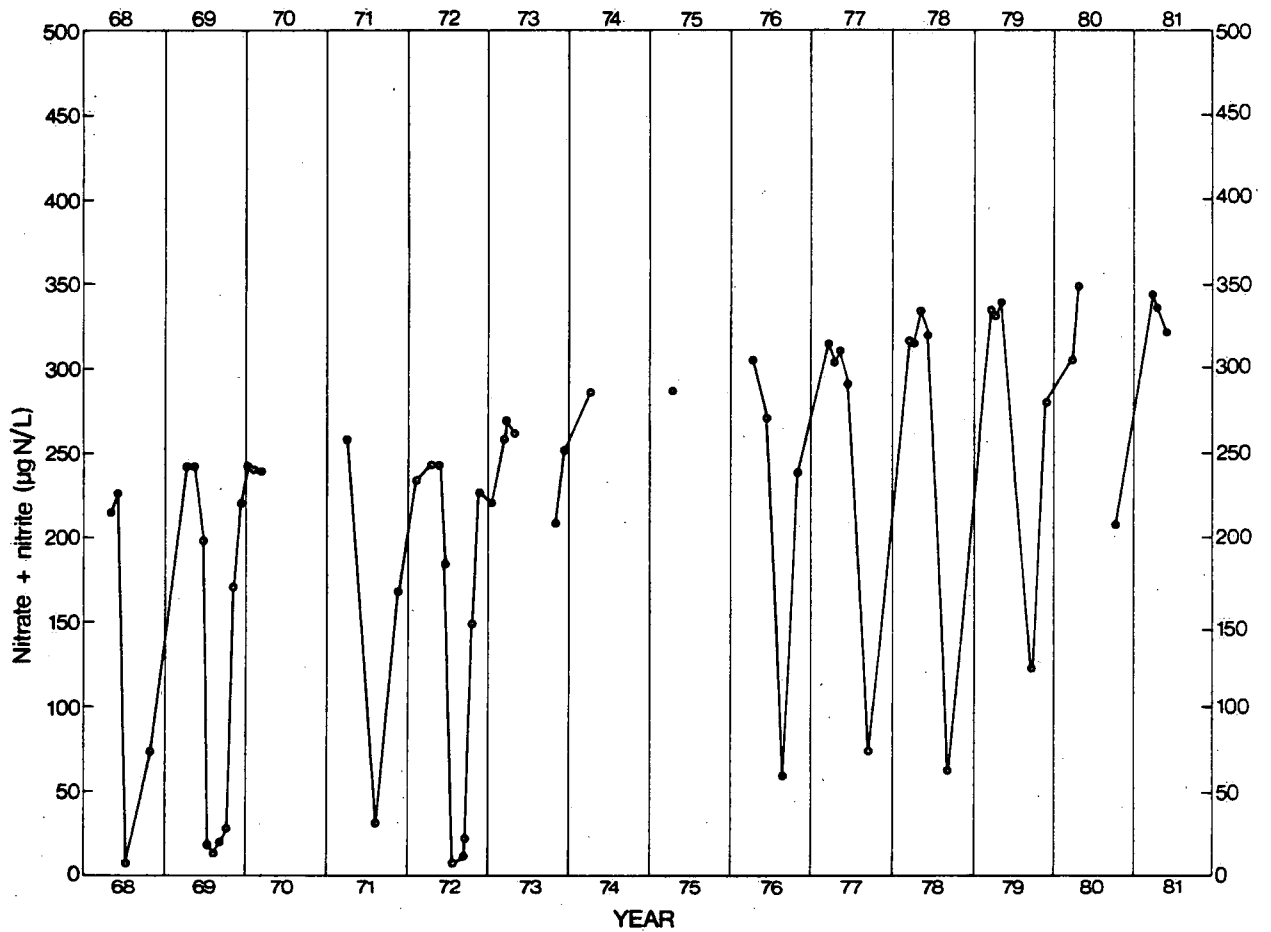
Lake Ontario, chlorophyll a and phaeopigments in offshore, near-surface waters, cruise-mean values in the years 1967 to 1981

Figure 63.



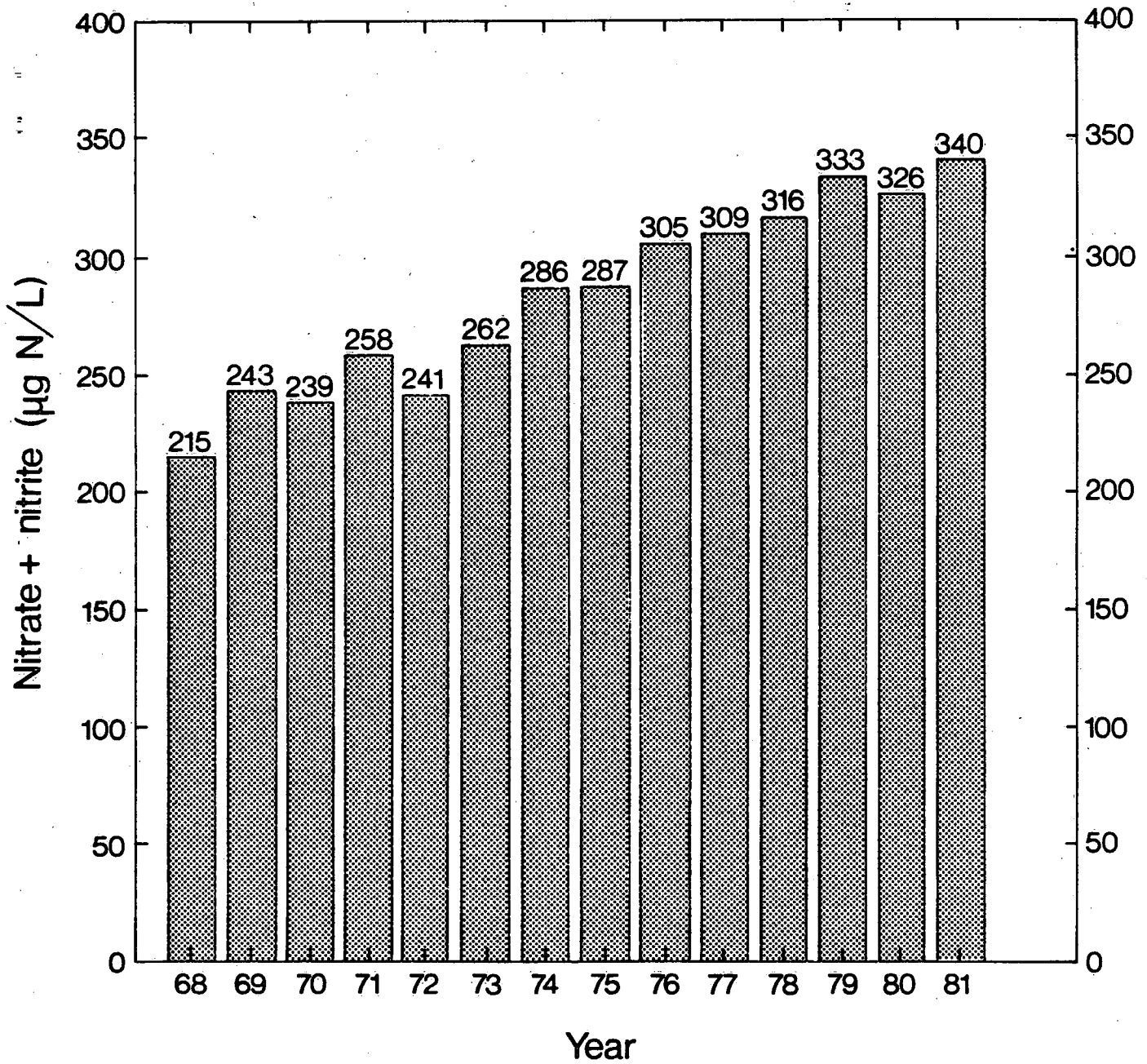
Lake Ontario, total chlorophyll a, mean values for August/September in offshore near-surface waters, observed by CCIW, 1967 to 1981.

Figure 64.



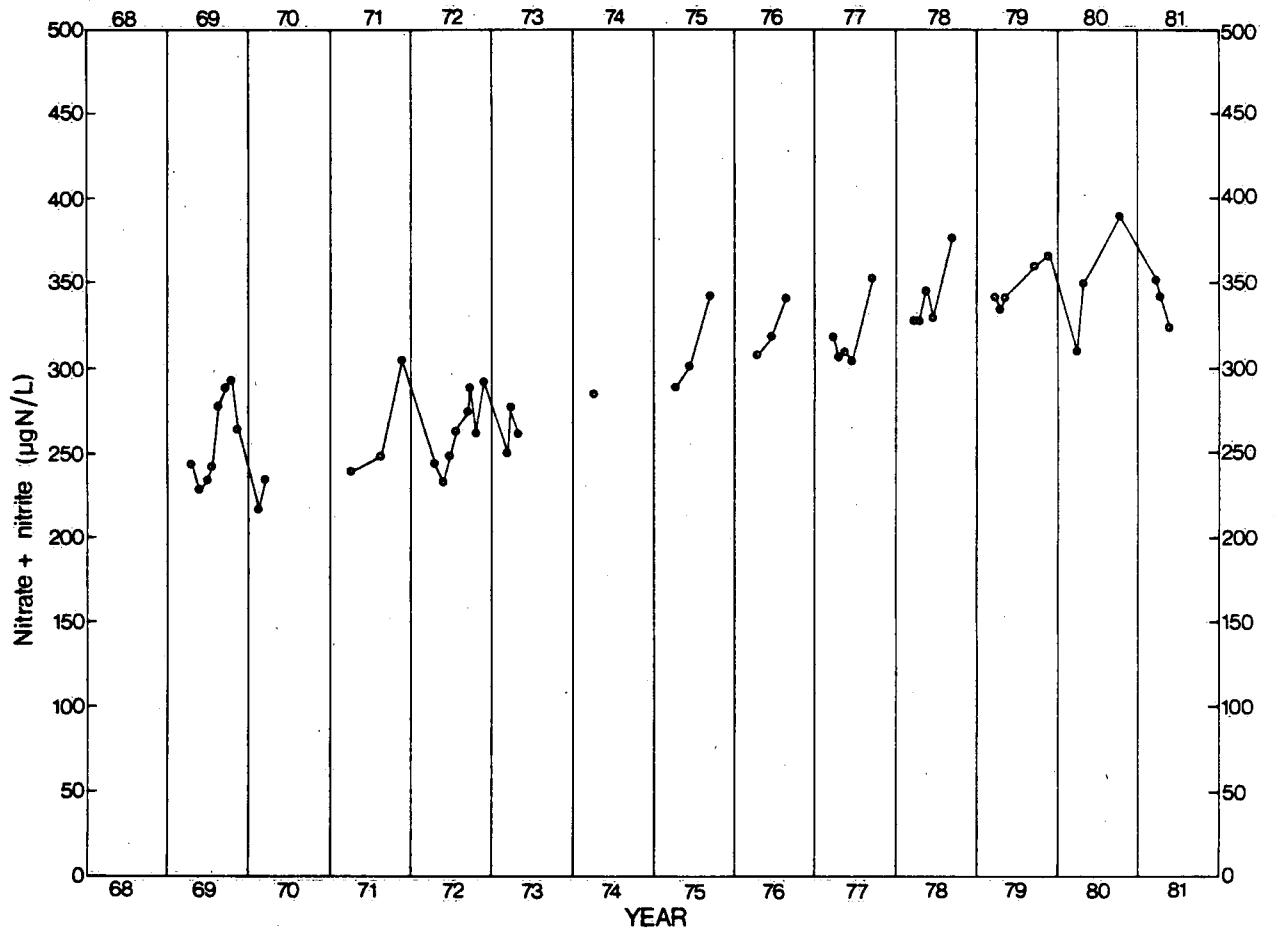
Lake Ontario, nitrate + nitrite in offshore, near-surface waters in the years 1968 to 1981, cruise - mean values. The seasonal minimum was poorly-defined in the years 1977 to 1980 which lacked data for August.

Figure 65.



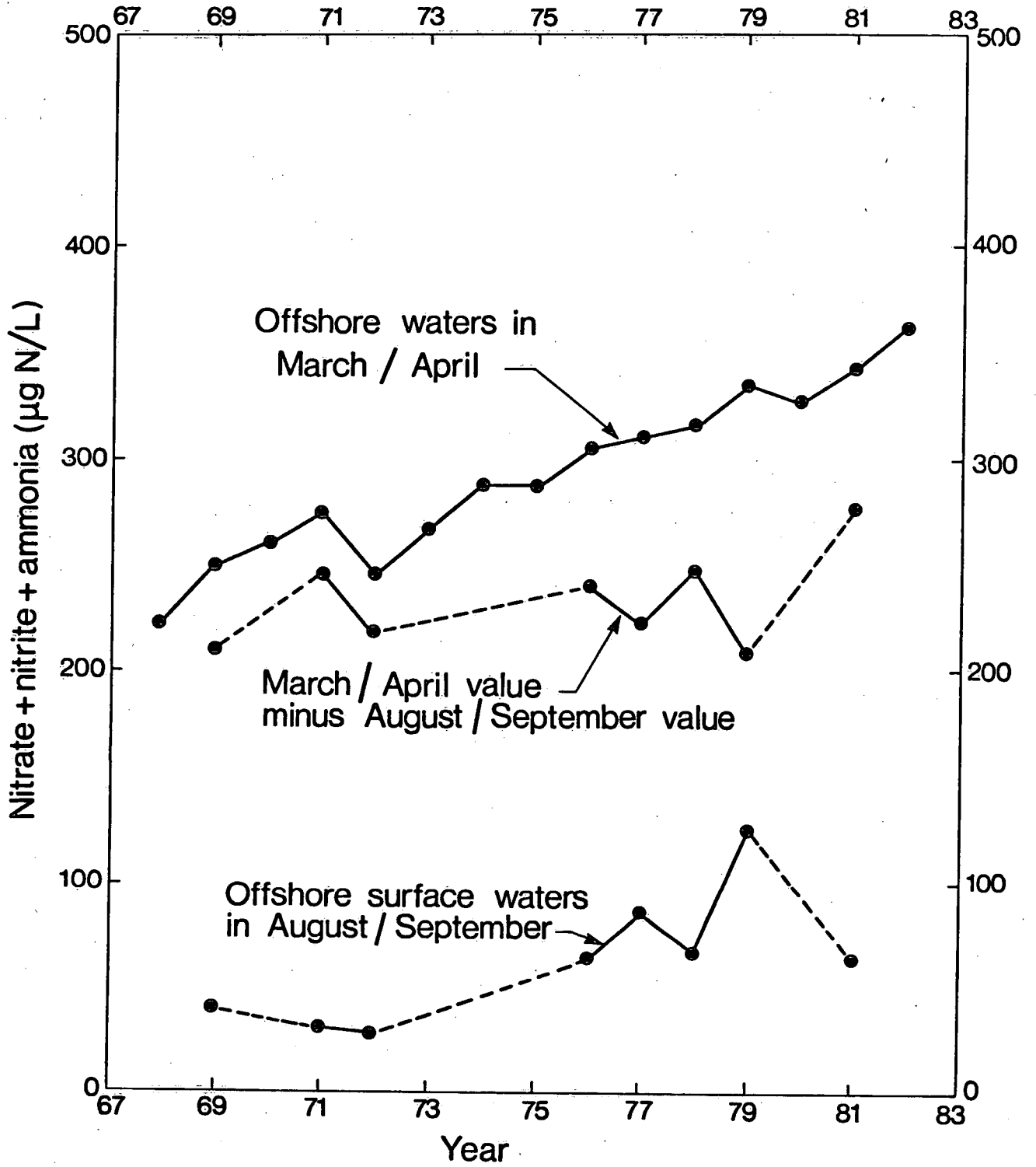
Lake Ontario: nitrate + nitrite, mean values in offshore, near-surface waters during March & April, 1968 to 1981.

Figure 66.



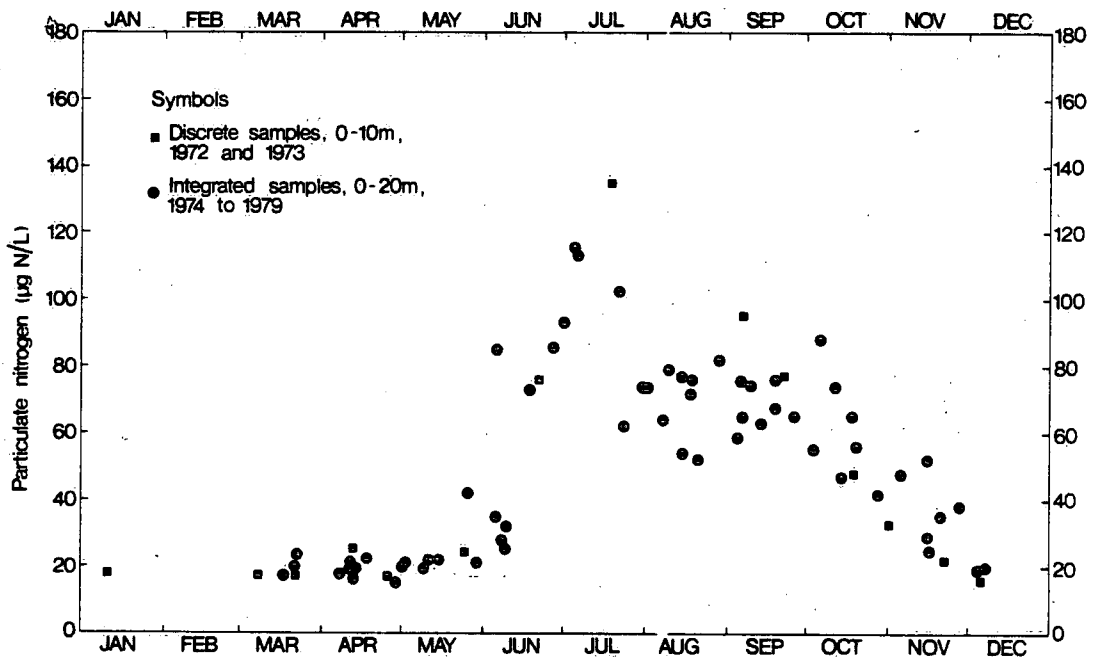
Lake Ontario, nitrate + nitrite in offshore, near-bottom waters in the years 1969 to 1981, cruise-mean values.

Figure 67.



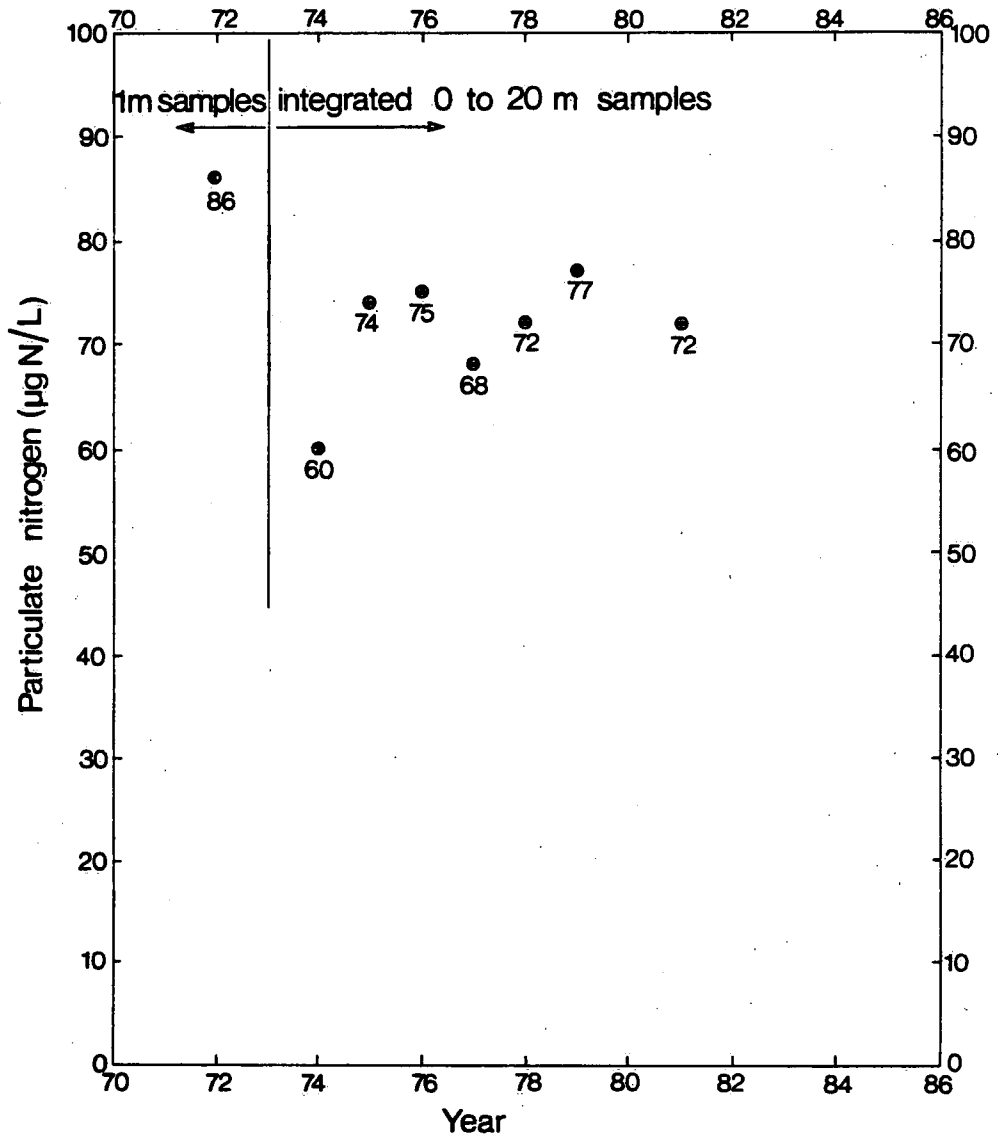
Lake Ontario, nitrate+nitrite+ammonia, 1968 to 1982 (CCIW data).

Figure 69.



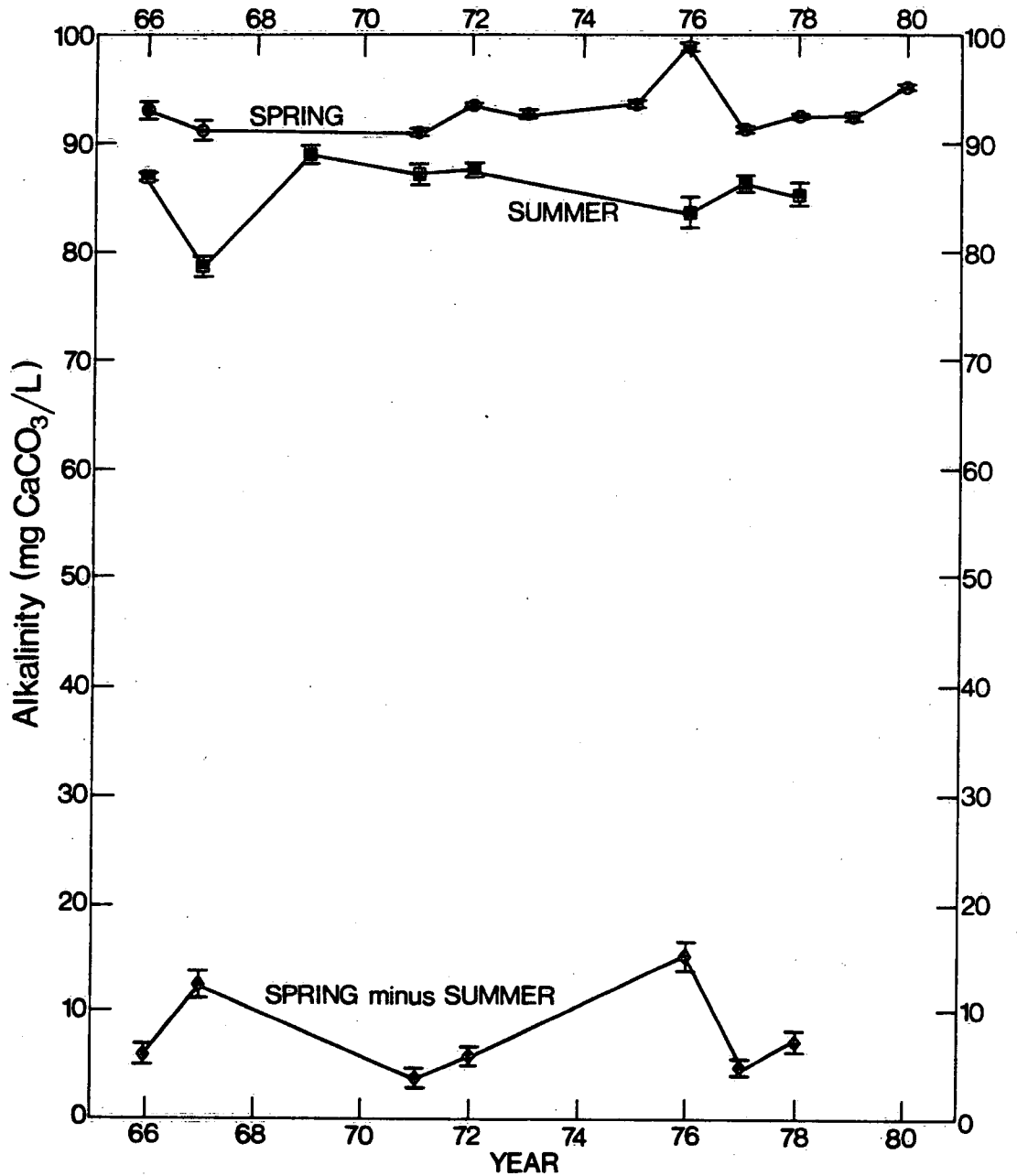
Lake Ontario, particulate nitrogen in offshore near-surface waters, cruise-mean values in the years 1972 to 1979.

Figure 70.



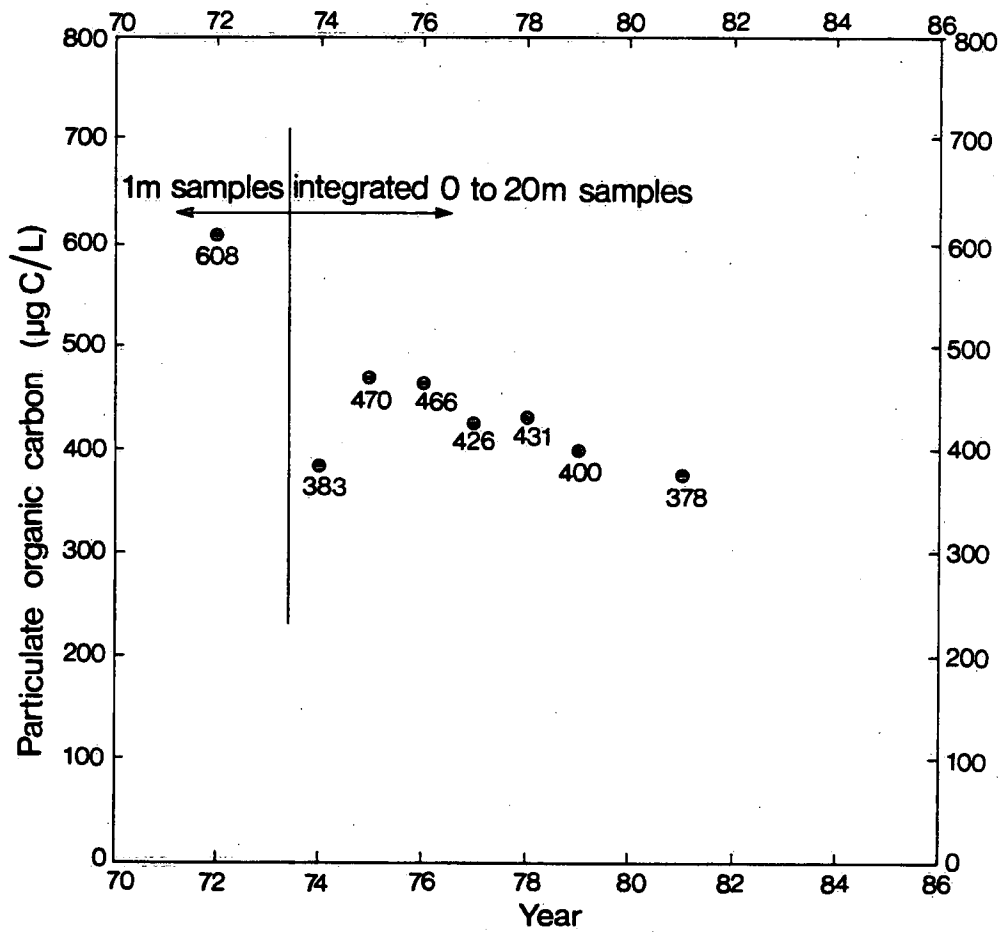
Lake Ontario, particulate nitrogen, mean values for August/September in offshore near-surface waters, observed by CCIW, 1972 to 1981.

Figure 71.



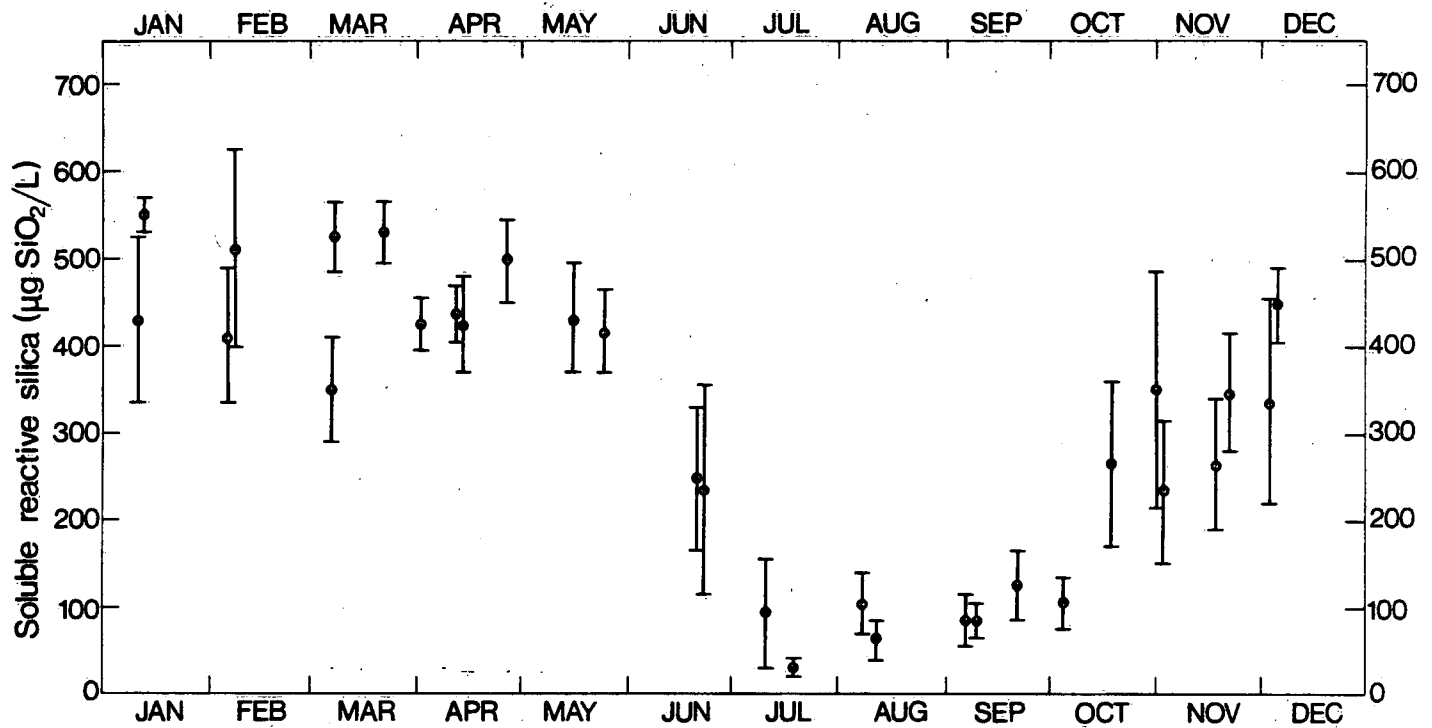
Lake Ontario, alkalinity in offshore surface water: Spring overturn period, summer (August 1 to September 15), and their difference. Error bars are 95% confidence intervals.

Figure 72.



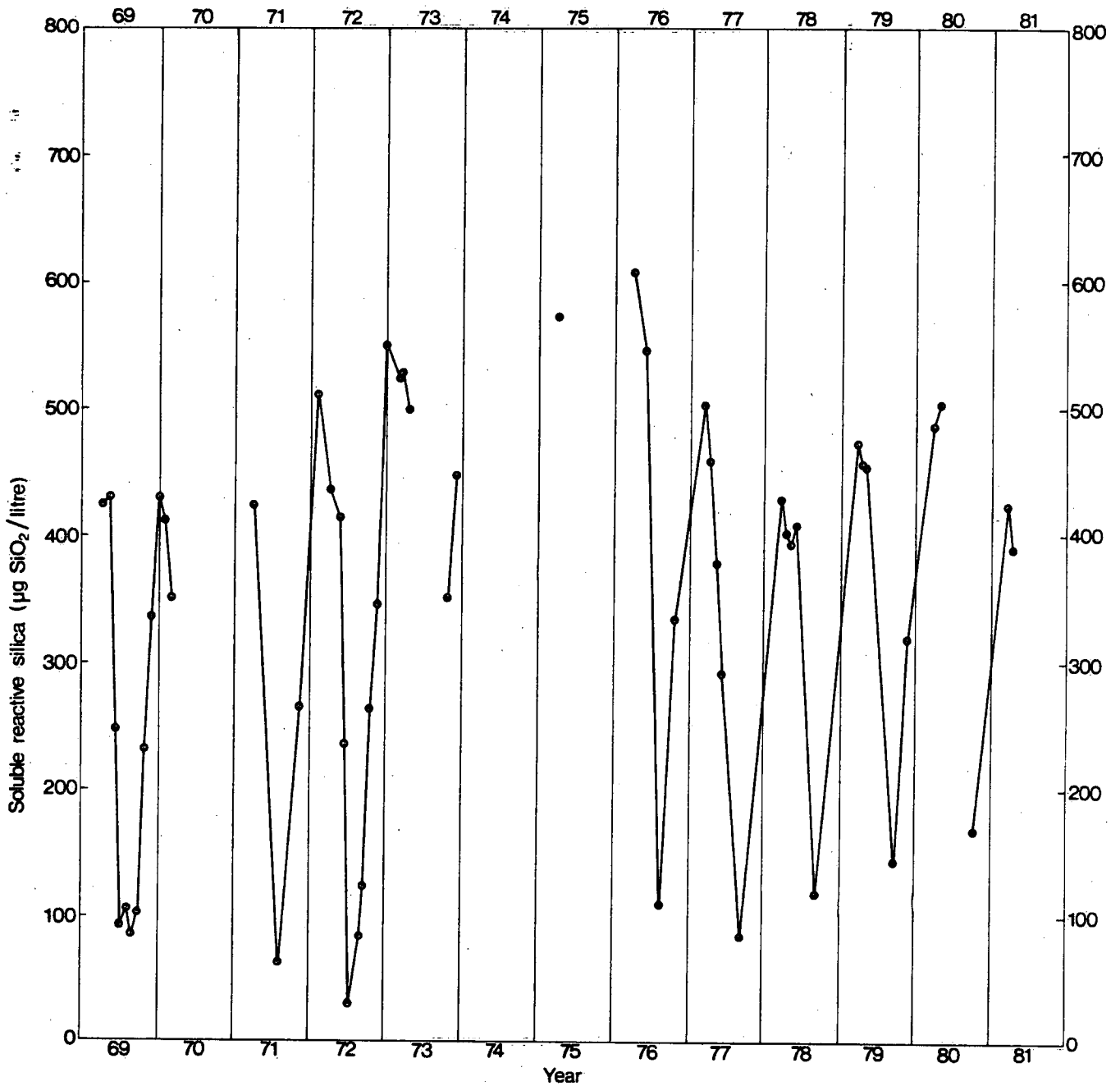
Lake Ontario, particulate organic carbon, mean values for August / September in offshore near-surface waters, observed by CCIW, 1972 to 1981.

Figure 73.



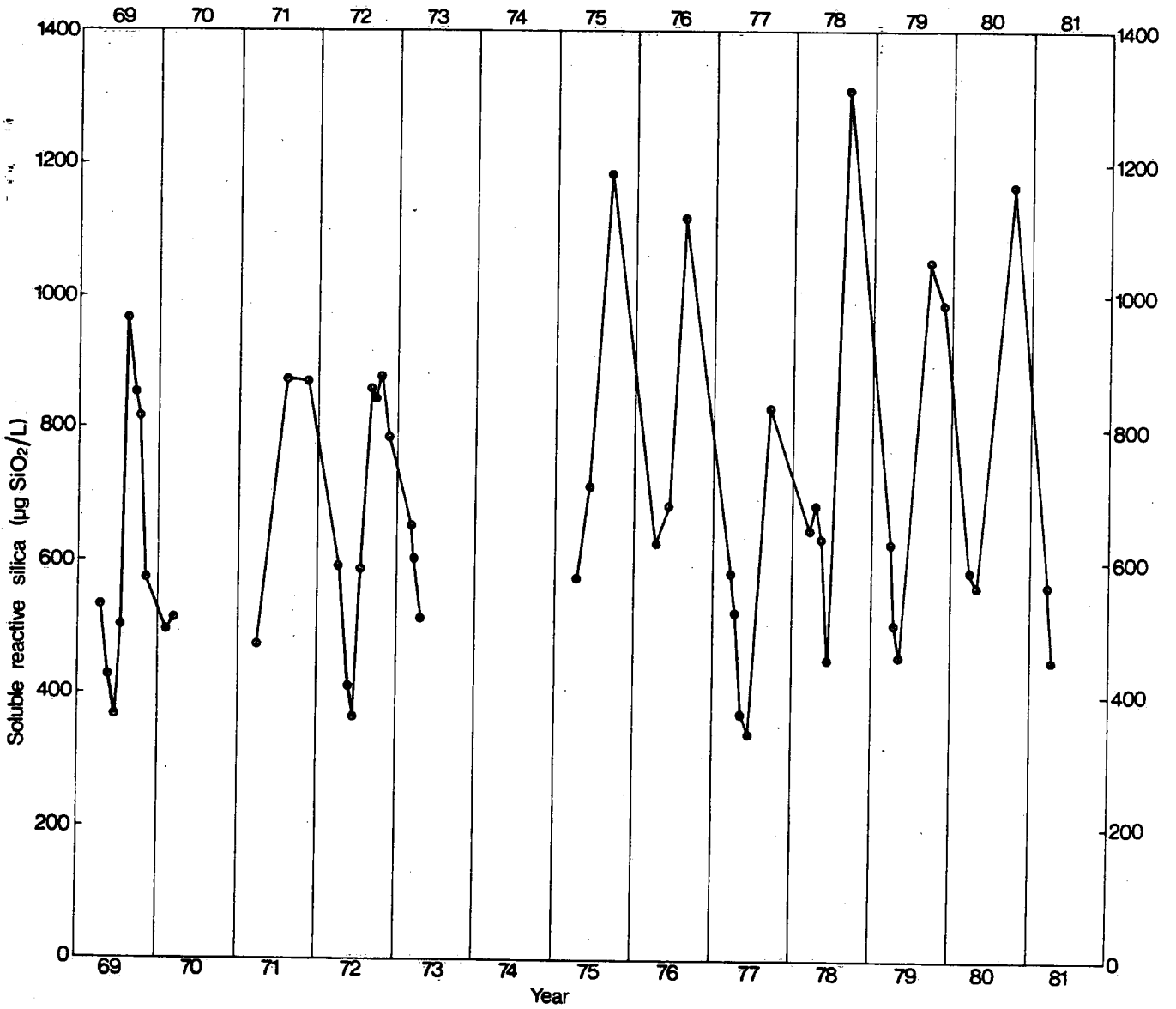
Lake Ontario, soluble reactive silica, seasonal cycle in offshore, near-surface waters: cruise-means and one standard deviation for 30 cruises in the years 1969 to 1973, data of CCIW. Soundings >100m, sample-depths ≤10m.

Figure 74.



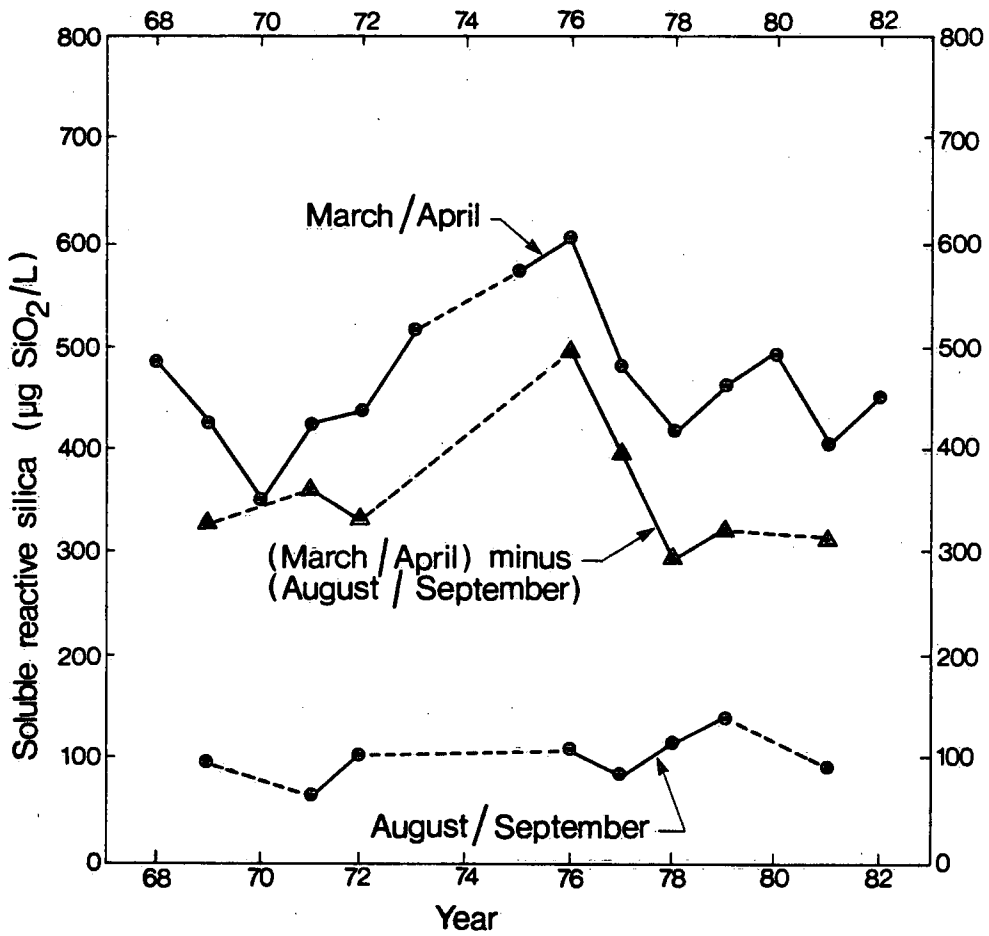
Lake Ontario, soluble reactive silica in offshore, near-surface waters: cruise-mean values, 1969 to 1981.

Figure 75.



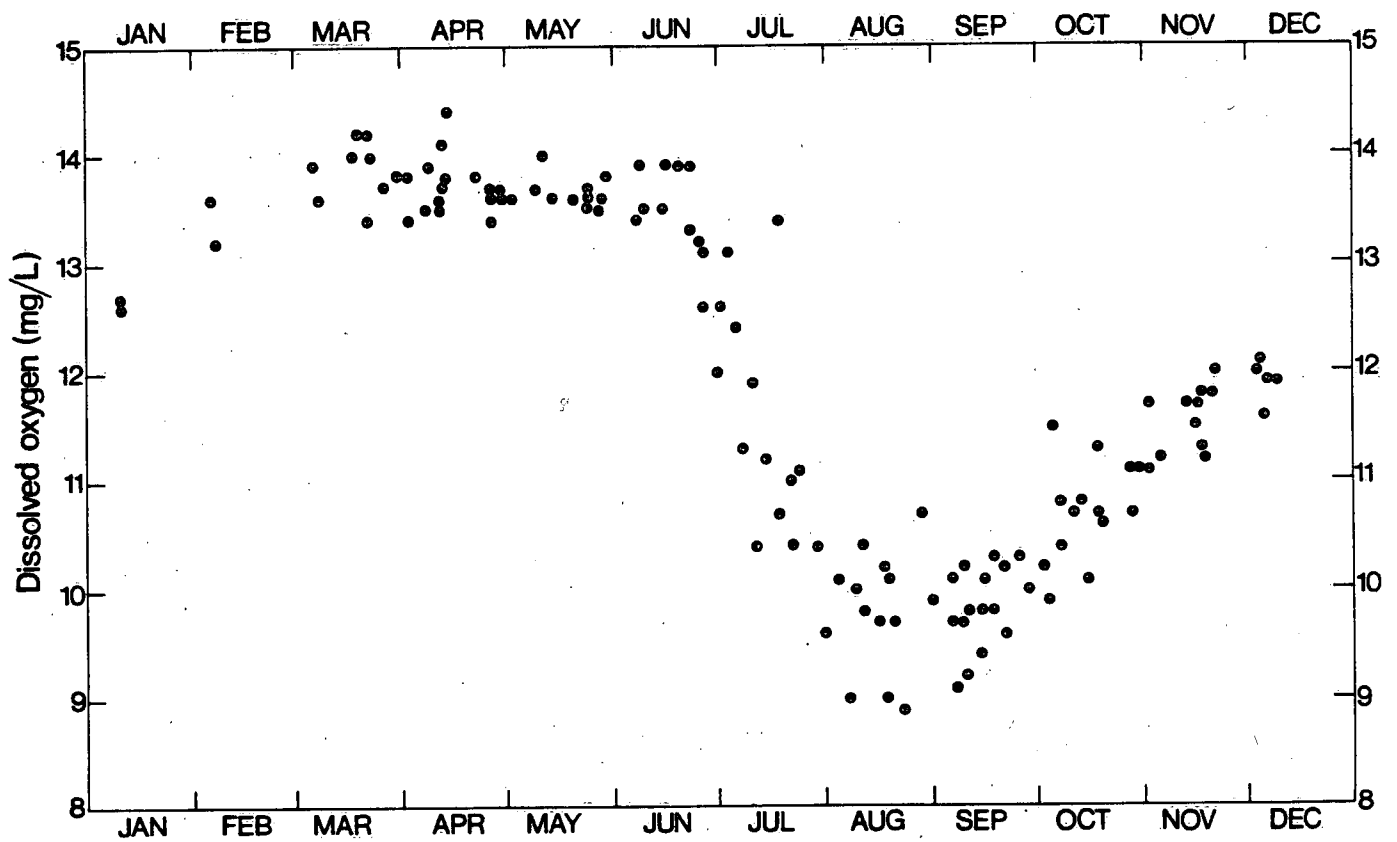
Lake Ontario, soluble reactive silica in offshore near-bottom waters: cruise-mean values, 1969 to 1981.

Figure 76.



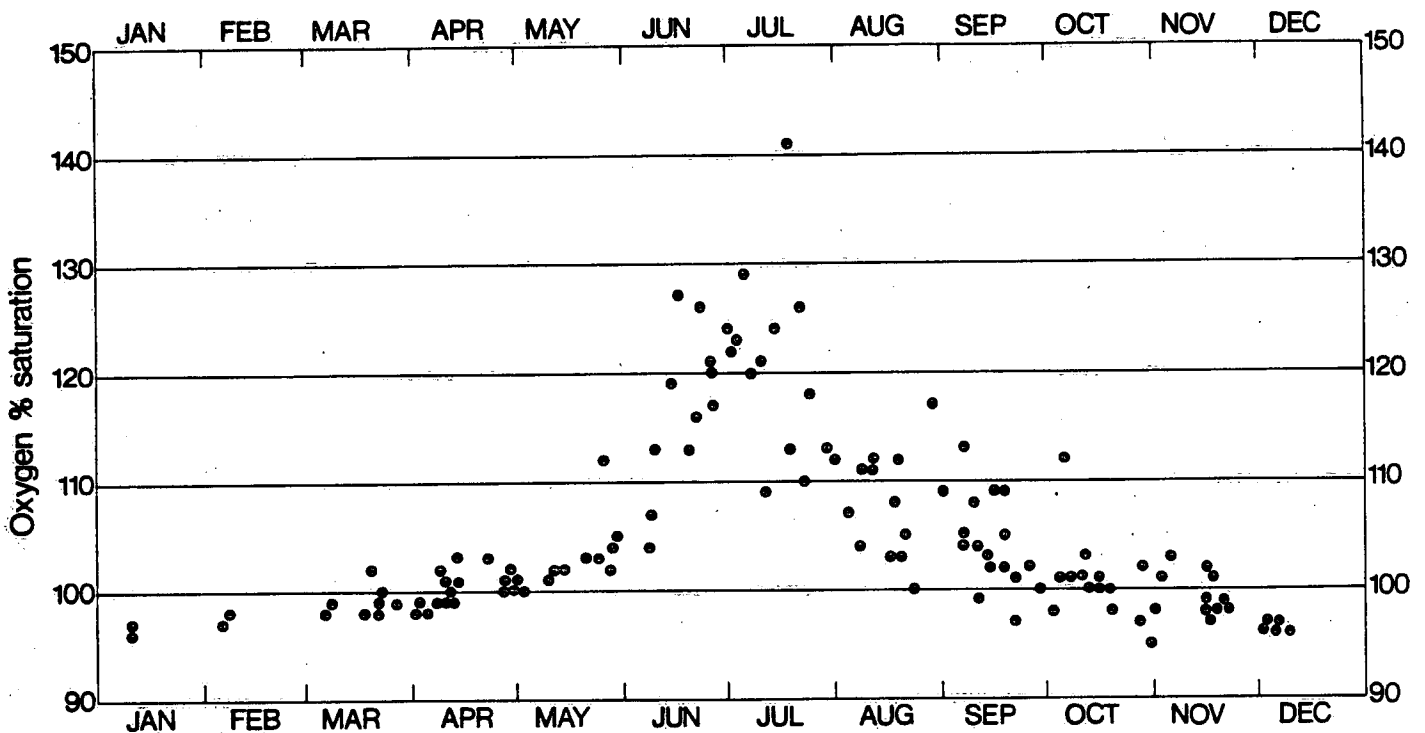
Lake Ontario, mean values of soluble reactive silica in offshore, near - surface waters, 1968 to 1982, data of CCIW: winter values, summer values, and their difference.

Figure 77.



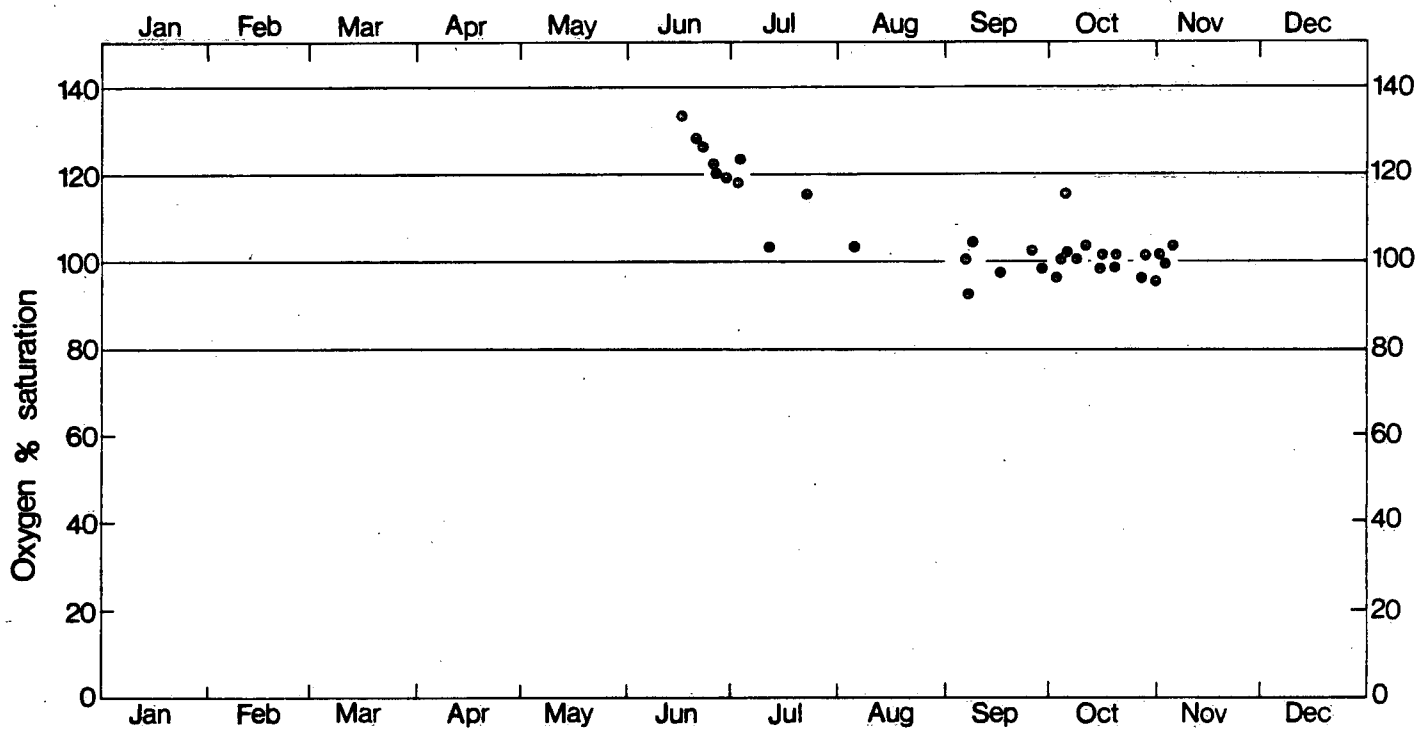
Lake Ontario, dissolved oxygen (mg/L) in offshore, near-surface waters: 124 cruise-mean values in the years 1966 to 1981, data of CCIW. Soundings >100 m, sample-depths ≤10 m.

Figure 78.



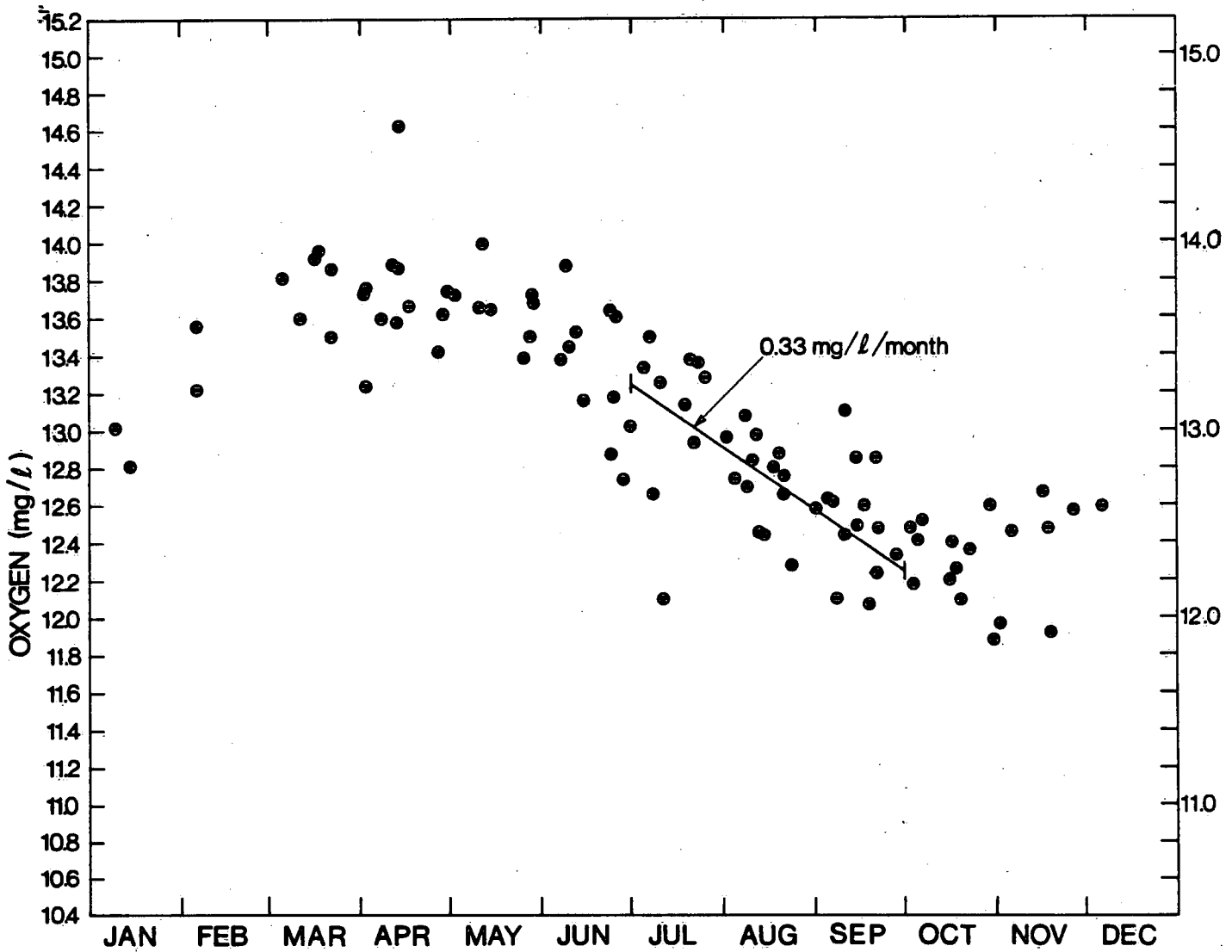
Lake Ontario, oxygen % saturation in offshore, near-surface waters: 124 cruise-mean values in the years 1966 to 1981, data of CCIW. Soundings >100 m, sample-depth ≤10 m.

Figure 79.



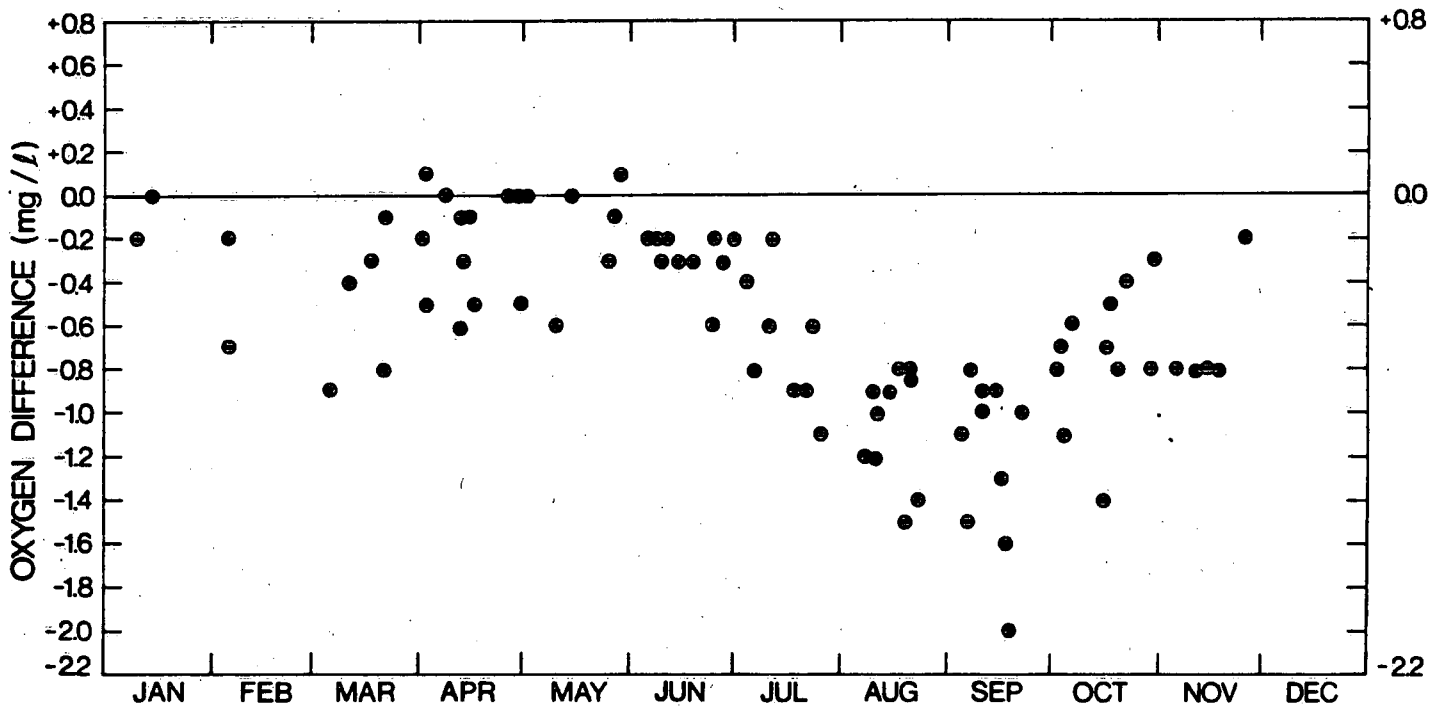
LAKE ONTARIO, OXYGEN % SATURATION: CRUISE-MEAN VALUES AT OFFSHORE STATIONS (SOUNDINGS >100m), FOR SAMPLES WITH TEMPERATURES IN THE RANGE 10 to 15°C, DATA OF CCIW, FROM 33 CRUISES IN THE YEARS 1966 to 1981.

Figure 80.



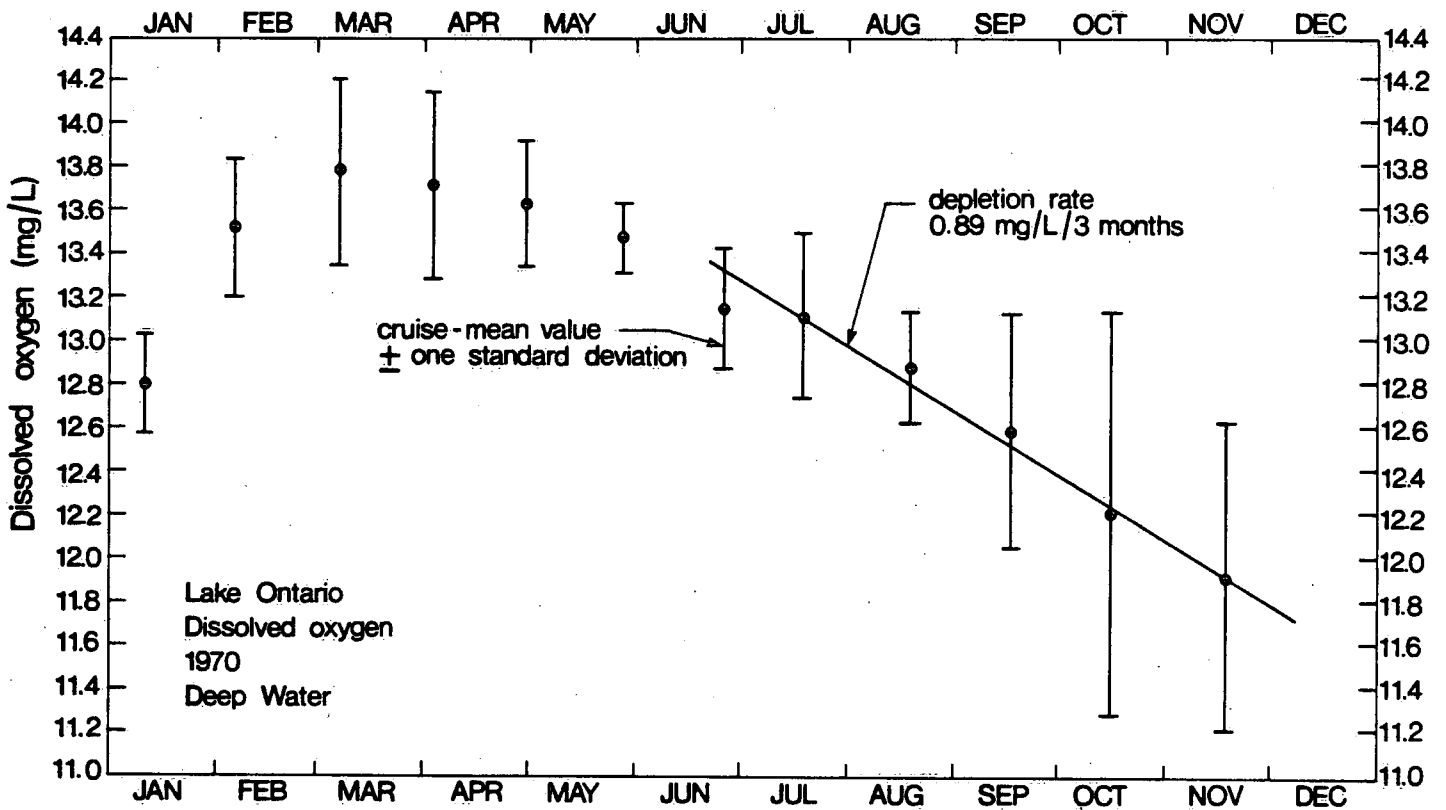
LAKE ONTARIO, DISSOLVED OXYGEN (mg/l): MEAN VALUES ON EACH CRUISE, ALL YEARS FROM 1966 TO 1978, FOR SAMPLES COLDER THAN 4.00°C AND NOT WITHIN 10m OF THE LAKE BOTTOM (OFFSHORE PART WHERE SOUNDING IS > 50m).

Figure 81.



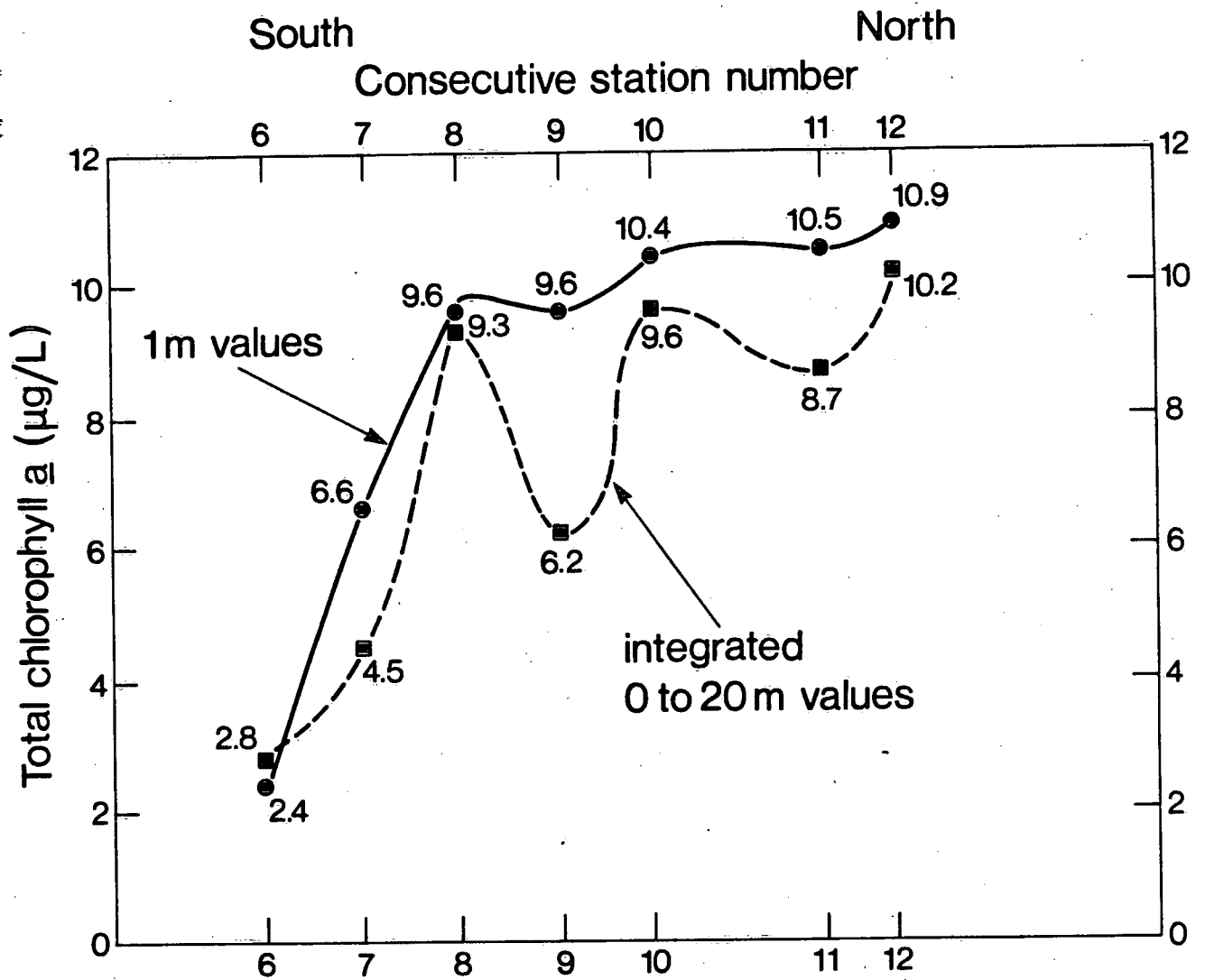
LAKE ONTARIO, DISSOLVED OXYGEN (mg/l): MEAN VALUE OF NEAR-BOTTOM SAMPLES (WITHIN 10m OF BOTTOM) MINUS MEAN VALUE OF OTHER SAMPLES COLDER THAN 4.00°C, ON EACH CRUISE IN THE YEARS 1967 TO 1978 (OFFSHORE PART WHERE SOUNDING IS > 50m).

Figure 82.



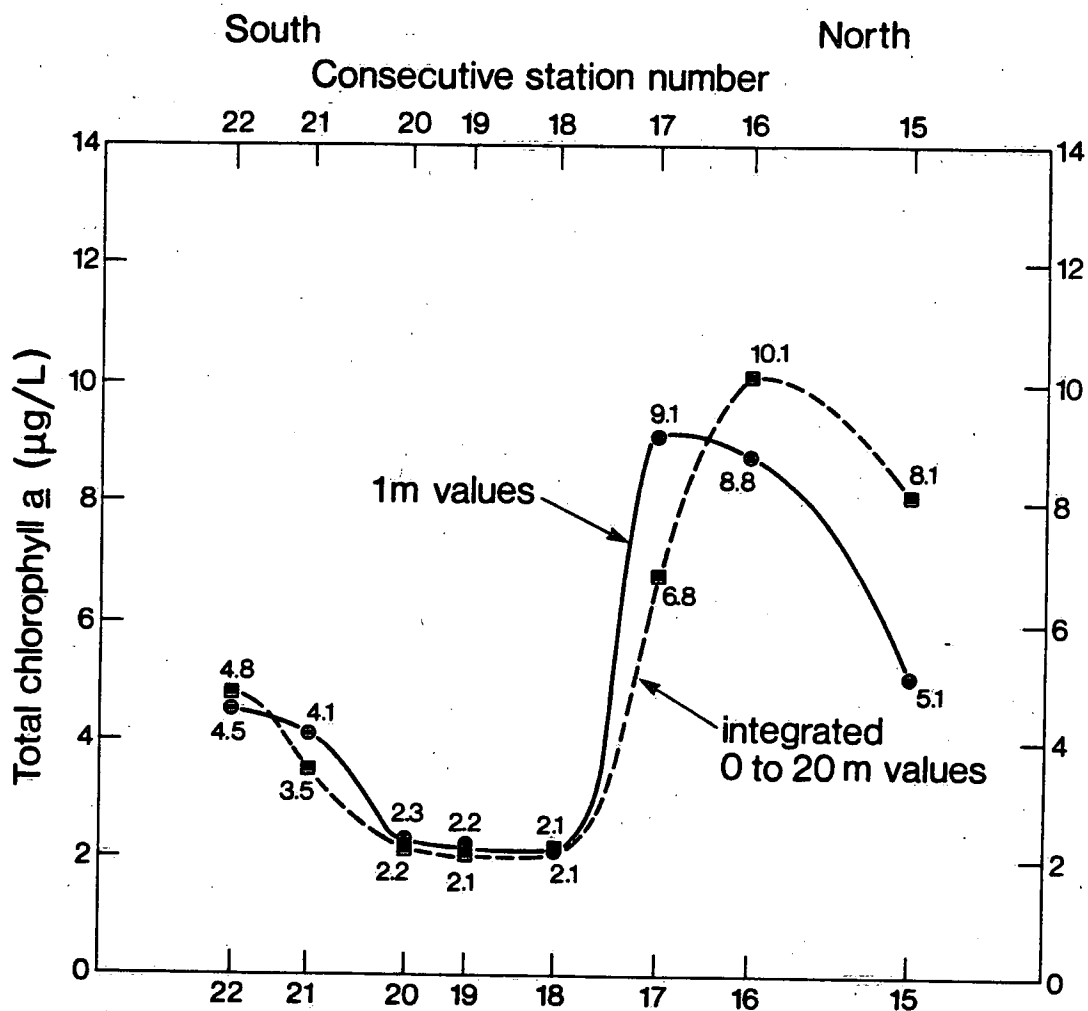
Lake Ontario, dissolved oxygen (mg/L) in the Deep Water (samples with temperature $<4^{\circ}\text{C}$ and not within 10m of the bottom), the year 1970, data from 12 cruises of the vessel Martin Karlsen.

Figure 83.



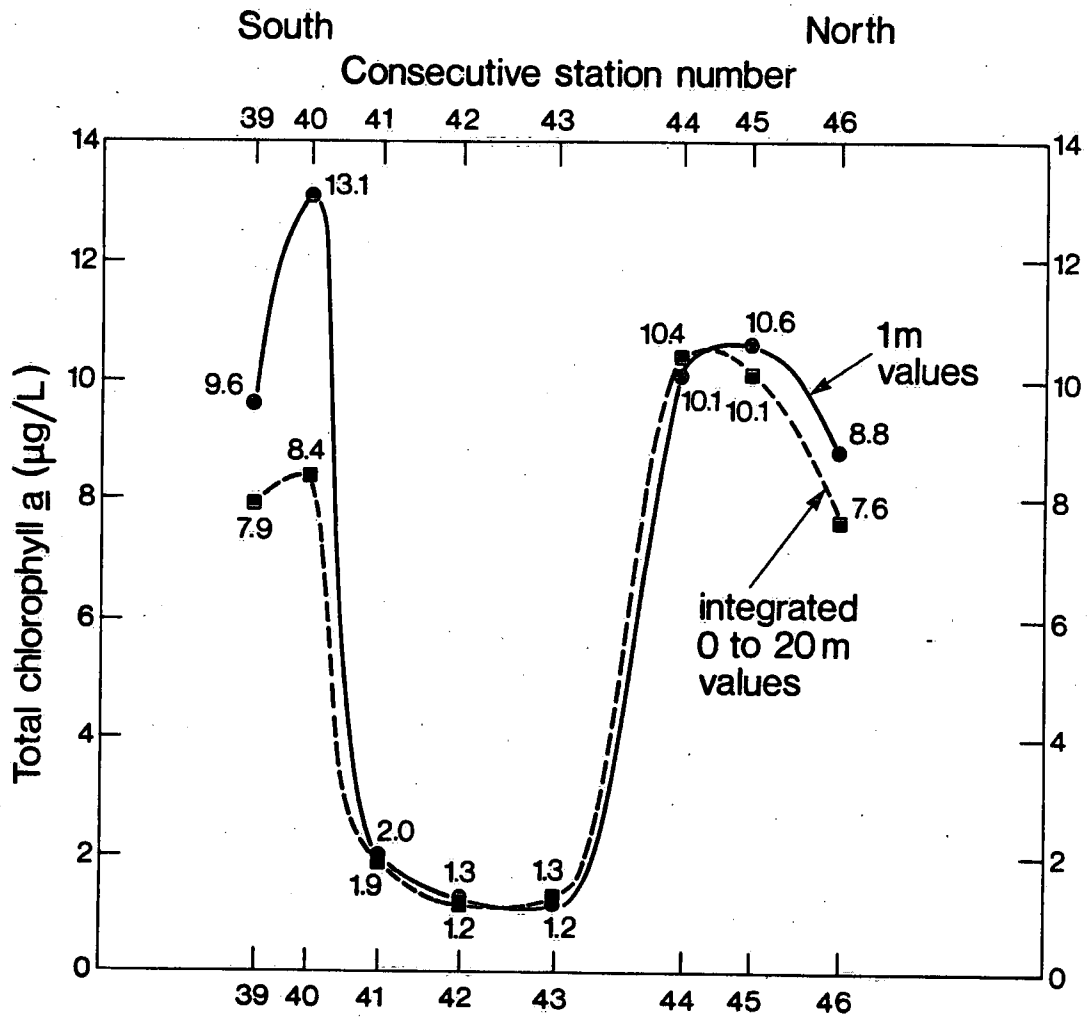
Lake Ontario, total chlorophyll *a* in transverse section "A", June 20, 1972, vessel "Martin Karlsen": comparison of 1m values and integrated 0 to 20 m values.

Figure 85.



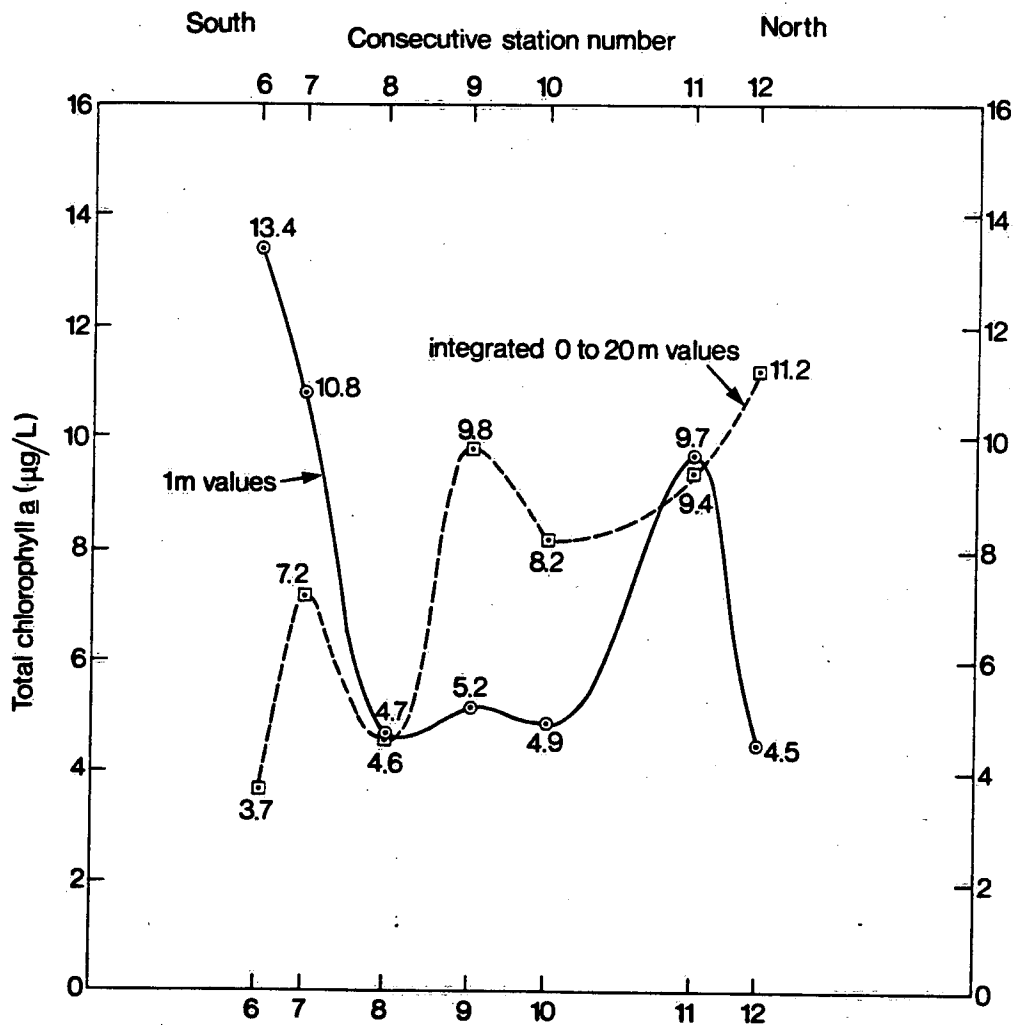
Lake Ontario, total chlorophyll *a* in transverse section "B", June 20 & 21, 1972, vessel "Martin Karlsen": comparison of 1m values and integrated 0 to 20 m values.

Figure 86.



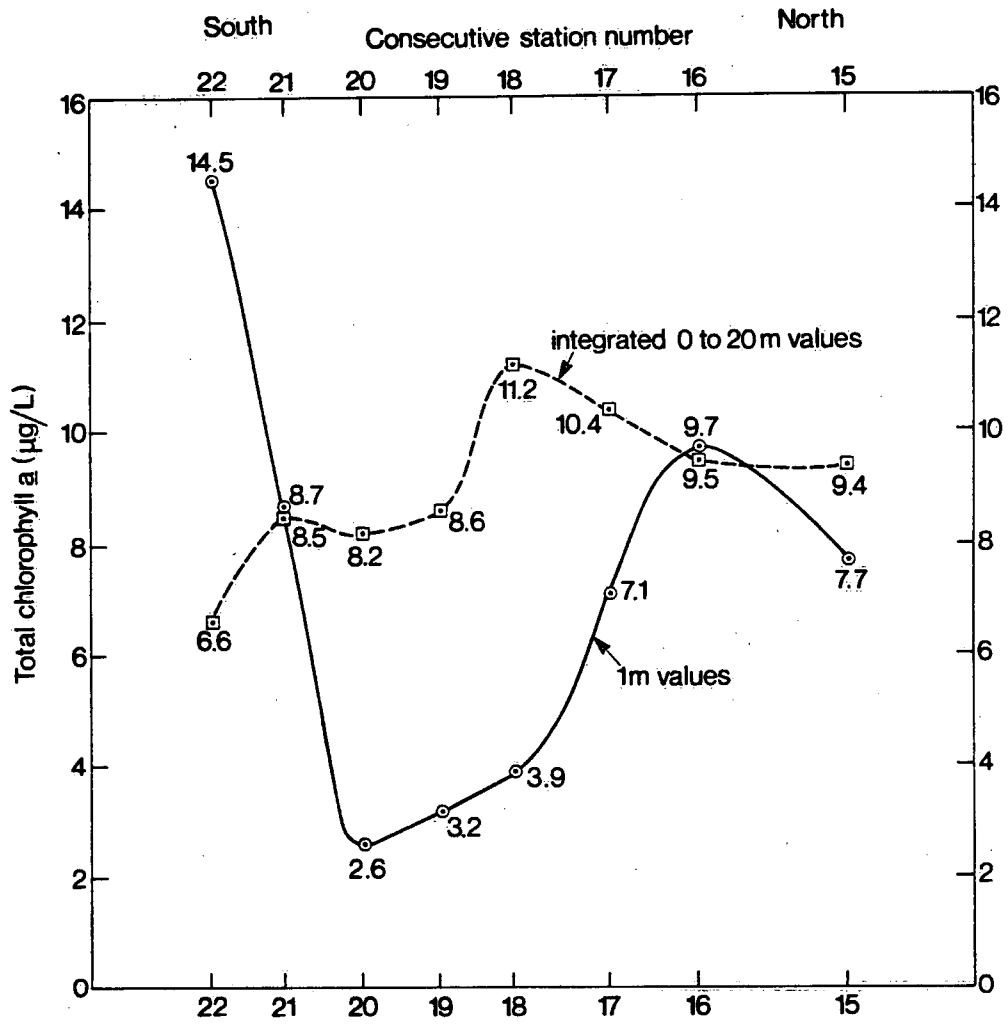
Lake Ontario, total chlorophyll *a* in transverse section "C", June 22 & 23, 1972, vessel "Martin Karlsen": comparison of 1m values and integrated 0 to 20 m values.

Figure 87.



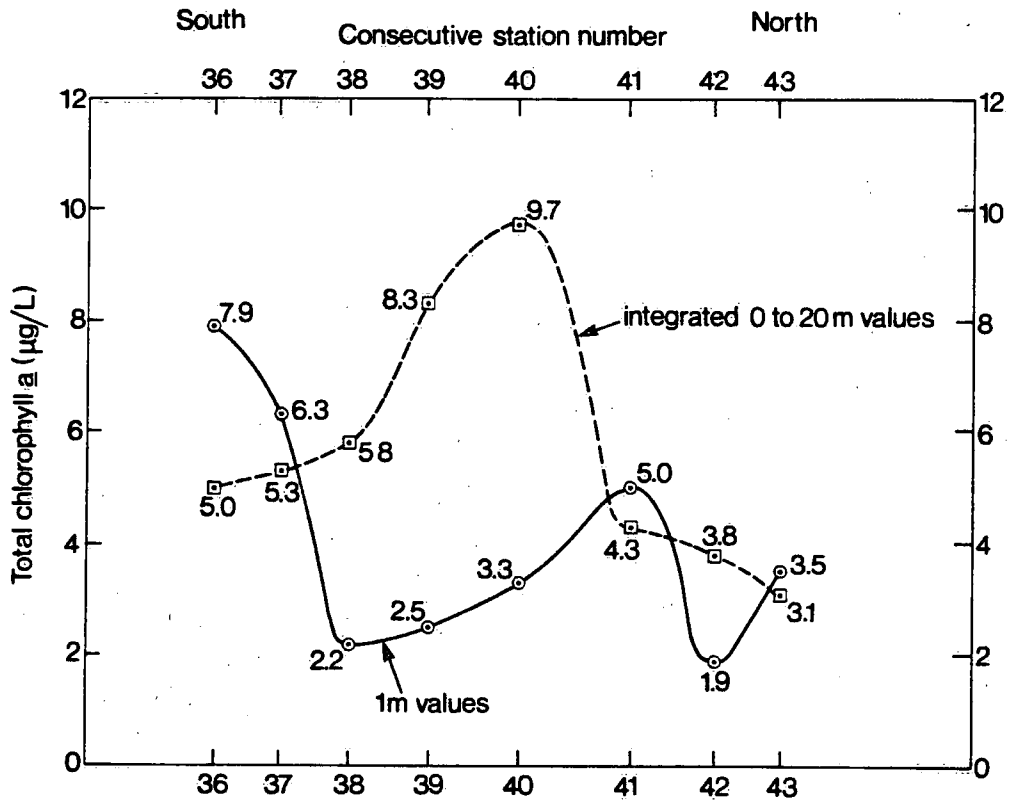
Lake Ontario, total chlorophyll *a* in transverse section "A",
 July 18, 1972, vessel "Martin Karlsen":
 comparison of 1m values and integrated 0 to 20m values.

Figure 88.



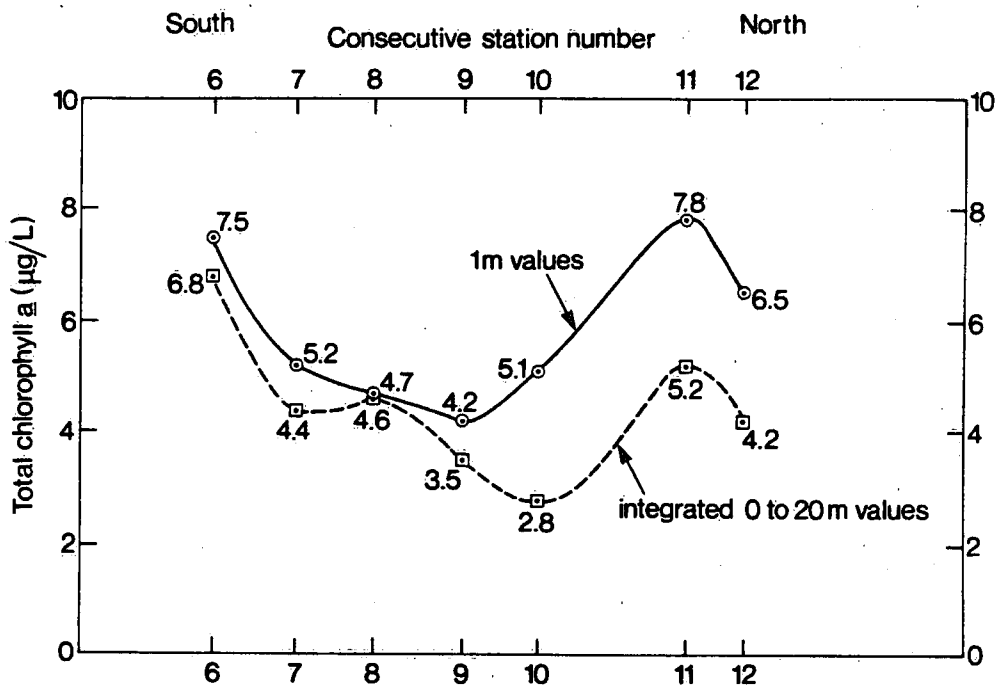
Lake Ontario, total chlorophyll *a* in transverse section 'B', July 18 & 19, 1972, vessel "Martin Karlsen": comparison of 1m values and integrated 0 to 20m values.

Figure 89.



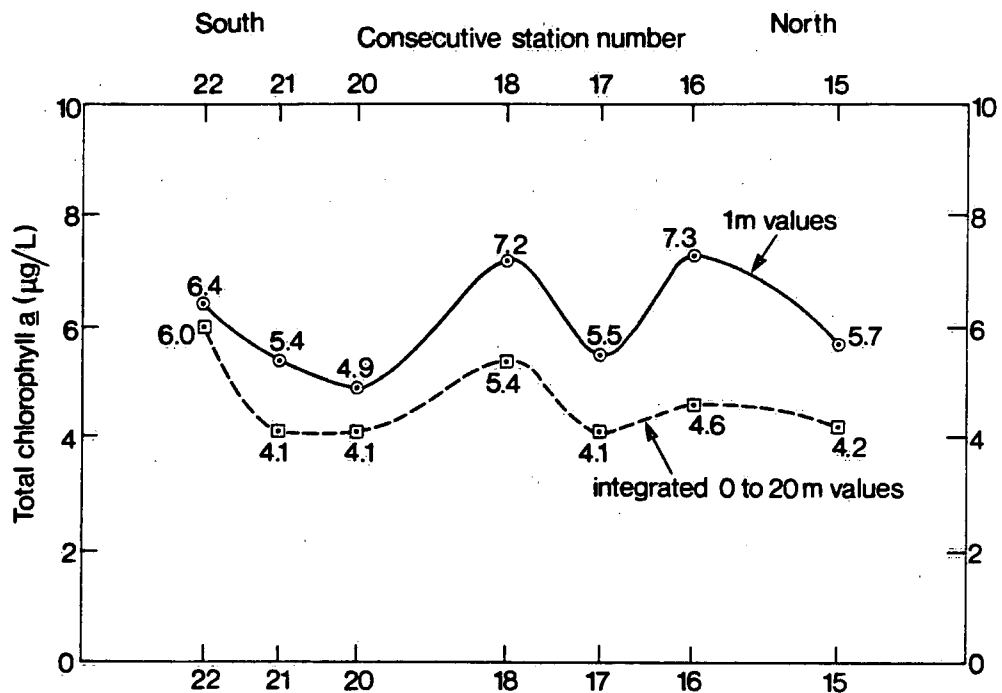
Lake Ontario, total chlorophyll *a* in transverse section 'C',
 July 20 & 21, 1972, vessel "Martin Karlsen":
 comparison of 1m values and integrated 0 to 20m values.

Figure 90.



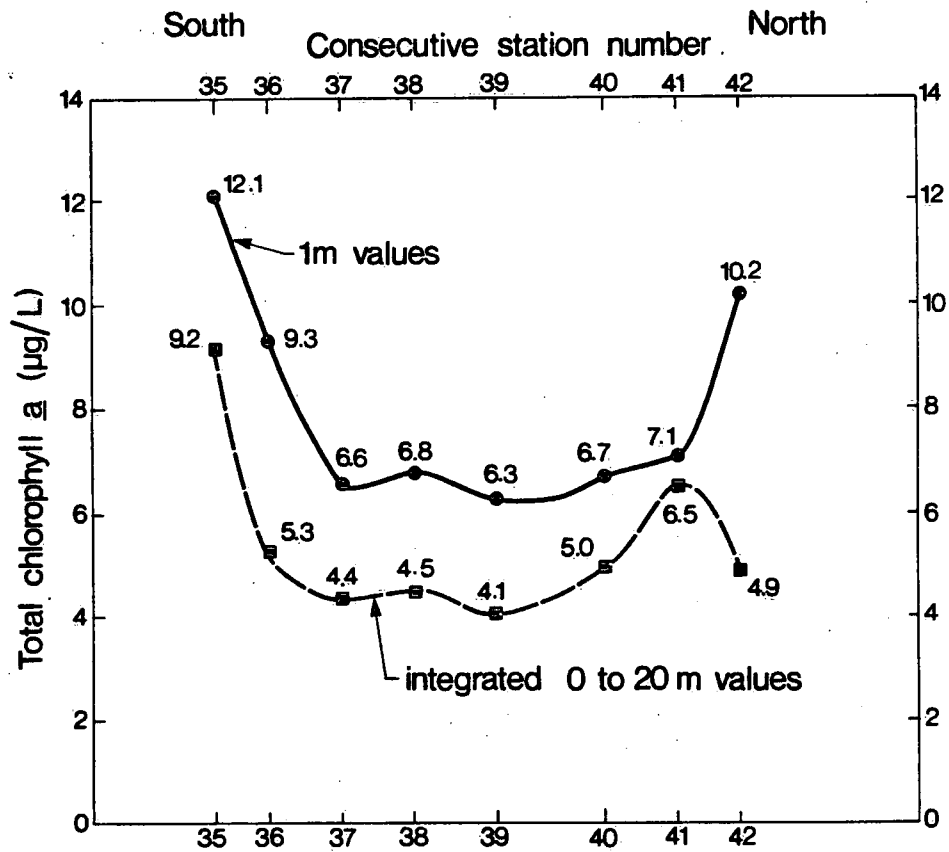
Lake Ontario, total chlorophyll *a* in transverse section "A",
 September 6, 1972, vessel "Martin Karlsen":
 comparison of 1m values and integrated 0 to 20m values.

Figure 91.



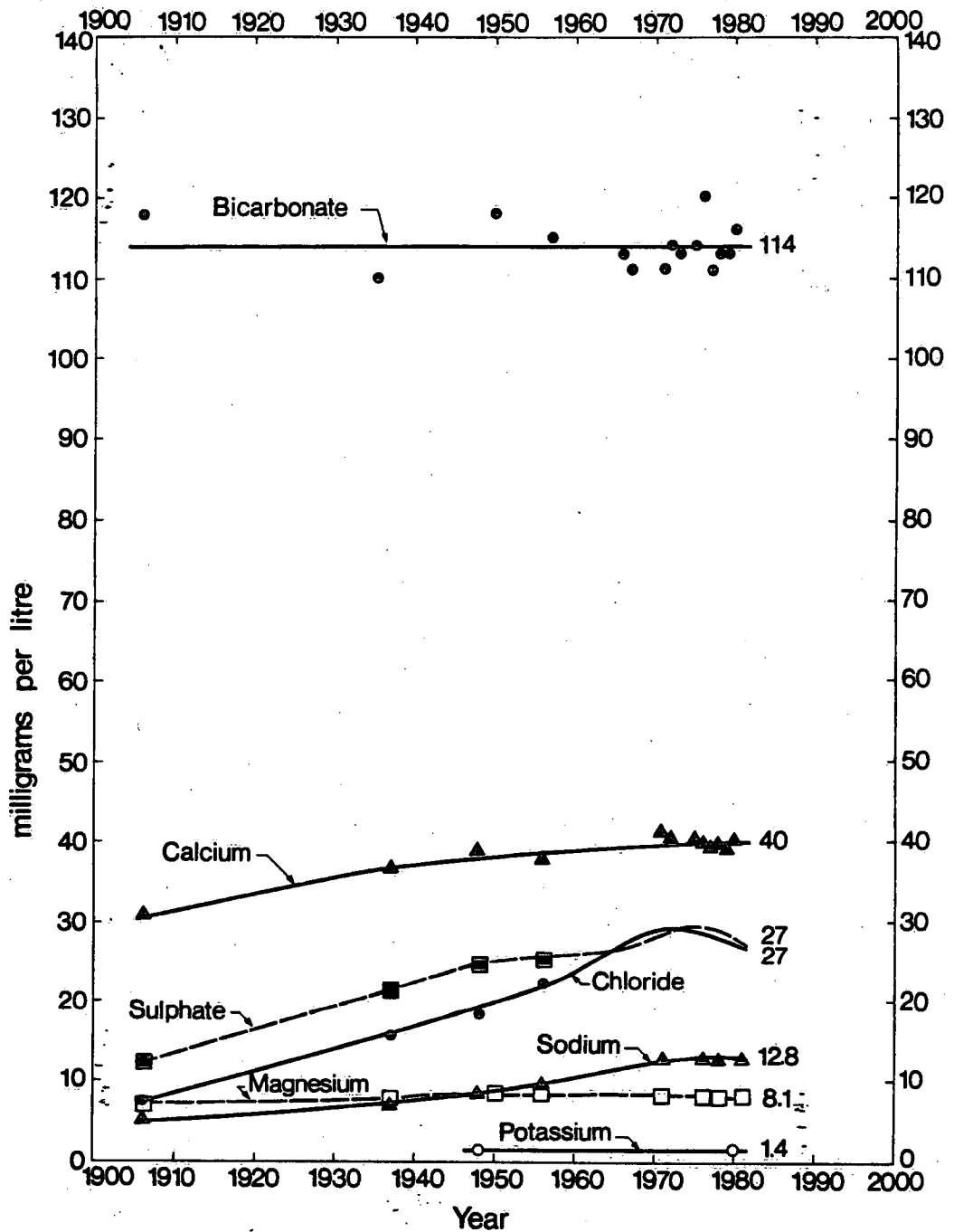
Lake Ontario, total chlorophyll *a* in transverse section "B",
 September 6 & 7, 1972, vessel "Martin Karlsen":
 comparison of 1m values and integrated 0 to 20m values.

Figure 92.



Lake Ontario, total chlorophyll a in transverse section 'C', September 8 & 9, 1972, vessel 'Martin Karlsen': Comparison of 1m values and integrated 0 to 20m values.

Figure 93.



Lake Ontario: trends in the concentrations of seven major ions, 1906 to 1981.

Figure 94.

R0149