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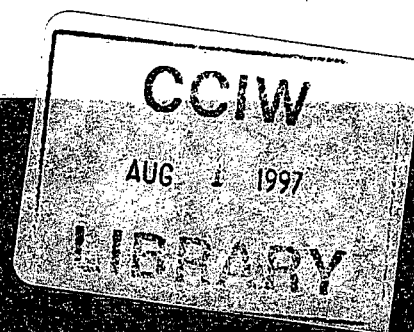


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One of the main goals in limnological research in Canada has been the study and understanding of the various physical limnological processes and their effect on the biological and chemical cycles of lakes. Theoretical and experimental research related to physical limnology of lakes have addressed phenomena such as waves (surface as well as internal), circulation (coastal and basin-wide) and turbulent transport and diffusion processes. These, in turn, are related to the density structure and fluxes of heat and momentum across the air-water interface. Such studies are complex and numerical models have been developed to simulate many processes. Applications of the studies range from providing a lake climatology accessible for the researcher and public alike, to providing mathematical models to assess such matters as lake water quality.

The following is a discussion of some important larger-scale physical processes observed in the Great Lakes which is intended for those with some limnological background. It forms a narrative for understanding of lake physics and the generalized interactions between the lake with the surrounding land and atmosphere. Examples from current research are given. The discussion first considers the extent of the Great Lakes Basin and hydrological influences on it. This is followed by a description of temperature structure and progress of stratification including the thermal bar, and the thermocline. Finally, a description of the circulation patterns for selected lakes is presented and the differences between nearshore and offshore water movements are discussed.

Great Lakes Basin

The Great Lakes Basin is located along the international boundary between Canada and United States. The Basin includes portions of eight states: Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania and New York; and the Province of Ontario. In extent the basin encompasses an area of 772,053 km². Responsibility for managing the vast freshwater resource is a shared commitment between the two countries coordinated by the International Joint Commission.

The Laurentian Great Lakes comprise the largest continuous volume of fresh water on Earth. Its present form is largely attributable to the effects of continental glaciation and glacial erosion.

The system is comprised of five major lakes; Lake Superior, Michigan, Huron, Erie, and Ontario, which together occupy nearly one third of the total basin area (Figure 1). Flow from the headwaters at Lake Superior to the final outflow into the Atlantic Ocean is continuous; water is transported through the various connecting channels such as the St. Mary's River, Straits of MacKinac, St. Clair and Detroit Rivers, Niagara River and the St. Lawrence River.

Details of the Great Lakes Basin and lake bathymetry are given in Figure 1 and Table 1 where values are referenced to the International Great Lakes Datum (IGLD) and an arbitrarily set Low Water Datum (LWD). A general profile of the Great Lakes is illustrated in Figure 2 in which it is evident that Lakes Huron, Michigan and Ontario have comparable depths, that Lake Erie is the shallowest and that Lake Superior is the deepest and largest. Net flow from Lake Superior to the St. Lawrence River is due to a progressive drop in elevation. Approximately 7 m separates Lake Superior and Lakes Michigan, Huron and Georgian Bay which are at the same level, while only 2 m separates Lakes Huron and Erie. A drop of nearly 100 m separates Lakes Erie and Ontario, hence the hydro-electric developments at Niagara Falls. It is interesting to note that the volume of the Great Lakes exceeds that of Lake Baikal in the USSR and in areal extent alone, Lake Superior exceeds all other freshwater lakes, except the Caspian Sea which is moderately saline.

Physical Properties of Fresh Water

The Great Lakes represent a vast reservoir of freshwater for consumptive, industrial and recreational uses. Knowledge of its properties are fundamental to scientific studies of its movement and interaction with the atmosphere. Basic aspects of the physical properties of fresh water of interest to scientific research are briefly outlined here.

The physical characteristics of water depend primarily on temperature and pressure. Water reaches its maximum density while still in a liquid state at 3.98°C (4°C) at atmospheric pressure and decreases in density at warmer temperatures and as it cools to its freezing point at 0°C (Figure 3). The temperature of maximum density is affected by pressure; it decreases by 0.1°C for every 100 m depth of water. This characteristic of water accounts for many of the seasonal physical changes which the Great Lakes undergo. Temperature and density of a large lake are neither horizontally nor vertically uniform. A typical surface water temperature survey for Lake Ontario (Figure 4) and seasonal vertical temperature cycle for Lake Superior (Figure 5) illustrate this variability.

Large bodies of water moderate adjacent climatic extremes. For example, extremes of air temperature at the lake periphery and the lee-side are less than those in the hinterland. This is largely due to the high specific heat of water. (Specific heat is the amount of heat required to raise the temperature of one gram of substance 1°C). Because of this property, the Great Lakes can store great quantities of heat and react slowly to short term changes in temperature. Estimates of longterm heat content are given for the contrasting cases of Lake Superior and Lake Erie (Figure 6). The presence of ice on a lake surface tends to reduce heat losses during the winter season.

Other physical properties of water have to be considered for a full appreciation of lake thermal processes and water movement. Latent heats of fusion and vaporization for water refers to the amount of energy required to change water from its liquid phase to the solid or vapour phase with no temperature change. The latent heats of fusion and vaporization for water are among the highest of all substances. Evaporation from the water surface requires approximately 590 cal/gm and results in heat loss from the lake surface.

Another interesting property of water is electrical conductivity. Although pure water is effectively considered as electrically neutral the specific conductance and dissolved ion concentration measured in the Great Lakes is increasing and this is partly due to increased human activity especially in the Lower Great Lakes. Figure 7 shows an example of surface conductivity contours for Lake Ontario. Maps such as these are useful as tracers for such things as the Niagara River plume in Lake Ontario.

Lake Level Fluctuations

Variation of the mean water levels and wind-waves are two of the most important lake phenomenon affecting shipping, recreation and erosion at the shores of the lake. The difference between the processes lies in time scales and whether meteorological forcing or lake volume changes are the dominant factors.

Seasonal fluctuations in mean lake levels result from an imbalance in the amounts of precipitation, evaporation, runoff, ground-water flow and the inflows and outflows to a particular lake. Water losses occur through evaporation and outflow while other factors cause an increase in supply. Water balance investigations are useful for deriving reliable estimates of the various components. The process of water addition and loss is referred to as the hydrological cycle.

The large surface areas of the Great Lakes and the relatively narrow outlets of the connecting rivers have the effect of slowing the response of the mean lake levels to sudden changes. In

general, any increases in outflow from Lake Superior are first absorbed by Lakes Huron and Michigan. The storage capacity of these lakes is so large that it is estimated that about 3 years time is required before 50 percent of any increase in outflow from Lake Superior would be noticed in Lake Ontario. Lake Erie receives a relatively steady supply of water through the Detroit River due to the vast surface area of the Lake Huron-Michigan system which absorbs the initial input from changes in water supply. However, fluctuations in the water level of Lake Ontario can cause large and sometimes dangerous fluctuations of flow and stage in the St. Lawrence River. Consequently, the outflow from Lake Ontario is regulated. Figure 8 shows longterm annual water level variations for each lake.

The mean annual outflows and the lake volumes can be combined to yield a water flushing time. The flushing time, which is of interest for water quality studies and predictions is the average length of time that molecules or ions of a dissolved, non-reactive constituent of the lake water remain in the lake before being transported out by the outflowing rivers; the flushing time, therefore, is the lake volume divided by the rate of outflow. Estimates of the flushing times in years for the Great Lakes are as follows:

Lake Superior	165.0
Lake Michigan	69.5
Main Lake Huron	10.6
Georgian Bay	5.7
Lake Erie	2.5
Lake Ontario	7.5

Although there are various estimates of the actual flushing times based on different estimates of volumes and discharge rates, the long flushing times for water in Lake Superior and Lake Michigan indicates that the recovery from an undesirable state of water quality might take a long time.

Fluctuations of water level at periods of less than a day are generally termed waves and do not involve changes in lake volume. One method used to assess surface motions is the time period for two successive crests to pass the observer. Surface motions of less than 1 second are termed capillary and ultragravity waves. Wind-waves and swells usually have periods ranging from 1 to 30 seconds. Water level oscillations in the nearshore area with periods 30 seconds to 5 minutes, are classified as infragravity waves. Seiches, storm surges, wind tides and astronomical tides have periods ranging from 5 minutes to 24 hours and are generated primarily by meteorological forces. These water level motions are short term but in the case of storm generated waves, water levels on the lee-side of Lake Erie have been observed to rise between 1 and 2 meters causing significant shoreline damage. Seiches, which are similar to the sloshing oscillations set

up in a bathtub by vigorous stirring, can result in surface fluctuations in excess of 30 cm, whereas changes in atmospheric pressure can result in water level variations of up to 15 cm. In comparison, tidal variations are in the range of a few centimeters. Figure 9 illustrates an extreme water level change during a storm surge event on Lake Erie in response to a severe storm with winds gusting up to speeds of 28 m/s aligned along the axis of the lake.

Air-Water Interactions

The general westerly atmospheric circulation and local modifying influence of the Lakes which act as heat sources or sinks have a dominant influence on the climate of the Great Lakes Basin. A few of the effects include moderation of air temperature, increases in over-lake windspeed and humidity and modification of precipitation patterns. Environmental climatologies for these factors have been developed. Examples of monthly wind stress field is given for Lake Ontario (Figure 10). Wind stress is the major forcing mechanism for water movement. The wind exerts a stress on the free surface thereby setting the surface water in motion. This energy is redistributed horizontally and vertically throughout the water column.

Heating and cooling processes in the Lakes are the result of the interaction of meteorological and hydrological factors. Some processes are confined to the lake surface, others are transmitted through the surface to some depth while others produce heat changes by mixing water masses. Figure 11(a) is a summary of major heating and cooling processes considered in the heat balance of a lake. The basic energy processes include energy produced by the sun's radiation, sensible heat transfer to or from the atmosphere, heat loss by evaporation, energy storage within the lake and net advected energy into or out of the lake. Meteorological factors such as radiation, air temperature, precipitation and evaporation affect the surface temperature while winds provide the mechanical energy required to mix the heat downwards. Hydrological factors such as inflow or outflow cause local temperature changes by horizontal movement and mixing with the lake waters. Figures 11(b) and (c) show the relative importance of these energy processes for Lake Superior. Penetration of solar radiation into the water column affects the heating of the uppermost layers. The rate of penetration is governed by the vertical extinction coefficient (Figure 12), an optical property related to water clarity.

Surface heat flux and meteorological data collected external to the lake can be used as inputs to a mathematical model which estimates vertical temperature profiles. Since many chemical and biological processes are temperature dependant, such a physical model forms the core of a predictive water quality model.

Spring Warming and Thermal Bar

The Great Lakes are subject to major seasonal changes in the net heat input and as a consequence goes through an annual thermal cycle. These large deep lakes mix from top to bottom (overturn) twice yearly, in the spring and the fall. The timing of the overturn is very closely related to the time when the surface water temperatures of the lake fluctuates through the temperature of maximum density of fresh water, i.e., 4°C , because at this time both surface heat fluxes and wind help stir the Lake.

In the winter, the surface waters are all generally below the temperature of maximum density. As the spring warming phase begins, the water in the shallow littoral regions warm more rapidly than the waters in deeper regions. With progressive warming the nearshore waters reach temperatures above 4°C while waters immediately offshore are still below 4°C . As a consequence of the anomalous temperature-density relationship of water around 4°C , a zone of convergence is formed and is referred to as the "Thermal Bar". Figure 13 shows a conceptual model of the thermal bar circulation. Sinking is shown to occur near the 4°C zone with surface convergence into this zone from the warm inshore and possibly the cold offshore side of the bar. Flows from the inshore region converge towards the thermal bar and accelerate the sinking motion.

The "Thermal Bar" first forms along the Lake's perimeter at a surface temperature of nearly 4°C and as the heating of the nearshore waters proceeds, the bar advances offshore leaving behind a weakly stratified nearshore water mass. Thus the thermal bar marks the onset of summer stratification in large, deep lakes in temperate climates. The "Thermal Bar" advances toward the center of the lake as heating progresses, and when the central portion reaches 4°C , the "Thermal Bar" disappears. In deep lakes such as Lake Ontario, Huron and Michigan, this process takes as much as six to eight weeks. Typical summer stratification is achieved as the surface waters reach greater than 4°C over the entire lake and the 4°C water slides underneath.

The mechanism of the thermal bar and its significance on spring circulation and on waste dispersal in the nearshore zone are quite important in large lakes. The thermal bar is marked by abrupt horizontal temperature gradients and temporarily impedes free exchange between warmer often stratified inshore water and offshore unstratified colder water at less than 4°C . Large horizontal (Lateral) current shear and mixing between a shore parallel warm current and cold offshore water mass generates a zone of convergence, which accounts for sharp temperature gradients and accumulation of floating debris.

Summer Stratification

Although thermal stratification proceeds at varying rates over the Great Lakes, the rate of heat input is generally maximum in the mid-summer period and thermal stratification has become generally established over the entire basin. A thermocline is first formed close to the surface and gradually deepens as the heat gains continue to exceed heat losses in surface waters. Typical temperature depth profiles illustrating the progressive deepening of the mean thermocline level as well as the formation of the classical epilimnion-thermocline-hypolimnion thermal structure is shown in Figure 14 for Lake Ontario.

An interesting feature of stratified lakes such as the Great Lakes is the possibility of vertical displacement of the thermocline. A striking example of periodic vertical motion of the thermocline due to internal waves having periods close to the inertial period is shown in Figure 15. The plot shows isotherm depths as a function of time.

The formation of a thermocline largely prevents the transfer of heat and materials such as heavy particles to the layers below. The transport and dispersion processes are largely controlled by the properties of the thermocline and by the influence of wind stress on the water surface coupled with the effects of Earth's rotation. It is commonly observed that a strong thermocline acts as a 'diffusion floor' suppressing vertical turbulence and inhibiting diffusion of materials into the hypolimnion. For shallow Lake Erie, the position of the thermocline in the Central Basin can have pronounced effects by severely limiting the vertical transfer of oxygen and materials between the upper and lower layers. Figure 16 shows contours of temperature and total phosphorus for Lake Erie in cross-section indicating strong stratification in the Central Basin and high total phosphorus concentrations in the hypolimnion region. Complex models of circulation such as that shown for Lake Erie in vertical cross-section (Figure 17) and analysis of current meter observations (Figure 18) as shown for Lake Erie at the Pennsylvania Ridge are undertaken to understand the physical mechanisms.

Winter Cooling

Towards the end of summer, lakes have attained maximum heat content and by early fall the mean heat content starts declining due to autumn cooling. By mid-fall, the autumn cooling and associated mixing processes have nearly completed the breakdown of thermal stratification. With further cooling, the depth of mixing deepens until the entire water column is mixed around 4 to 5°C. Although horizontal temperature gradients persist close to the shore, vertical mixing of the open water is nearly completed by late fall. This is commonly referred to as the annual Fall overturn.

With continued cooling coupled with wind mixing, the main water mass continues to be well mixed during the winter. It attains isothermal conditions at the temperature of maximum density, 4°C , by mid-winter and the higher rate of cooling nearshore sets up horizontal temperature gradients which persist throughout the winter. During late fall and early winter, mixing of cold inshore water with warmer offshore water may set up a convective regime (thermal bar) described earlier. Towards the end of winter, the entire water mass has cooled down to below 4°C , with the coldest water remaining close to the shore.

General Circulation

The considerable seasonal changes of heat content which characterizes the annual thermal cycle of large lakes, cause corresponding large changes in the density distribution within the water masses. While the overall circulation in the lakes can be attributed primarily to wind stress, it is recognized that the changing thermal structures and the dynamic regime which accompanies each thermal regime play a dominant role in the generation of lake circulation. Experimental evidence on current climatology of the Laurentian Great Lakes shows that there are distinct differences between circulation features during summer and winter (homogeneous and stratified conditions).

Recently, numerical models of lake circulation have been developed for the purpose of establishing the transport framework for water quality models. Numerical computations are applied to describe short-term physical phenomena such as storm surge as well as being applicable to longer time scales associated with ecosystem studies. Models have been employed to simulate homogeneous and stratified conditions. Examples of computed and observed circulation for epilimnion and hypolimnion layers for specific periods are indicated in Figures 19(a), (b) and (c) for Lakes Superior, Erie and Ontario.

Currents in the open lakes often have nearly rotary motion, particularly after storms. These currents called "inertial currents", result from a balance between local particle acceleration and Coriolis force due to the rotation of the Earth. The period T of such oscillations is given by $T = 2\pi/f$, where f is the rotational frequency of the Earth, defined by $f = 2\Omega \sin \phi$, Ω is the angular speed of rotation of the Earth and ϕ is the latitude. At the latitude of the Laurentian Great Lakes, T is approximately 17 hours. Physically what this means is that the current vector rotates by 360° every 17 hours in the Great Lakes. However, in the coastal zones, these rotary currents must be modified since particle velocities perpendicular to the coast must vanish there. Consequently, there is an adjustment zone, typically 5 to 10 km wide, where rather high currents are forced to flow more or less parallel to the local shoreline (Figure 20). This zone has been

referred to as a "Coastal Boundary Layer". The process of adjustment of the "inertial currents" to the presence of the shore is illustrated in Figure 21. Shown here are current meter data obtained simultaneously from three locations each at different distance from the coastal boundary. The data displayed in Figure 21 are hourly averages of the current vector, with the tail of each consecutive vector placed appropriately oriented at the head of the preceding one. This type of data display is often called a Progressive Vector Diagram, PVD, and simply represents the current flow past a fixed point as it changes in time. Most important here is the changing pattern of the flow as the distance from shore decreases. About 16 km, the current vector rotates completely every 17 hours (inertial currents described earlier) with an irregular displacement. Closer to the shore, 11 km offshore, the oscillatory motion is still present but the net flow assumes an orientation closely parallel to the shore. At only 6 km from the shore, the rotary motion has altogether disappeared for all practical purposes with well-defined shore parallel flow.

Coastal Currents

Coastal areas are increasingly used for recreation and resource development. Human activities are bound to intensify with increasing urbanization and heavy concentration of population along the coastal regions. Such continued pressure for utilization of coastal waters can be expected to have deleterious effects on the coastal zone environment. The ecology of the coastal zone environment is strongly influenced by the water movements, thermal structure, and the capacity to disperse the pollutants discharged into it.

The physical processes of transport and dispersion in the coastal zone are extremely complex. Not only are there differences from one location to another, but there are distinct seasonal variation at the same location. Current speeds for example, are usually greater in summer than in winter. In addition, stratification has the effect of altering the vertical changes in currents. There are many days when the deeper currents flow in opposite direction from those near the surface. In addition to the above complexities, there are intervals of extremely low almost stagnant currents, that can persist for several days.

Longshore currents are accompanied by upward and downward movements of water in the coastal zone. When the water is thermally stratified the upward motions bring cold sub-surface water into the coastal zone, whereas the downward motions bring warm surface water there. Upwelling and downwelling of water in the coastal zone are important processes affecting the use of water for various human needs. Associated with the changeover, the water mass as indicated by its temperature undergoes a complete mass exchange. This mass exchange undoubtedly occurs even when the lake is homogeneous.

Coastal Dispersal Processes

Mixing and dispersal processes in the coastal zone are equally complex as evidenced from a number of experiments carried out in several locations of the Great Lakes. From a waste disposal point of view, the worst situations are stagnant or very weak current periods during which the discharged effluents form stagnant pools with very little transport and mixing. With onshore transport, there is likelihood of fumigation of the nearshore zone.

Under conditions of steady shore parallel currents, any pollutant source located in the coastal zone would result in a regular effluent plume. The "mixing zone" (depending on the desired dilution) is the net result of the average current-speed persistency of current in a given direction and turbulent mixing. However, after a period of steady currents, one can encounter current shifts (or meandering currents). Under these conditions, what appeared to be a steady and regular plume shifts in the direction of the current shift with "accelerated diffusion" accompanied by rapid dilution. Although determination of the "mixing zone" is rather difficult under such complex cases, shifting currents have beneficial aspects from the point of view of minimizing the impact of contamination of the coastal zone through efficient dispersal of effluents. The mixing and dispersal of effluents in cases of complete flow reversals is very efficient. The periods are extremely favourable from the point of view of large scale dumping of waste effluents.

Several physical processes contribute to the mixing and dispersion of pollutants discharged into the coastal zone; eddy diffusion due to turbulence, shear diffusion due to the interaction of current shears and the turbulence, and diffusion due to turbulence generated by breaking surface and internal waves. In reality, since it is difficult to separate out the processes, one attempts to quantify the overall effects on mixing and dispersion by defining certain dispersion parameters and their relationship to the observed environmental conditions.

Measurements

Research on the Great Lakes involves diverse measurements and observations from many sources. Meteorological input data are acquired from meteorological stations operational at the lake periphery and also from specially designed and equipped buoys, towers, barges, and other platforms. Conditions within the lake can be surveyed at locations chosen to give the maximum information for inshore and offshore regimes.

Currents and lake temperatures are monitored by using sophisticated electronic equipment often moored at specific locations for extended periods. In specialized studies, various tracers such as drogues, drift cards and dyes may be used to derive information regarding current direction and speed. Other techniques which use indirect methods such as temperature and density distributions are also used to deduce currents. Current climatologies may be summarized in the form of wind and current rose histograms and vector time series plots. A typical vector time series plot for currents is shown in Figure 22.

The instruments and equipment used to gather and store data in lake physics research must themselves undergo continuous improvement if they are to be effective in meeting the main body of research. Areas of particular interest are greater accuracy and repeatability in current methodology as well as the development of capabilities for measuring new parameters. Data intensive research and complex models of hydrodynamics and water quality have put great emphasis on the requirements for efficient computer systems.

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Table 1. Physical Characteristics of the Great Lakes

	Superior	Michigan	Huron	St. Clair	Erie	Ontario
Low water datum (LWD)	182.90	175.80	175.80	174.30	173.30	74.00
Length	563.00	494.00	331.00	42.00	388.00	311.00
Breadth	259.00	190.00	294.00	39.00	92.00	85.00
Shoreline length	4795.00	2670.00	5120.00	272.00	1377.00	1168.00
Total surface area	82100.00	57750.00	59500.00	1113.00	25657.00	19000.00
Surface area in US	53350.00	57750.00	23600.00	419.00	12893.00	8960.00
Volume at LWD	12230.00	4920.00	3537.00	4.00	483.00	1637.00
Average depth below LWD	149.00	85.00	59.00	3.00	19.00	86.00
Maximum depth below LWD	407.00	282.00	229.00	6.00	64.00	245.00
Average surface elevation (IGLD)	183.11	176.50	176.50	174.77	173.96	74.25
Maximum surface elevation (IGLD)	183.63	177.49	177.49	175.59	174.69	75.66
Minimum surface elevation (IGLD)	179.23	175.48	175.48	173.81	173.08	73.64

(Compiled from: Great Lakes Basin Commission 1976, G.B. Upchurch)

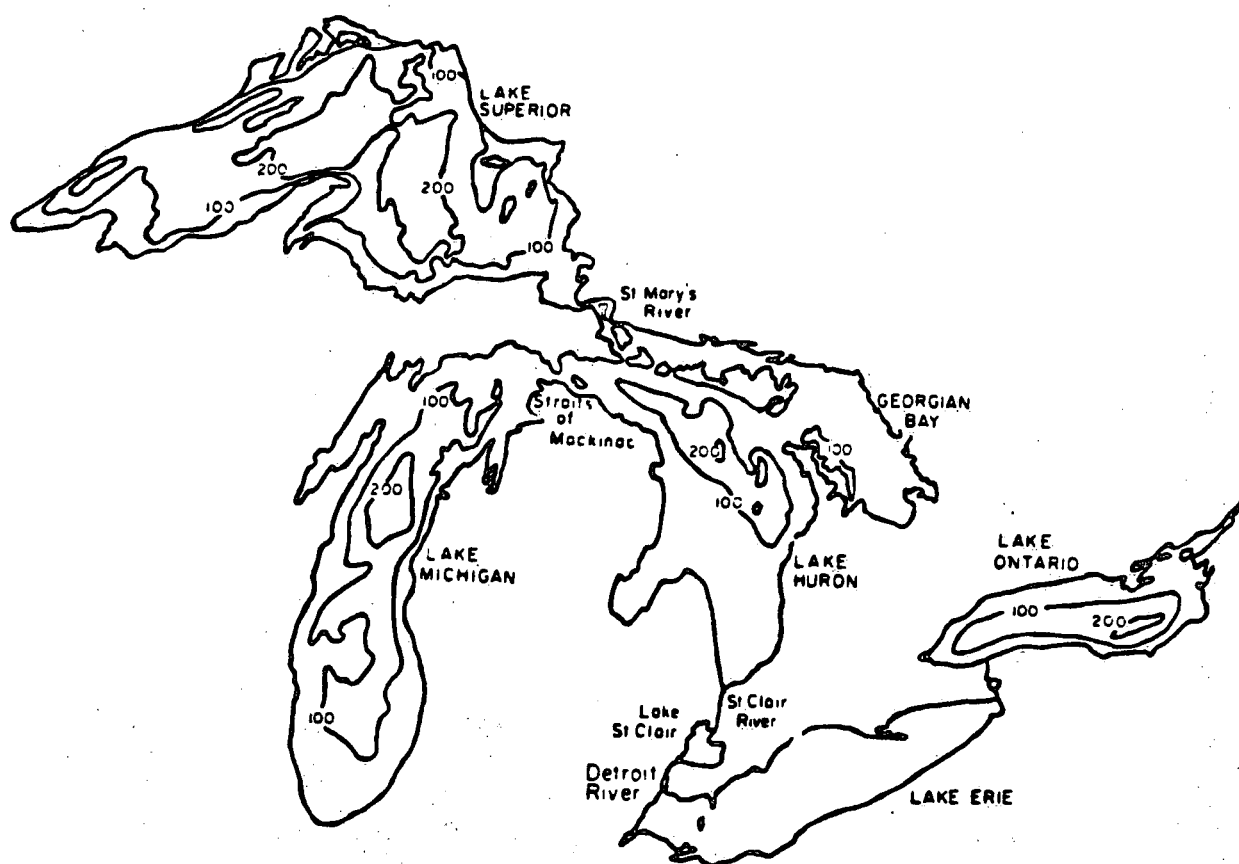


Figure 1 Great Lakes basin and bathymetry
(Rodgers, 1969)

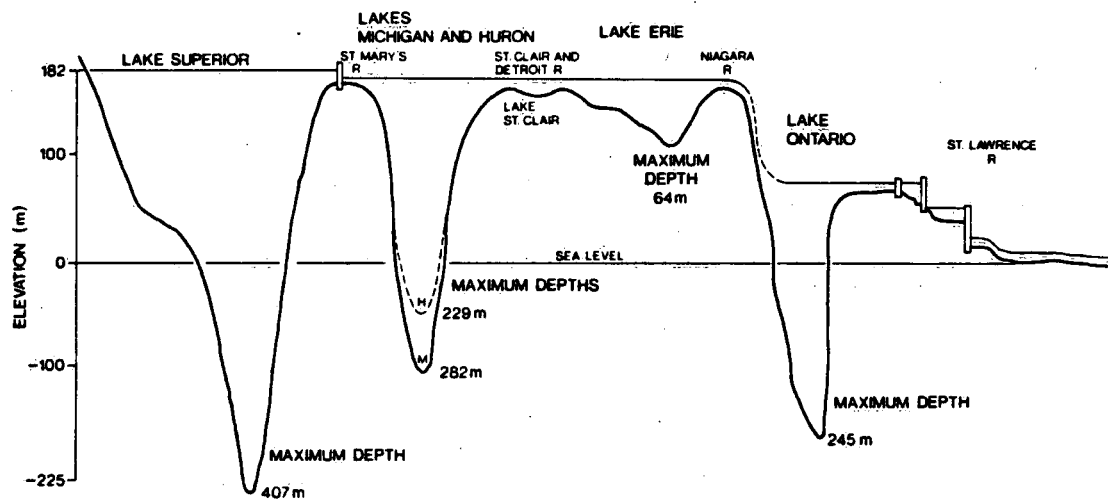


Figure 2 Depth profile of the Great Lakes
(Rodgers, 1969)

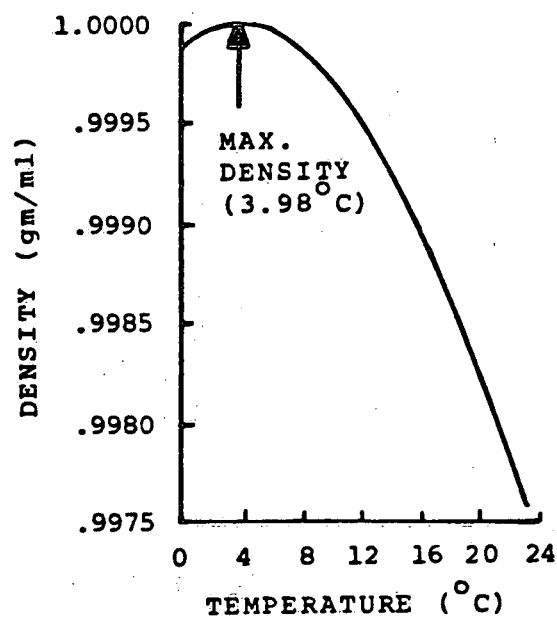


Figure 3 Water density as a function of temperature (at a constant pressure of 1 atmosphere) (Rodgers, 1969)

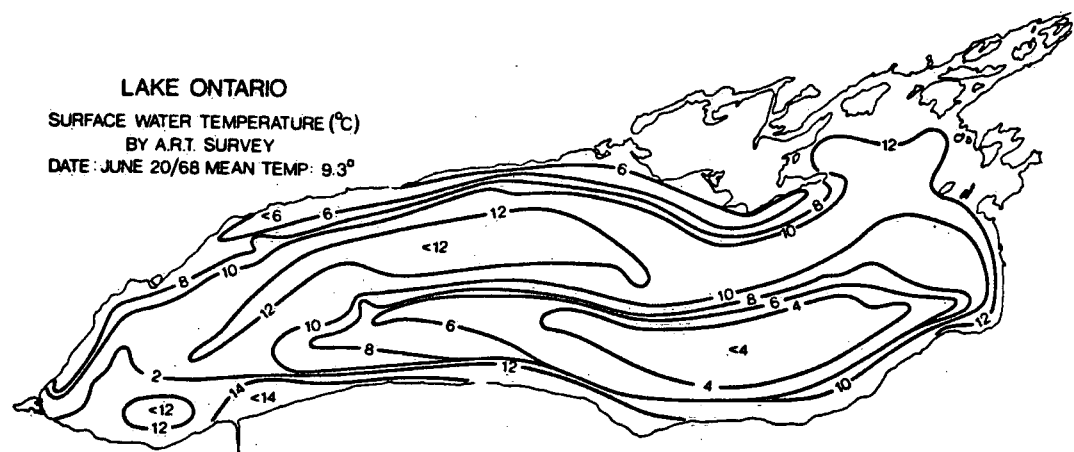


Figure 4 A typical surface water temperature survey of Lake Ontario
(Richards, Irbe and Massey, 1969)

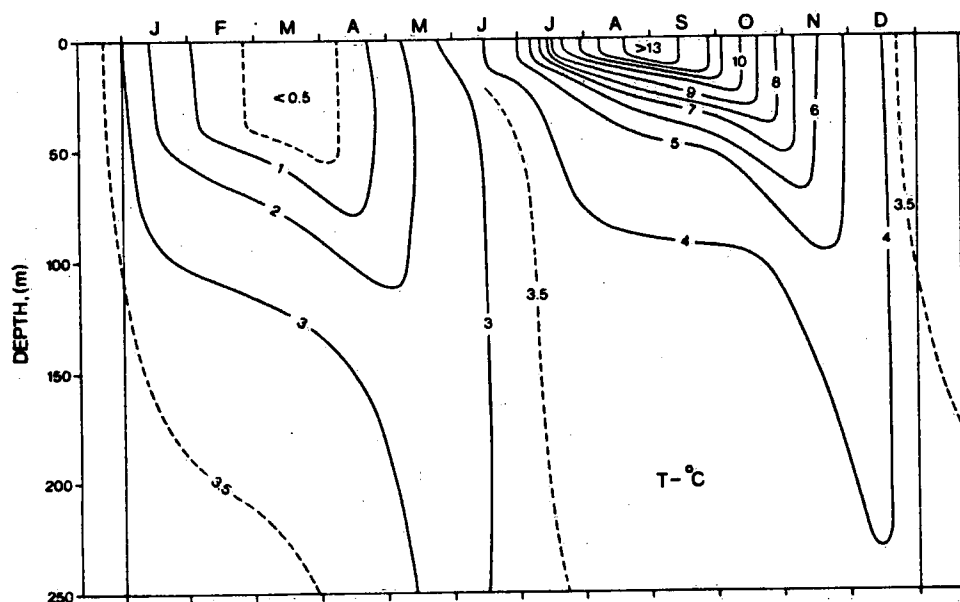


Figure 5 Seasonal cycle of the lake-wide averaged vertical distribution of temperature (°C) in Lake Superior (Bennett, 1978)

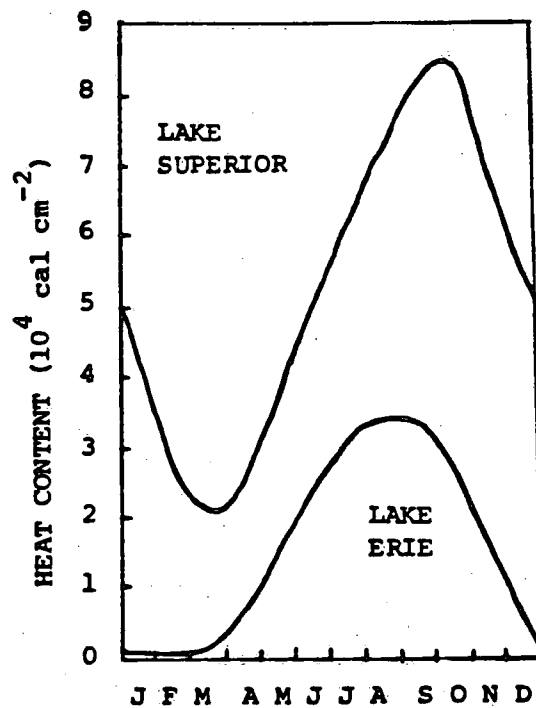


Figure 6 Heat content of Lake Superior and Lake Erie (Schertzer, 1978)

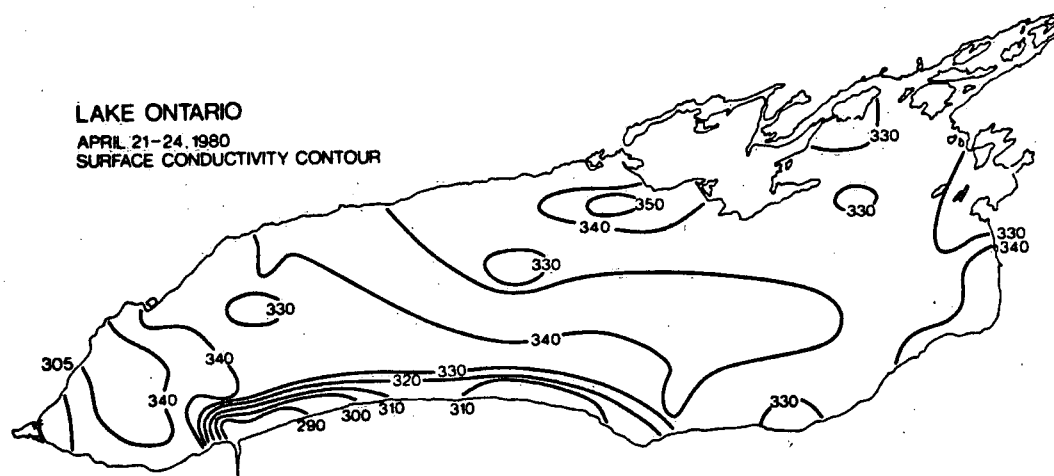


Figure 7 Surface conductivity for Lake Ontario in the period April 21 to 24, 1980 (CCIW, 1980)

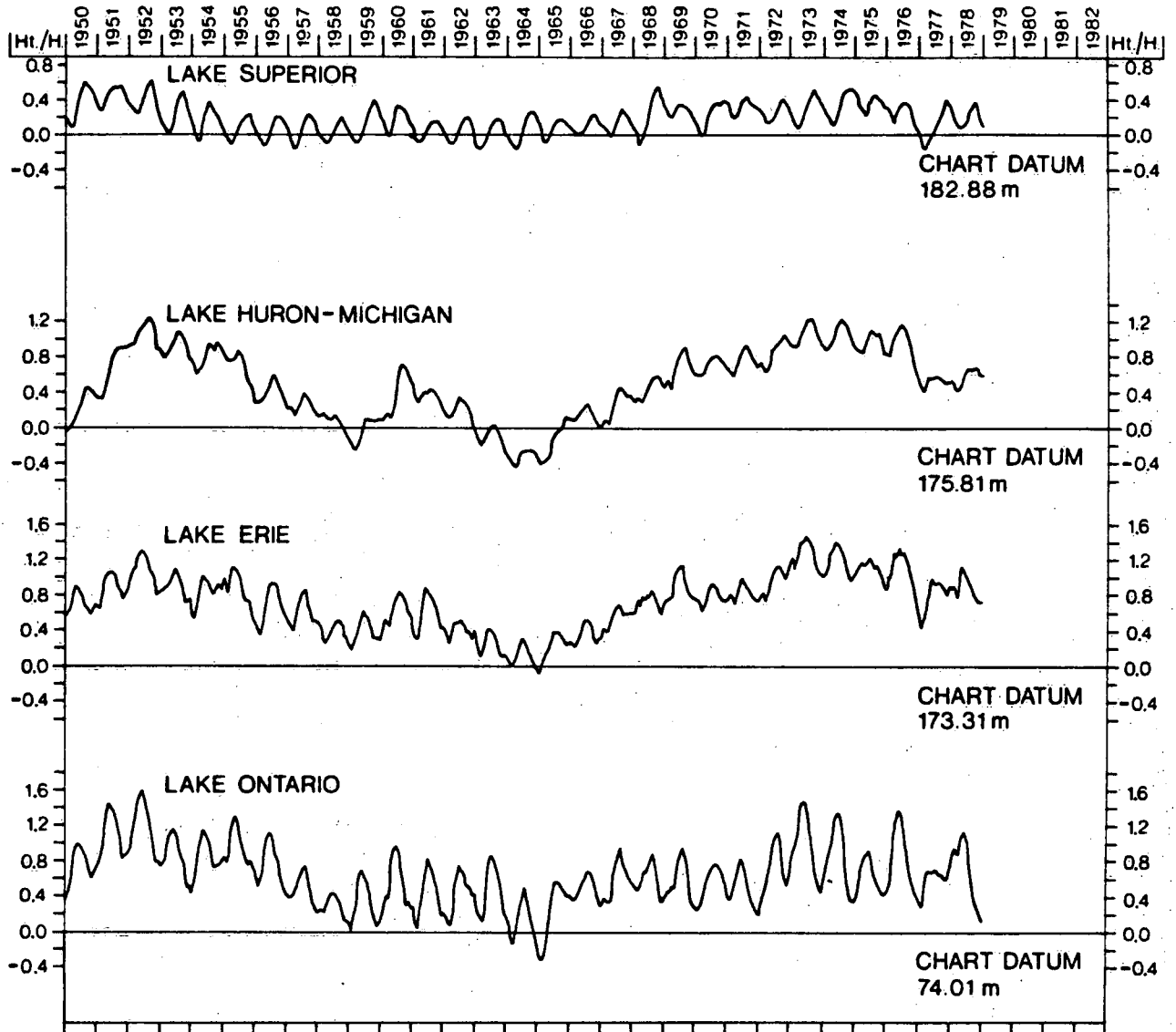


Figure 8 Longterm water level variations on the Great Lakes
(Canadian Hydrographic Service)

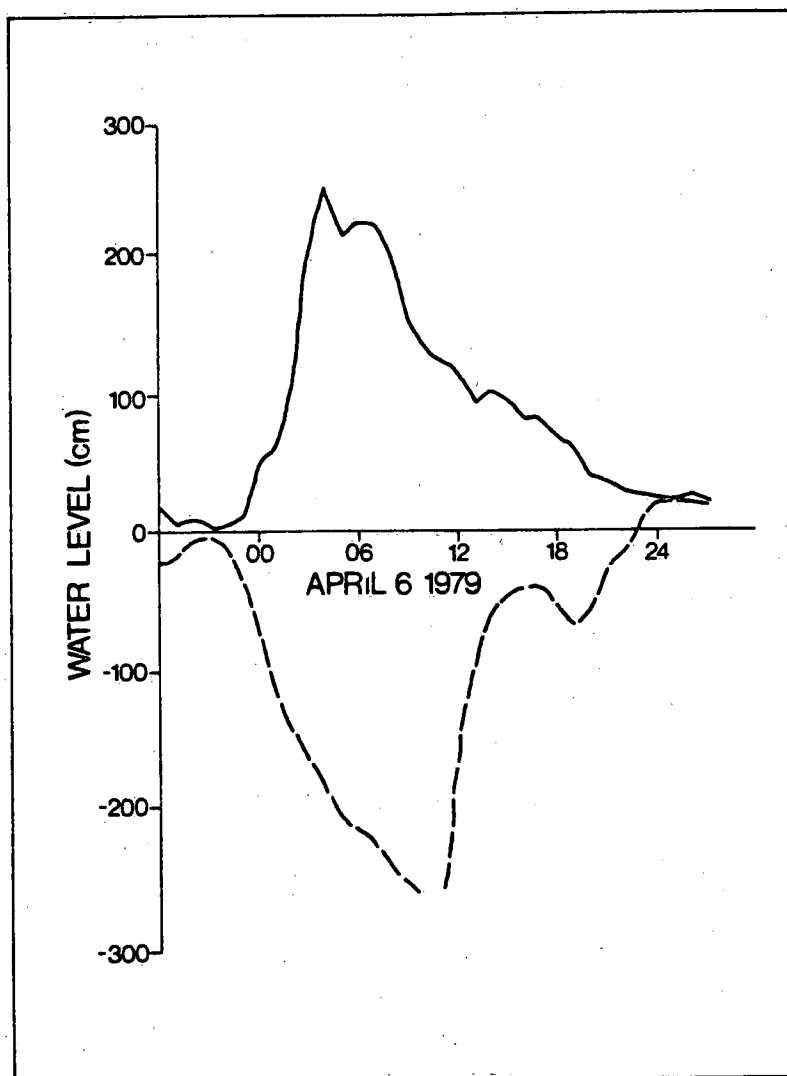


Figure 9 Water level records showing storm surges at the ends of Lake Erie, Toledo (---) and Buffalo (—) (Hamblin, 1978)

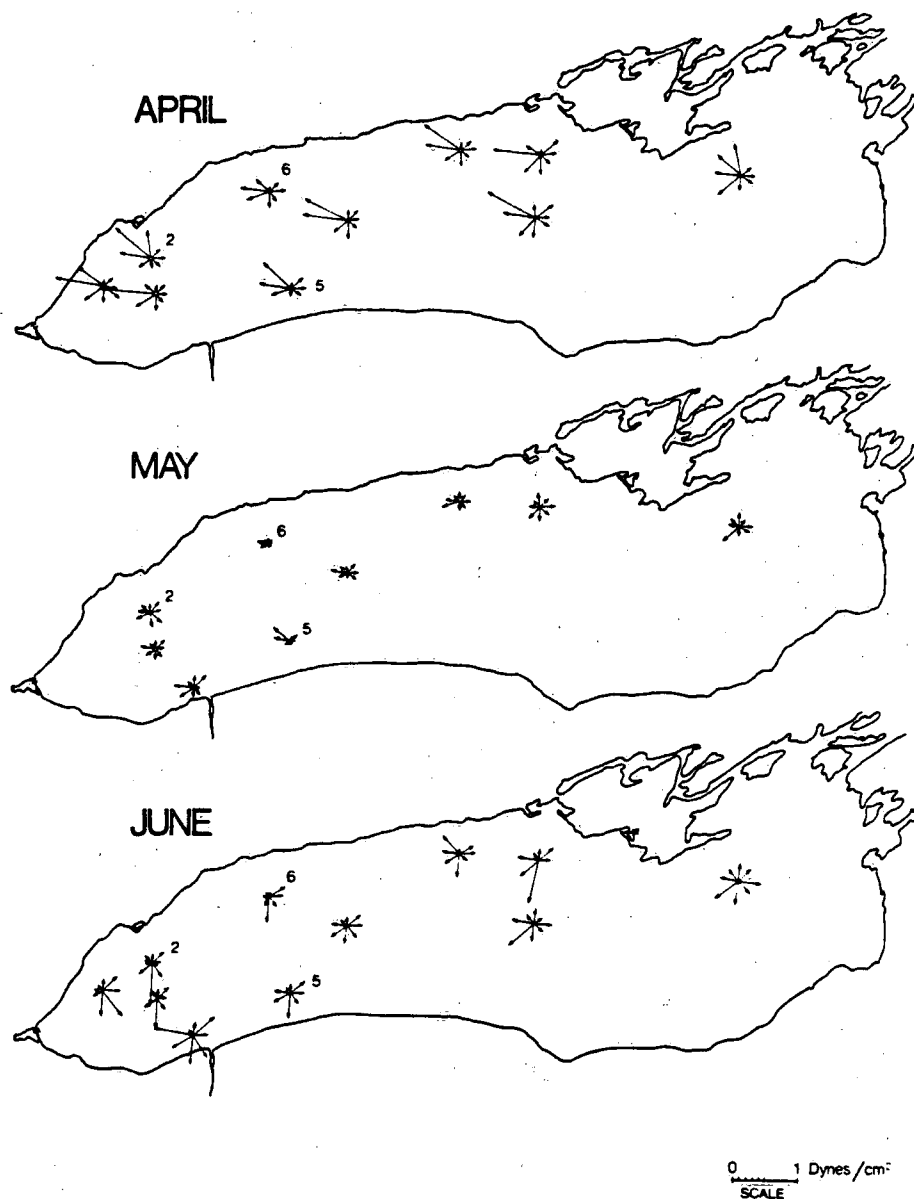


Figure 10 Monthly wind stress roses for Lake Ontario
(Hamblin and Elder, 1973)

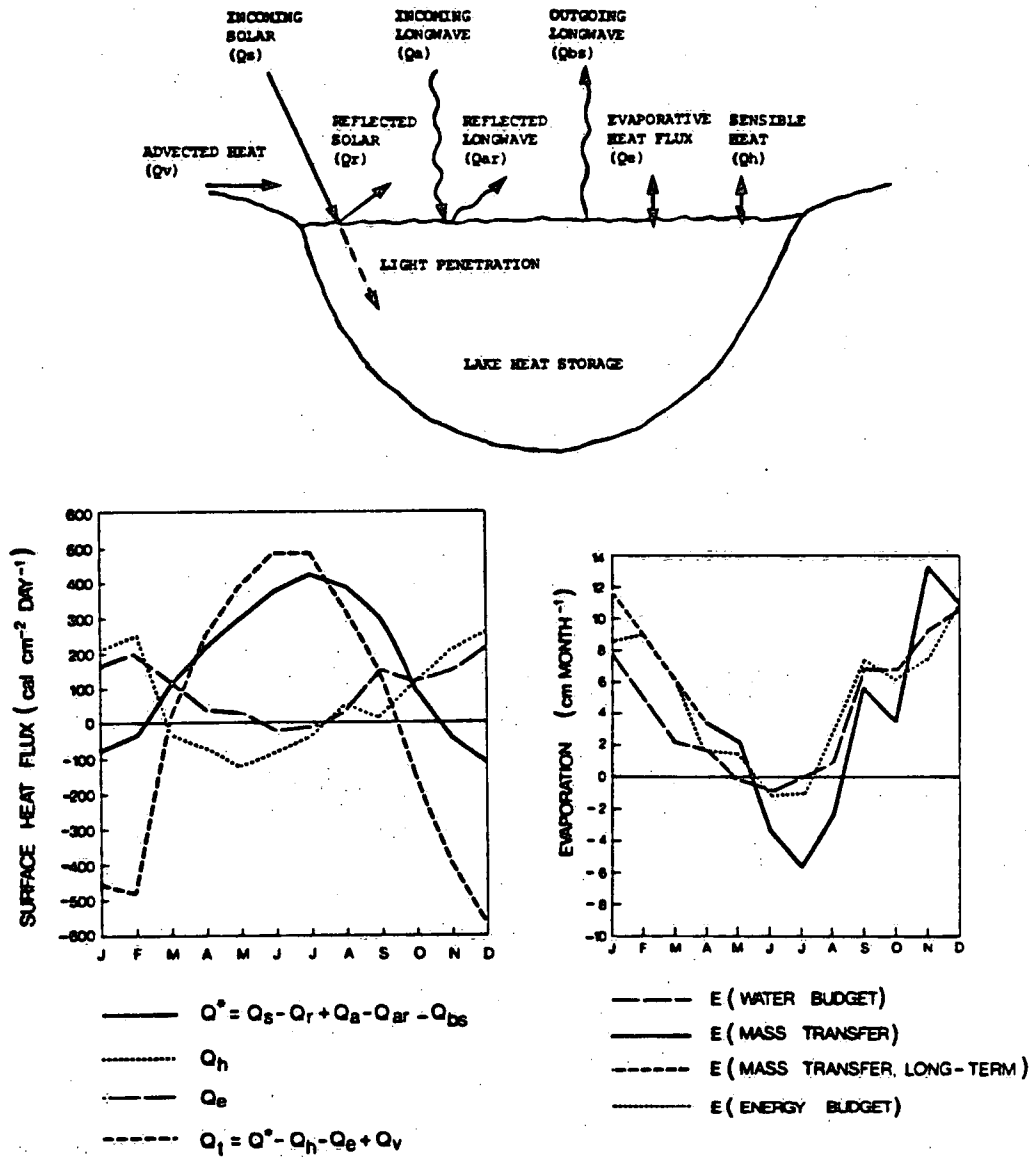


Figure 11 Surface heat flux and evaporation for Lake Superior in 1973 (Schertzer, 1978)

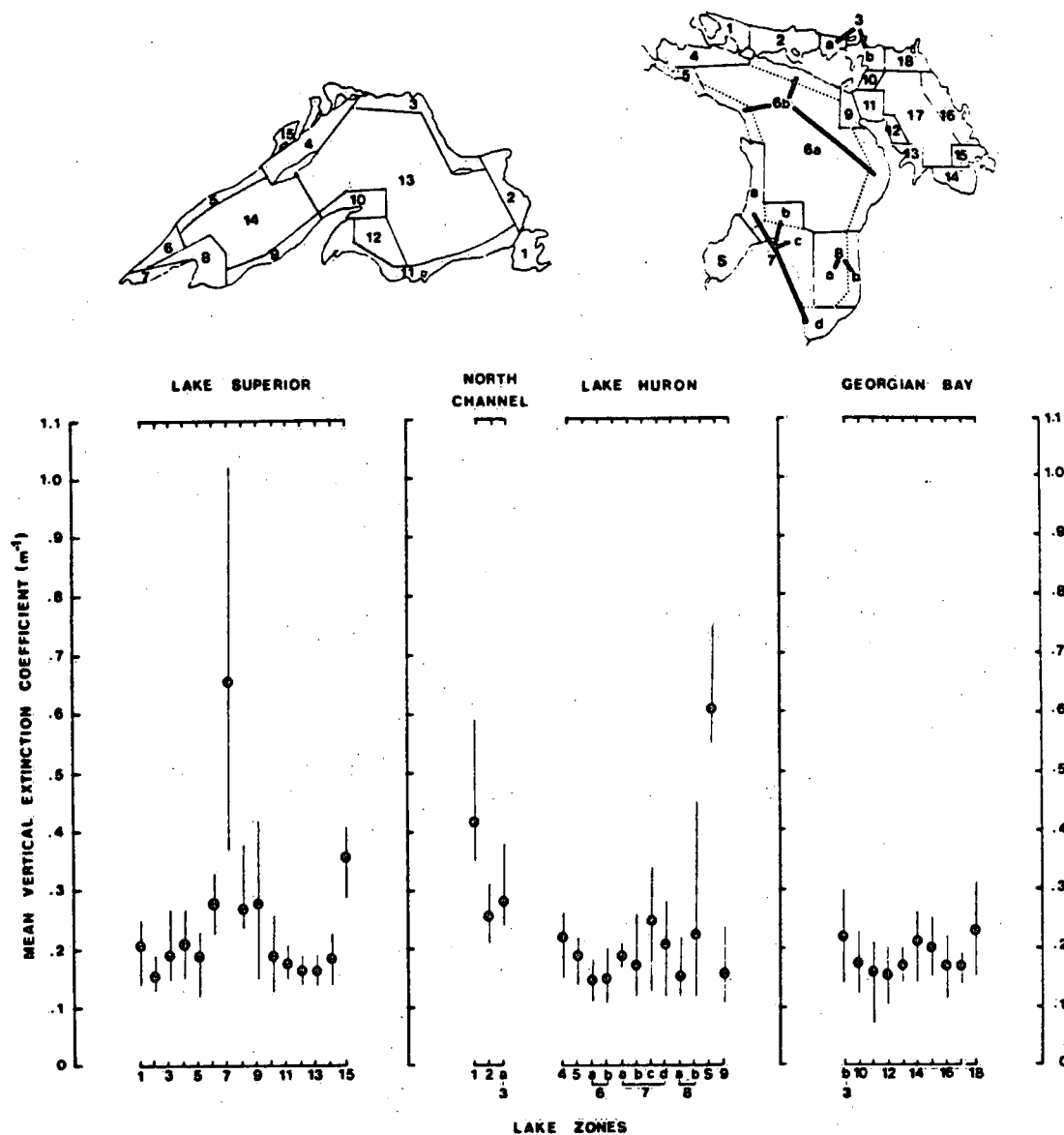


Figure 12 Mean vertical extinction coefficient and ranges of mean for Lake Superior (1973) and Lake Huron and Georgian Bay, 1974 for the period May through November (Schertzer, Elder and Jerome, 1978)

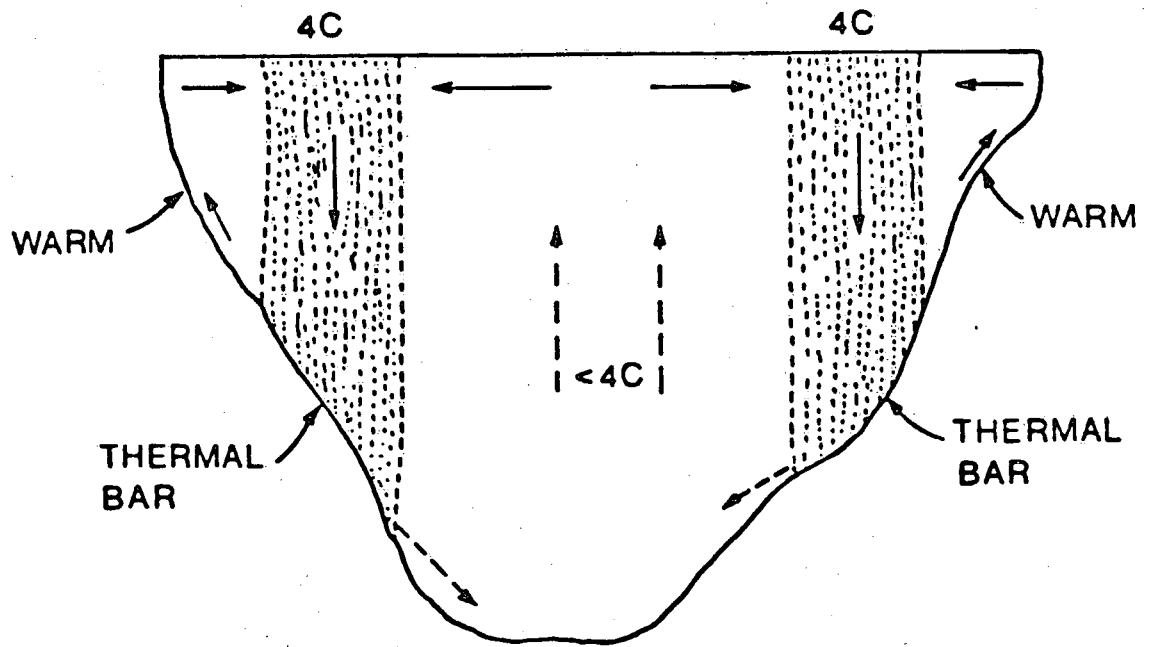


Figure 13 Hypothetically deduced Thermal Bar circulation
(Rodgers, 1965)

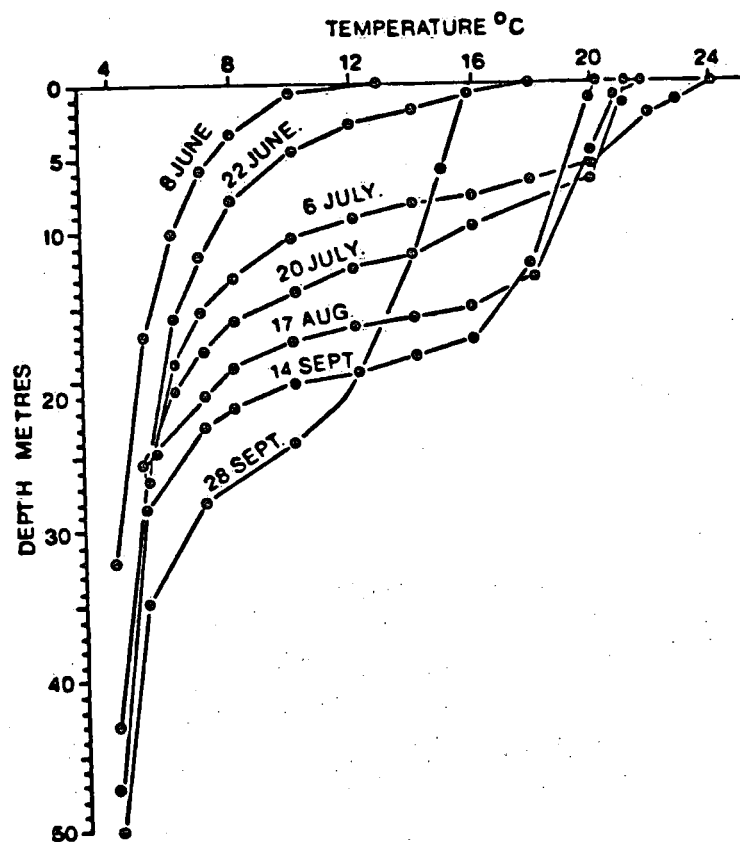


Figure 14 Lake Ontario, June 8 to September 28, 1966. Whole-basin mean vertical depth distribution of temperature (Sweers, 1969)

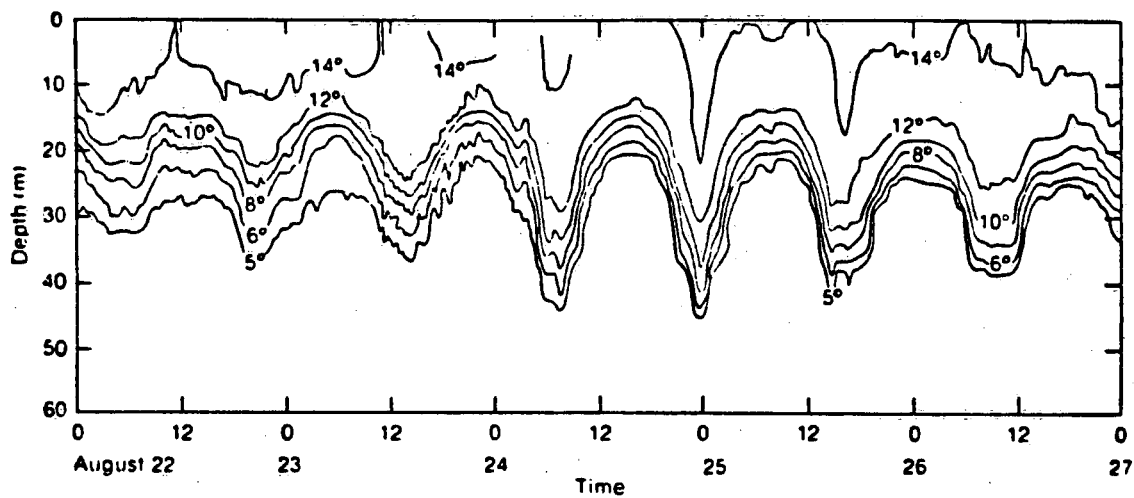


Figure 15 Periodical vertical motion of the thermocline in Lake Ontario
(Boyce, 1974)

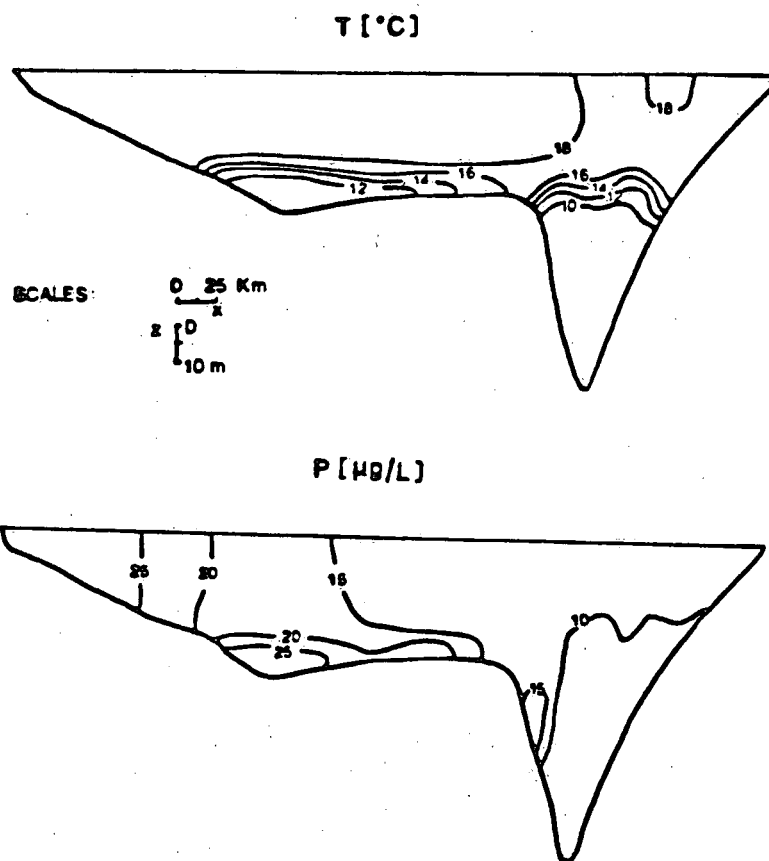


Figure 16 Observed temperature (T) and total phosphorus concentration (P) for Lake Erie (September 30, 1978) (Lam, Schertzer and Fraser, 1981)

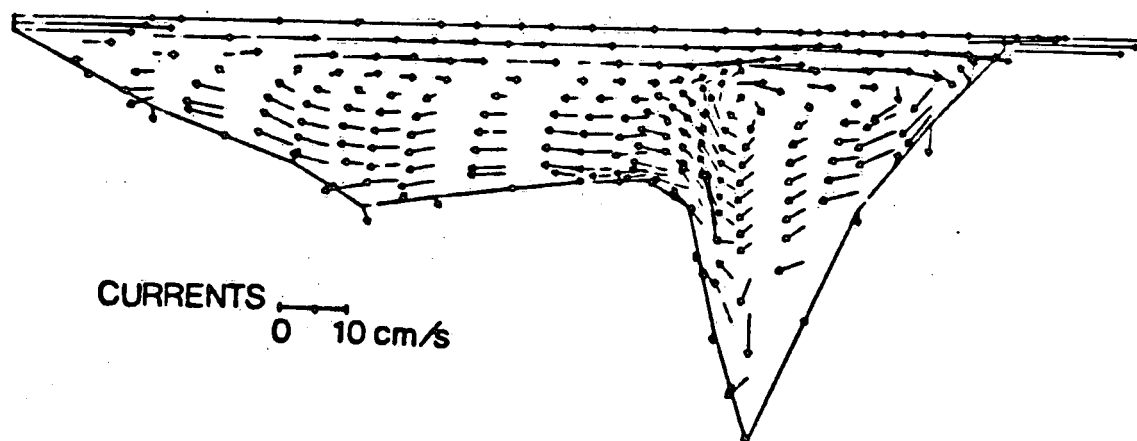


Figure 17 Computed currents for Lake Erie using 2-dimensional finite element model for September 30, 1978 (Lam, Schertzer and Fraser, 1981)

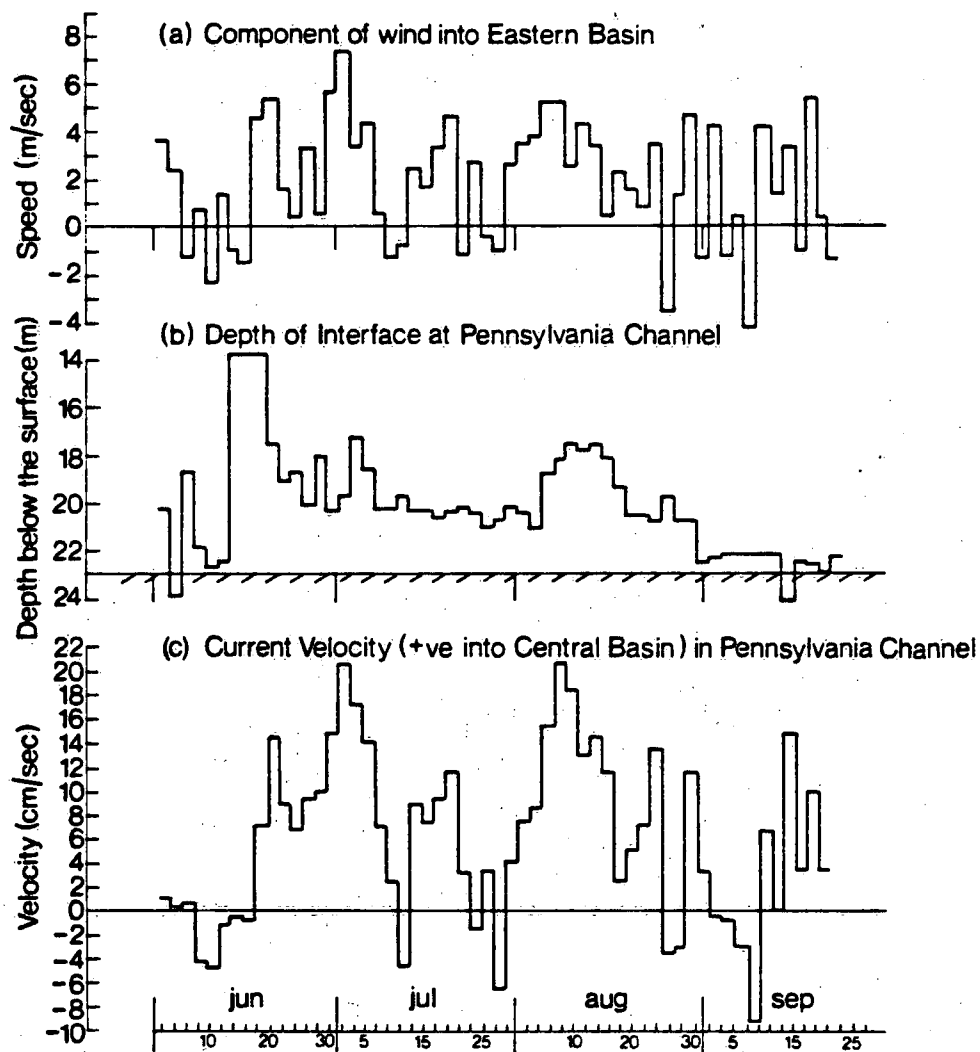
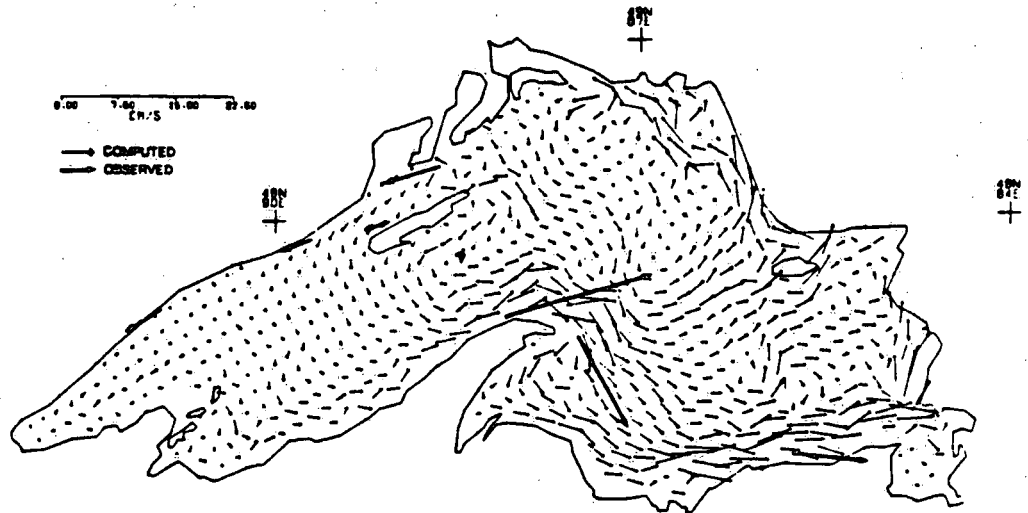


Figure 18 Time series representation of 48-hour averages of wind speed, current (component normal to section) and depth of the interface over the stratified period at Pennsylvania Ridge in Lake Erie (Boyce et al., 1980)

LAKE SUPERIOR
MEAN CURRENT JUN-SEP 73 LAYER 1.2 (EPIIMNION)



LAKE SUPERIOR
MEAN CURRENT JUN-SEP 73 LAYER 3.4 (HYPOLIMNION)

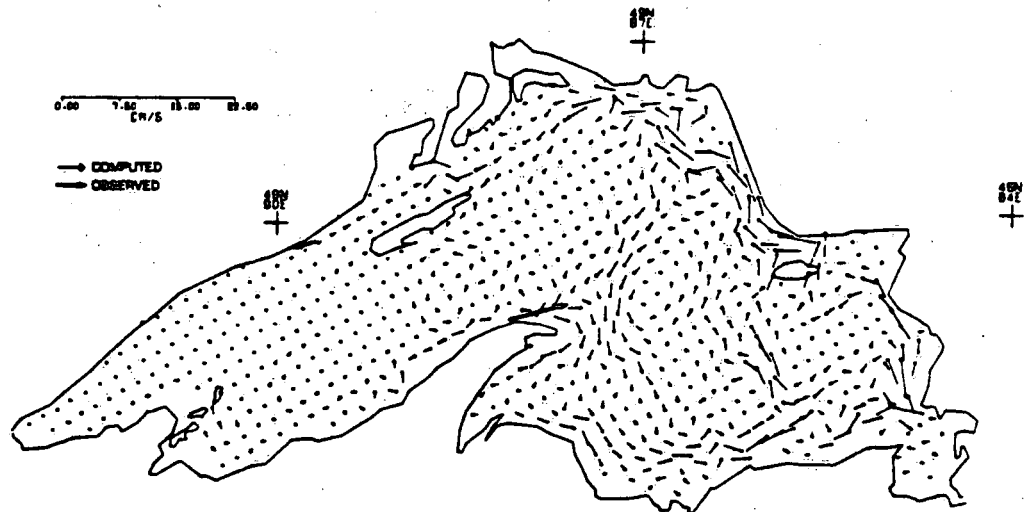


Figure 19a Computed Lake Superior epilimnion and hypolimnion currents with observed currents (heavy arrows) for June to September 1973 (Lam, 1978)

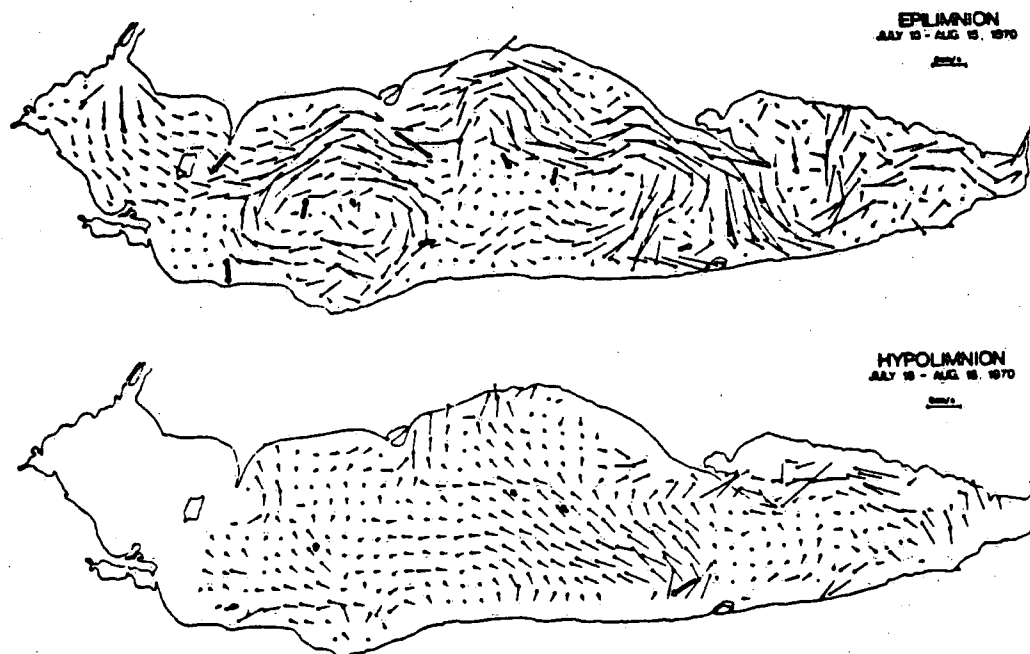


Figure 19b Computed Lake Erie epilimnion and hypolimnion currents with observed currents (heavy arrows) for July 16 to August 16, 1970 (Simons, 1976)

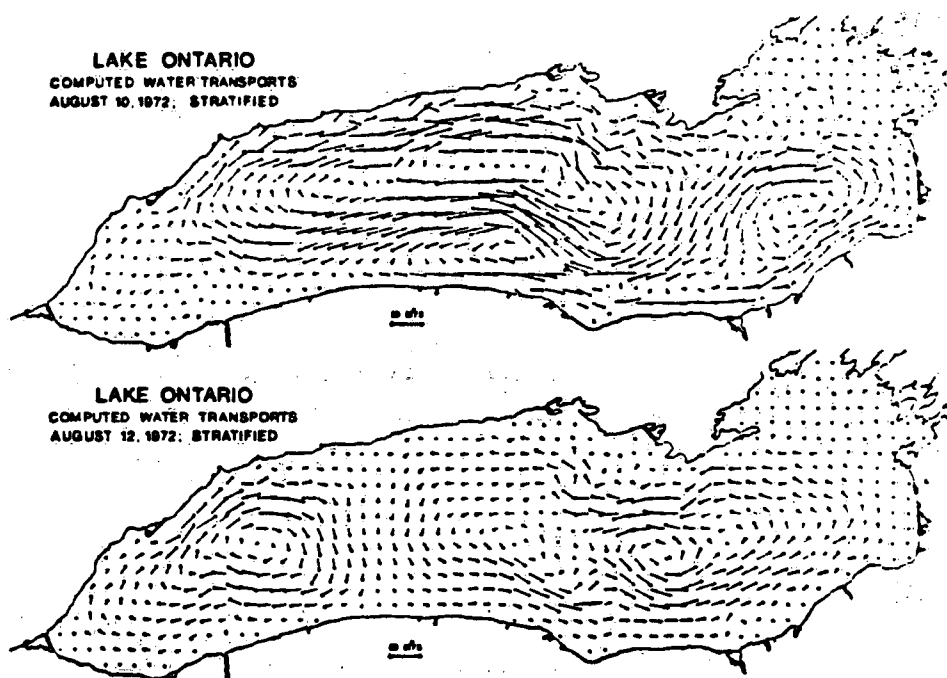
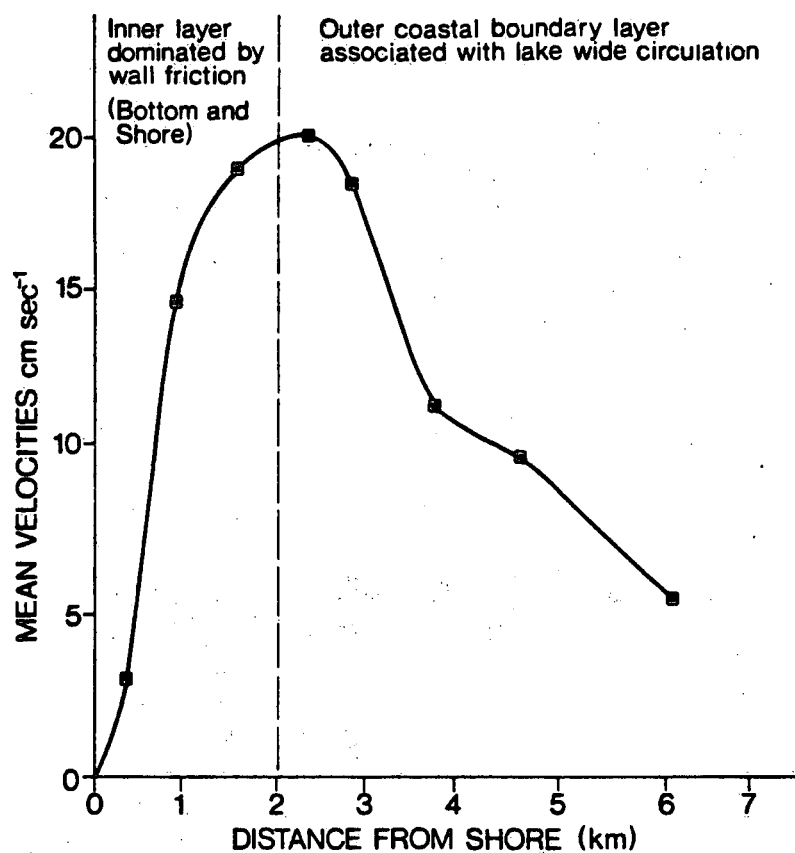


Figure 19c Vertically integrated water transports for Lake Ontario after the storm of August 9, 1972 (Simons, 1975)



Jul 29 - Aug 9, 1974

Figure 20 Coastal boundary layer at Douglas Point, Lake Huron (Murthy and Dunbar, 1981)

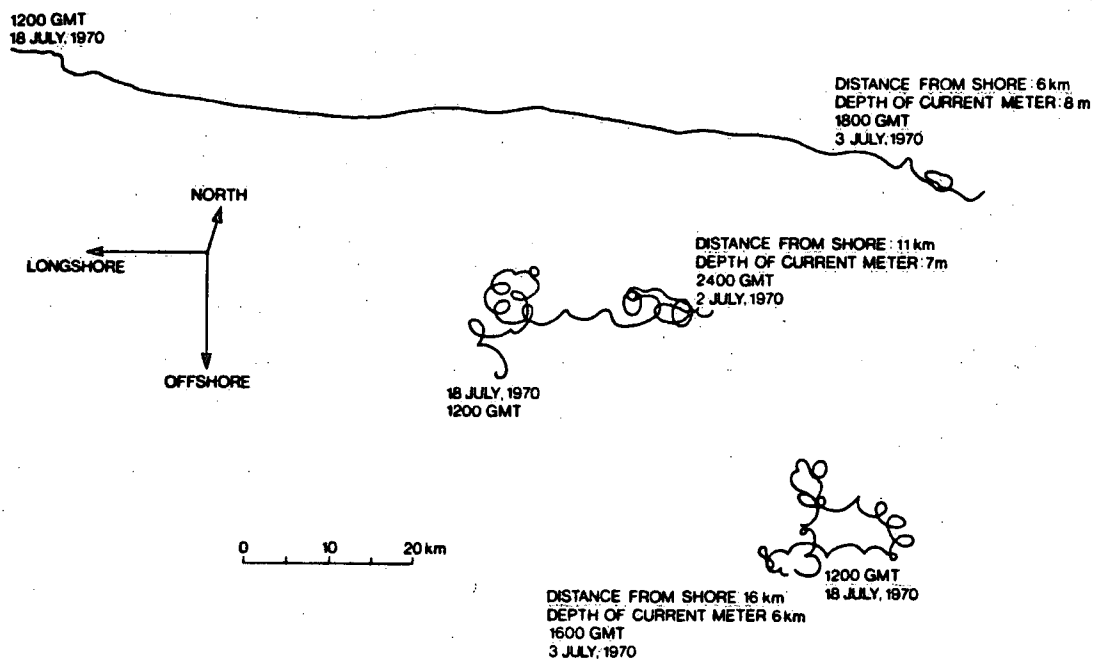
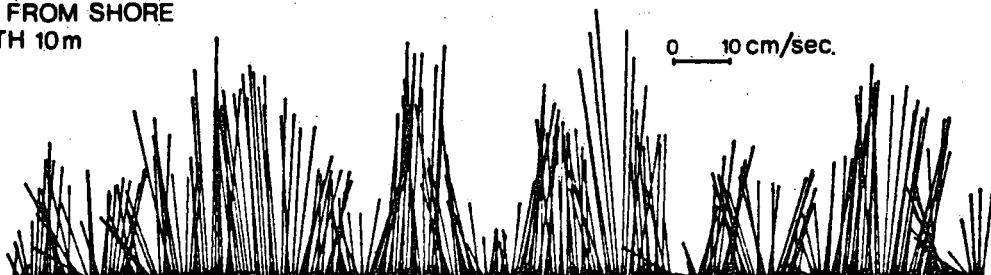


Figure 21 Progressive vector diagrams from current meter data off Oshawa, Lake Ontario (Murthy and Blanton, 1975)

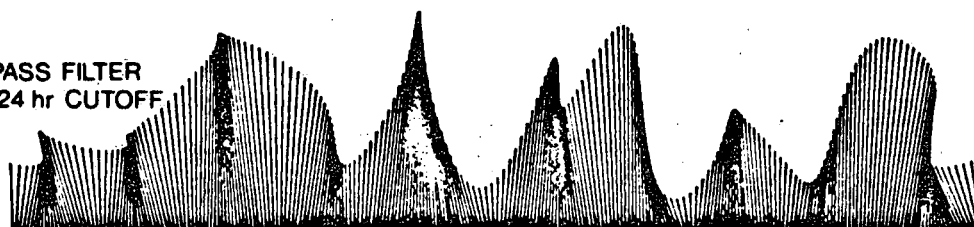
CURRENT VECTORS

1 km FROM SHORE
DEPTH 10m

0 10 cm/sec.



LOW PASS FILTER
18 TO 24 hr CUTOFF



| 29/7 | 30/7 | 31/7 | 1/8 | 2/8 | 3/8 | 4/8 | 5/8 | 6/8 | 7/8 | 8/8

Figure 22 Time series vector plot of currents in the coastal zone at Douglas Point, Lake Huron (Murthy and Dunbar, 1981)

10051

