THERMAL STRUCTURE AND

CIRCULATION IN THE GREAT LAKES

by

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MANAGEMENT PERSPECTIVE

The past 20 years have witnessed a parallel development of coastal oceanography and large-lake limnology with a vigorous sharing of ideas between the two communities and widely overlapping literature. This paper is a review of the physical limnology of the Great Lakes and features the progress made in this period. The treatment is non-mathematical but is intended for persons with a science background. The historical development of Great Lakes physical limnology is briefly reviewed: a modern, "oceanographic" era begins to emerge in the early 60's. The main body of the paper describes basin-scale, long-term circulations, the response forced directly by winds and the recovery phase that is dominated by whole-basin waves governed by various combinations of surface and internal pressure gradients, Coriolis force, and bottom topography. Present understanding has depended on a close interaction of theory, numerical models, and detailed observations. The role of physical processes in distributing materials through the lakes is emphasized, and it is recognized that greater understanding of sediment transport processes will be required to account for the pathways of many toxic contaminants entering the lakes. Well-orchestrated multi-agency and multi-disciplinary experimental programs are strongly recommended.

PERSPECTIVES DE GESTION

Au cours des vingt dernières années, nous avons assisté à un développement parallèle de l'océanographie côtière et de la limnologie des Grands Lacs caractérisé par de fructueux échanges d'idées entre les chercheurs des deux disciplines et une documentation à multiples recoupements. Le présent document fait le point sur la limnologie physique des Grands Lacs et décrit les progrès réalisés au cours de la période considérée. Le traitement n'est nullement mathématique mais il s'adresse toutefois aux personnes ayant des connaissances scientifiques. Les auteurs retracent brièvement l'évolution de la limnologie physique des Grands Lacs: une ère "océanographique" moderne a vu le jour au début des années soixante. La document traite principalement des modèles de circulation à long terme dans tout le bassin, de l'effet direct des vents et de la phase de régénération dominée par les vagues soumises à l'action combinée des gradients de pression internes et superficiels, de la force de Coriolis et de la topographie du fond. Les connaissances actuelles reposent sur une interaction étroite entre la théorie, les modèles numériques et les observations détaillées. Le rôle des processus physiques dans la répartition des matériaux dans les lacs est mis en évidence, et l'on reconnaît qu'une meilleure compréhension des processus de transport des sédiments est essentielle pour déterminer la dynamique des nombreuses substances toxiques introduites dans les lacs. Il est fortement recommandé de mettre au point des programmes expérimentaux multidisciplinaires bien orchestrés faisant appel à de multiples organismes.

ABSTRACT

Thermal Structure and Circulation in the Great Lakes

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Large enough to include many oceanic phenomena, the Laurentian Great Lakes are more accurately described as inland seas. With the exception of the shallow Western Basin of Lake Erie, the lakes are stratified in summer, homogeneous in winter, with average temperatures passing through the temperature of maximum density of fresh water (4°C) in both the spring and the fall. The circulation is mainly powered by the wind but is strongly modified by thermal stratification and basin geometry. Effects of the earth's rotation are present in all large-scale flows. Current speeds are typically 10 cm/s; they are too small, with rare exceptions, to present difficulties to navigation but knowledge of the patterns of water movement is essential to interpreting the behaviour of these valuable lakes as complex ecosystems. This paper will review more than a century of physical study of the Great Lakes.

RÉSUMÉ

Structure thermique et circulation dans les Grands Lacs

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Les Grands Lacs, où se produisent de nombreux phénomènes océaniques, sont considérés plus précisément comme des mers intérieures. À l'exception du bassin occidental peu profond du lac Érié, les lacs sont stratifiés en été, homogènes en hiver, et la température moyenne de l'eau est supérieure à la température de densité maximale des eaux douces (4 °C) au printemps et à l'automne. La circulation est principalement régie par les vents, mais elle est fortement influencée par la stratification thermique et la géométrie du bassin. La rotation de la Terre influe sur tous les modèles d'écoulement à grande échelle. La vitesse du courant est généralement de l'ordre de 10 cm/s, ce qui ne pose habituellement pas de problèmes à la navigation, mais une compréhension des modèles du mouvement de l'eau est essentielle à l'interprétation du comportement de ces lacs importants qui constituent des écosystèmes complexes. Le présent document passe en revue les études physiques sur les Grands Lacs effectuées depuis plus d'un siècle.

INTRODUCTION

The combined surface area of the Laurentian Great Lakes is slightly larger than the United Kingdom (245,000 km^2) (Robertson and Scavia, 1984) and they contain enough water to flood the entire North American continent to a depth of 1 m. Basic physical data on the Great Lakes is contained in Table 1. Geologically, they are very young lakes, having been formed in the recent glacial period some 13,000 years ago; they contain relatively few species compared with some of the very old lakes of the world, such as Lake Tanganyika (Livingstone and Melack, 1984). Prior to 1800, the Great Lakes Region was forested and sparsely populated. Since that time, the basins of Lakes Michigan, Erie, and Ontario, with much of the Lake Huron basin, have been cleared for agriculture, and many centres of heavy industry are located on the lakeshores. By 1970, there were 30 million people living in the Great Lakes region, one third of the population of Canada, and one eighth of the population of the United States (Robertson and Scavia, 1984) (Figure 1). Many of these people obtain their drinking water from the Lakes. Environmental stresses associated with agriculture, large urban populations, and industrialization have degraded the lakes in numerous ways. While this degradation is serious, potential for recovery remains large, and progress has been made in recent years (Robertson and Scavia, 1984). Limnological study of the Lakes, in all its many disciplines, helps to inform management choices, and it has been said that the effort to rehabiltate the Great Lakes into a healthy equilibrium with the industrialized society in the basin constitutes the largest ecological experiment of all time. This paper attempts to demonstrate how physical processes, the scientific domain of physical limnologists, mediate the responses of the lakes to imposed environmental stresses through their control of the distribution of temperature, dissolved and suspended materials. It would be incorrect, however, to suggest that the only reason for studying physical processes on the Great Lakes was because of their implications for environmental management, important as these may be. Over the last two decades in particular, large-lake physical limnology and coastal oceanography have progressed together, as will be seen below, and they share a large, overlapping literature (Simons, 1980, Csanady, 1982, 1984). It must also be said that these magnificent lakes contain their own intrinsic interest and beauty that makes their study a pleasure.

With horizontal scales of hundreds of km (Figure 2), depth scales of 100 m (exception: Lake Erie), and well-developed seasonal thermal stratification, the major Great Lake basins are host to many of the physical phenomena associated with the coastal oceans or inland seas. The earth's rotation (Coriolis force) and basin topography strongly affect large-scale circulations. The dynamics of the region where the open-lake flows adjust to the presence of the shoreline (coastal boundary layer) , so important to the transport of shore-introduced nutrients and contaminants, are similar in both the Great Lakes and the oceans, as are the manifestations of stratification. Stratified flow phenomena may in fact be more easily studied in the Great Lakes than in the oceans because the density field in the lakes depends only on temperature, although the fact that fresh water has a maximum density at 4°C leads to some physical phenomena unique to the Lakes. Aside from vigorous tidal currents, the major difference between the Great Lakes and the coastal oceans having significant physical ramifications is the nature of the boundaries, open on one side in the case of the coastal ocean, but closed on basin scales in the Great Lakes.

This paper will review (briefly) the historical development of Great Lakes physical limnology and then describe the salient features of the seasonal thermal structure and the large-scale circulation. Other processes to be described are storm surges, small-scale turbulent mixing, onshore/offshore exchanges in the nearshore zone, surface waves and their effects on wind stress, and sediment resuspension and transport. The value of modelling studies as a means of synthesizing and testing of physical theories will be apparent. Many of the examples will be drawn from Lake Ontario and Lake Erie because of the larger body of information on those lakes. The reader will be aware of a natural bias of the authors to dicuss work in which they themselves have participated, but they wish to acknowledge the very close personal and professional associations among Great Lakes limnologists in both the U.S. and Canada. The reviews by Csanady (1984) and Mortimer (1984) stress the linkages between Great Lakes physical limnology and coastal oceanography. Because of the great public concern about water quality in the Great Lakes, emphasis here will be given to the relevance of the physical processes to water quality.

HISTORICAL DEVELOPMENT OF PHYSICAL LIMNOLOGY IN THE GREAT LAKES: 1671 - 1972.

The earliest known physical observations were made by a Jesuit missionary in 1671, describing the "tides" at the head of Green Bay (Andre, 1672). In 1848, Professors Agassiz and Keller toured the North Shore of Lake Superior by canoe with a group of students (Agassiz and Cabot, 1850). Of the physical properties of the lake itself, their report says little, but there is much discussion of the evidence of geologically recent glaciation. In 1892, 1893, and 1894 M.W. Harrington of the U.S. Weather Bureau (Harrington, 1895) released drift bottles in the Great Lakes and mapped the patterns of drift of the surface waters (Figure 3). His general results have been confirmed by many subsequent studies (Csanady, 1982, Murthy et al. 1986). The precipitous decline of the Lake Erie fishery in the years 1915 through 1925 prompted a multidisciplinary survey of the lake in the summers of 1928 and 1929 (Fish and associates, 1960). Oceanographic sampling bottles with reversing thermometers were used to map the distribution of temperature and dissolved oxygen, among other parameters, in the major basins of the lake. This study was the first to determine that the relatively shallow Central Basin of Lake Erie retains a thin, cool hypolimnion (bottom layer) late into the summer, and it serves as a benchmark to assess the trend to increasingly severe oxygen depletion in that bottom layer (Dobson and Gilbertson, 1972, Charlton, 1987, Rosa and Burns, 1987). In 1941-42 Church (1942, 1945) collected temperature profile data from railway ferries crossing Lake Michigan and provided the first detailed description of the seasonal thermal structure of a Great Lake. Mortimer (1984) signaled the beginning of the modern era with "the first major university committment to whole-basin investigation on the Laurentian Great Lakes" (Ayers et al., 1958) and the first large scale numerical simulation of lake motion by Platzmann (1958). The adaptation of oceanographic techniques to the Great Lakes continued with the whole lake current meter surveys undertaken by the U.S. Health Service in 1963 (Verber, 1964). Attempts to synthesize the observations of thermal structure and currents into conceptual and theoretical models of the circulation of closed basins were pioneered by Birchfield (1967), Csanady (1968), and Mortimer (1963, 1968). The multidisciplinary study of Lake Erie's Central Basin in 1970 led by Burns (Burns and Ross, 1972) was instrumental in the decision to reduce phosphorus loading by treating domestic sewage. The most intensive lake basin survey to date, including the atmospheric components, has been the 1972 - 73 International Field Year on the Great Lakes during which over 600 participants (limnologists of all disciplines, meteorologists, hydrologists) participated in a study of the circulation, heat balance, biology and chemistry of Lake Ontario (Aubert and Richards, 1981). This voluminous data stimulated the rapid development of theoretical and numerical lake circulation models (Simons, 1980; Csanady, 1982).

SEASONAL THERMAL STRUCTURE OF THE GREAT LAKES.

With the exception of Lake St. Clair and the shallow Western Basin of Lake Erie, the Great Lakes are stratified during the summer months. There are regional differences through the Great Lakes Basin; full stratification of Lake Superior may not occur until August (Bennett, 1978, Assel, 1986), whereas the Central Basin of Lake Erie may be stratified as early as May (Schertzer et al. 1987). The IFYGL data provide a good description of the seasonal thermal cycle in Lake Ontario, and probably the best study to date of large lake heat balance (Auberts and Richards, 1981). The distribution of heat in lakes and reservoirs is amply discussed in limnological textbooks and reviews (see, for example Wetzel, 1975; Ragotzkie, 1978). A recent analysis of the optical properties of Great Lakes waters is provided by Bukata et al. (1985a, 1985b). Most of the oceanographic literature on formation and decay of surface mixed layers applies equally well to the Great Lakes, including the determining influence of the earth's rotation upon the maximum depth of stratification prior to maximum heat content (Pollard, Rhines, and Thompson, 1973; Gorham and Boyce, 1985). The major difference between oceans and the Great Lakes is a consequence of the equation of state of fresh water that shows a density maximum at 4°C, significantly above the freezing temperature of 0°C. Thus convective overturning (destabilization of the water column by the surface heat flux) occurs not only in the fall but also again in the spring as the water warms from temperatures close to freezing through the 4°C range. A weak, stable stratification may also be set up in the winter (Aubert and Richards, 1981). The period of spring overturn results in physical phenomena peculiar to large, deep lakes of the temperate zone and will be discussed more fully below.

The Thermal Bar

In Tikhomirov's studies of the spring warming of Lake Lagoda (1963) the term "thermal bar" is used to describe a differential heating effect in a large, deep lake that cools to an average temperature of less than 4°C in winter. In the spring, surface heating causes convective overturning over the entire lake, and the local heat income is distributed more or less uniformly through the water column. The temperature rise in the shallow nearshore zone is therefore larger than in the deep water offshore. In an early phase of this process, a band of water next to the shore is heated to temperatures higher than 4°C, but overall density contrasts are small. At the 4°C isotherm, the water, at its highest density, tends to sink, and a zone of convergence is observed, which with its barrier-like aspects was called the "thermal bar". Rodgers (1965) documented an identical process occuring in the Great Lakes. During the initial phase of the thermal bar, its offshore progress can be predicted by a simple heat budget, taking into account the bottom slope (Elliott and Elliott, 1969). The vertical circulations arising from the non-linear equation of state of water near 4°C have been studied by Hamblin and Ivey (1983) and by Marmoosh and Hamblin (1985).

Since the water remains cooler than 4°C offshore, the surface heat flux causes convective mixing and the average temperature of the deep zone of the lake increases very slowly. Nearshore, however, the temperatures become large enough (of the order of 10°C) that onshore/offshore pressure gradients created by the density contrast tend to push the warm water offshore. The effects of the earth's rotation (Coriolis force) deflect this offshore flow and set up a quasi-steady circulation with the warm water moving counterclockwise (northern hemisphere) and following the bottom contours around the lake. This is but one of the many examples of a Great Lakes flow moving towards a balance between

Coriolis force and presssure gradient force (geostrophic balance) (Bennett, 1971). Because of the stabilty of the air column above the lake (cool water, warm air), wind stresses are reduced, and this thermally driven horizontal circulation may persist for a month in Lakes Huron, Michigan, and Ontario, and even longer in Lake Superior (see Figure 12b). Figures 4 and 5 diagram the early and late phases of the thermal bar and the transition to full stratification in Lake Ontario. Figure 6 provides a graphic example of interannual variability of the sasonal thermal cycle (Rodgers, 1987). The duration of the thermal bar phenomenon in the Western and Central Basins of Lake Erie is very short due to (i) the shallow water, and (ii) the near-uniform offshore depths. The warm water and the supply of nutrients from spring runoff causes a rapid growth of algae in the nearshore zone. The increased chlorophyll concentration is visible in satellite images (Mortimer, 1987). During the time that the thermally-driven geostrophically-balanced currents dominate circulation in the nearshore zone, onshore/offshore mixing is reduced with river discharges and effluents being trapped in the warm water against the shore (Mortimer, 1987). This phenomenon has substantial implications for nearshore water quality in the spring.

Full Stratification

The last vestiges of the thermal bar period may persist through June in Lakes Huron, Michigan, and Ontario, with surface water of less than 4°C remaining over the deepest portions of the lakes. Eventually the entire basin becomes thermally stratified and the lakes' behaviour parallels that of the coastal ocean. Two main consequences of full thermal stratification are discussed below:

1) Stratification affects large scale vertical circulation. The static stability of a layer of warm water floating on cool water restricts the free vertical circulation occurring during homogeneous periods; displacements of surfaces of constant temperature (density) from the horizontal are resisted by buoyancy. The hypolimnion (lower layer) is thereby effectively cut off from contact with the atmosphere, and from most inflows (since their temperatures in the Great Lakes usually match those of the surface waters). Deepening of the thermocline occurs primarily by entrainment of the less turbulent hypolimnion. Primary productivity of the lake may be limited by the concentration of nutrients at spring turnover and the supply of nutrients to the epilimnion from external sources. In conjunction with the productivity in the epilimnion, organic material sinks to the hypolimnion. Bacteria decompose this material, drawing on the dissolved oxygen last replenished at spring turnover. In Lakes Ontario, Huron, Michigan, Superior and the Eastern Basin of Lake Erie, the hypolimnetic volume is large and the quantity of oxygen is sufficient to accomplish the decomposition without

reducing oxygen concentrations to the point where a viable cold-water fish population cannot be sustained. In the Central Basin of Lake Erie midsummer hypolimnion is only a few metres thick, and the available hypolimnetic oxygen is insufficient in some years to maintain well-oxygenated conditions. Anoxic bottom water has been observed there from time to time and it is generally considered that the probability of this occurrence has increasd over the years due to an excessive input of phosphorus. This conclusion has been instrumental in persuading both the U.S. and Canada to remove nutrients from domestic sewage effluents entering the lakes. A large literature exists on this problem (see Dobson and Gilbertson, 1972, Rosa and Burns, 1987, Charlton, 1987) ; for a recent assessment of this important interaction of long-term trends with random interannual variability, the reader should refer to the forthcoming special Lake Erie issue of the Journal of Great Lakes Research (see Boyce et al. 1987). A similar problem confronts those concerned with the restoration of Hamilton Harbour at the western end of Lake Ontario. Exchange between the harbour and the lake is limited by the 10 m deep ship canal; the bay (maximum depth 25 m)remains stratified through the summer but oxygen concentrations are unacceptably low.

It is an oversimplification to suggest that stratified lakes divide neatly into an epilimnion and a hypolimnion and that seasonal time scales only are important. The seasonal thermocline results from the major storms of the spring and summer; at other times transient mixed layers develop at diurnal and longer time scales. During periods of light winds which may stretch over several weeks a substantial portion of the water column may be stably enough stratified so as to virtually eliminate vertical turbulence (Boyce and Chiocchio, 1987). Doubtless these conditions are selective for a particular distribution of algal species. Numerical simulations of the main features of the lakewide average of the vertical temperature distribution are reasonably successful (Lam and Schertzer, 1987, Ivey and Patterson, 1984,) but further development is required before the simulations can both predict and account for the interactions between the profiles of mean velocity and density.

2) Stratification affects large scale horizontal circulation. The reduction of vertical turbulence in the region of strong vertical density gradients reduces the turbulent frictional coupling between the upper and lower layers. In the absence of other restraining forces, fluid layers are able to slide horizontally over one another with relative ease. In the open ocean, fluctuations of current at time scales of an hour to two days may be modeled by assuming that the wind stress acts only on the upper mixed layer, accelerating it over a quiescent lower layer (Pollard and Millard, 1970). This concept applies in the Great Lakes but must be modified to account for the closed nature of the basins. For example, water in the upper layer moving towards the shore must cause an accumulation of warm water there that can

be accomodated by a depression of the thermocline (downwelling). Similarly, warm water, forced to move offshore, will be replaced by cool, subsurface water (upwelling). The displacement of the surfaces of constant density away from the horizontal generates potential energy that is available to power subsequent motion. The relaxation of these elevations and depressions of the thermocline can take the form of internal waves. These effects will be discussed more fully in the section on horizontal circulations.

Seiches and storm surges.

The phenomenon reported by Father Andre in 1672 was undoubtedly a co-oscillation of Green Bay with Lake Huron, one of a group of motions occurring in lakes and enclosed seas. Nearly three hundred years were to pass before these particular oscillations were explained (Mortimer, 1965; Heaps et al., 1982). We are all familiar with such motions from childhood as the rythmic sloshing in a bathtub. They are called mass oscillations or seiches and may be visualized as the constructive reflection of a train of long gravitational free surface waves from the ends of a closed canal (standing waves). These oscillations constitute a family of resonant motions in closed basins; the periods depend on the physical dimensions of the basin, both length and depth, for the water depth determines the wave speed through the familiar formula $c = (gh)^{1/2}$, where g is the gravitational acceleration and h is the water depth. When the natural period of the oscillation approaches, but is less than, the local inertial period, the latter given by the formula 12/SIN(PHI) hours (PHI = latitude), the motions are affected by the earth's rotation (Rao and Schwab, 1974)(Figure 7).

A sudden wind will produce not only oscillating seiches, but also cause the water surface to set up or to tilt, more or less in oppositon to the wind stress, and for the duration of the wind. These changes in water level observed in response to extremely virorous wind forcing are known as storm surges. The largest change in level is produced by the sum of setup and seiche. Storm surges are largest at the ends of an elongated basin, particularly when the long axis of the basin is aligned with the wind. In deep lakes, such as Lake Ontario, the surge of water level rarely exceeds 0.5 m, but in shallow Lake Erie, a water level difference from one end of the lake to the other of 6 m has been observed (Hamblin, 1979) (Figure 8). In regions of low-lying shores, such as western Lake Erie and Lake St. Clair, such events may cause flooding and increased erosion, with attendant property damamge and risk to human lives. During periods of high water level, such as we are presently experiencing in the Great Lakes, storm surges may be particularly destructive.

Theoretical studies of storm surges and ocean tides have a long history as a branch of applied mathematics (Lamb, 1932). The practical importance of predicting both tides and surges led to an early exploitation of the numerical methods made possible by the computer notably by coastal engineers working in the North Sea. Pioneers of such work in the Great Lakes are Platzman and his students (Platzman, 1958, Rao, 1967, 1969, 1973). Routine predictions of storm surges on Lake Erie are made by Ontario Hydro as part of their management of power production in the

Niagara River. The Canadian Atmospheric Environment Service predicts water levels in western Lake Erie and Lake St. Clair using observed and forecast winds as inputs to storm surge models. The monograph by Murty (1984) contains an up-to-date summary of theory and techniques, while a detailed discussion of storm surge modelling on Lake Erie is given by Hamblin (1987).

Large Scale Wind-Driven Horizontal Circulations.

Long time-series of horizontal currents made with self-recording current meters reveal an important characteristic of Great Lakes currents. Between 1 and 10 km from the shore, the highest speeds are associated with shore-parallel currents that persist over several days before dying out or reversing. Offshore, beyond 10 km, the current directions are more variable and show in summer a distinct tendency to rotate clockwise with periods of 16 to 18 hours (Figure 9). One of the most prominent example of a fast, persistent coastal current is the Keewanaw Current along the south shore of Lake Superior, first documented by Ragotzkie and Bratnick (1965).

a) Winter Isothermal Period.

With the exception of the circulation associated with the intermediate phase of the thermal bar, lake circulations are driven by wind. The wind exerts a mean stress or drag on the water surface, parallel to the wind direction and proportional to the square of the wind speed. The coefficient of proportionality, known as the drag coefficient, varies with several envrionmental factors, and the estimates of wind stress under different conditions of atmospheric stability and in the presence of surface waves are discussed in a forthcoming paragraph. A typical value for moderately strong winds is 0.1 pa (1 dyne/cm**2). Because the Great Lakes have smaller horizontal dimensions than those of the weather systems passing over them, the wind stress, to a rough first approximation (see paragraphs on wind stress and waves), is spatially uniform across the basin.

The wind drag is transferred from the surface downward by turbulent friction. Because of the closed basins, the transport of water through any cross section, averaged over the period of the fundamental surface seiche, must be zero. Surface wind-driven transport must be balanced by a subsurface flow that is driven by pressure gradients caused by a net accumulation of surface water downwind. This is the wind setup described earlier. The three-dimensional details of such a circulation are complicated, but a study of the vertically integrated transport is simpler and revealing. Close to shore, wind drag is experienced all the way to the bottom, and this water is accelerated in the direction of the alongshore component of wind. The balancing return transport occurs in the middle of the basin (Bennett 1974). Thus the forced, vertically-averaged circulation takes the form of a double gyre (Figure 10).

The complicated vertical shear maintained during active wind-forcing soon dies out, leaving the two-gyre motion behind. At the ends of the basin the return transport of the forced flow pattern leaves the coast (downwind end) or impinges on the coast (upwind end), and thereby flows across the bottom contours. Within such cross-isobath flows, the Coriolis force and the pressure force no longer balance and an unsteady, wave-like disturbance results. Meteorologists and oceanographers have studied similar situations for over 50 years; for a review see LeBlond and Mysak, 1978, or Mysak, 1980. Theoretical studies show that the regions of cross-shore transport tend to migrate counterclockwise around the basin (northern hemisphere) at speeds that depend on the dimensions of the basin. The theorectical periods of these motions are of the order of 10 days for Great Lakes basins, and they could explain the tendency for the coastal currents initially generated by the wind to reverse direction a few days after the storm. They are called topographic waves or vorticity waves. The properties of these waves peculiar to closed basins have bee studied by Ball (1965), Hamblin (1972), and Rao and Schwab (1976). The effect of topographic circulation gyres on current reversals was also clearly demonstrated in the numerical studies of Simons (1974, 1975). Csanady (1976) interpreted the IFYGL coastal data in terms of topographic waves. Saylor et al. (1980) give convincing evidence for their existence in Southern Lake Michigan (Figure 11). Simons (1983) has studied these motions using a combination of theoretical and numerical models, and a circulation experiment led by Simons (Simons and Schertzer, 1985, Simons, 1984, 1985, 1986), has confirmed the presence of topographic waves in large lake circulations as well as showing how they interact with other modes of motion. Earlier studies by Pickett (1975, 1977) confirmed the presence of gyral motion, but the horizontal separations of the current meter network were too large for unequivocal interpolation of the current patterns. Particularly interesting results, therefore, were obtained from a closely-sapced north-south array of current meters spanning the mid-section of Lake Ontario during the summer of 1982 and the winter of 1982/83. For the homogeneous winter period Simons and Schertzer (1985) found that the nearshore current fluctuations were large and generally coherent with the alongshore component of wind while the offshore component tended to oppose the wind and to be uniform with depth. Although the time averaged alongshore component of wind stress is very small, the time averaged circulation is significant and consists of a belt of eastwards transport (maximum speed of several cm/s) along the south shore of the lake (transport equal to ten times the Niagara River flow) compensated by a broad, slow return current in mid basin. The net transport near the northern shore is very small (Figure 12a). Linearized numerical circulation models (Simons 1986) generally successful in simulating short and medium term circulations (timescales up to 10 days), do not simulate the observed longterm circulation. Simons demonstrates that non-linear terms must be retained in the model in order to simulate the interaction of topographic waves with each other and thereby to account for the observed circulation. That a persistent residual circulation should exist in Lake Ontario with a transport at least 10 times greater than the Niagara River flow suggests that 90% of the Niagara river flow is recirculated in the lake. Material dissolved in the Niagara river water is carried to all parts of the lake.

Unlike the other major basins that have conical or parabolic cross sections, the near-uniform depth of Lake Erie's Central Basin makes its circulations sensitive to the torque (curl) of the wind stress, and less sensitive to the topographic effects (Saylor and Miller, 1987, Schwab and Bennett, 1987). The wind-forced circulation of the Central Basin may take the two-gyre form described above or it may consist of a single basin-wide gyre that can rotate in either direction, depending on the torque of the wind stress. There appears to be no residual circulation in the Central Basin of Lake Erie such as that described by Simons and Schertzer (1985); Boyce and Hamblin (1975) modelled the annually-averaged distribution of chloride ions as a horizontal diffusion process superimposed on the hydraulic flow through the basin. As we shall see below, a correct assessment of the time-averaged, basin scale circulation is essential to determining how dissolved and suspended materials are distributed in a lake.

b) Summer Stratified Period.

In an earlier paragraph describing the effects of stratification on lake circulation, we indicated that there were two important consequences: (i) the tendency for layers of water to slip easily over one another in planes where the density gradient supresses vertical turbulence (viscosity), and (ii) the creation of potential energy and hence restoring forces when the surfaces of constant density are displaced from the horizontal. Thus when the wind blows over a stratified lake, the initial transport is confined to the upper mixed layer which slides over an unperturbed lower layer. At the shores of the lake, accumulations of warm water force the thermocline down, and where the warm water is moved offshore, the thermocline must rise. The pressure gradients that bring the surface layer to a halt at the shoreline move the lower layer as well, as indeed it must to accomodate the nearshore displacements of the thermocline. Given enough time, a steady wind would create a steady setup of the thermocline that would in effect mirror the setup of the free surface in such a way that below the thermocline the pressure gradients set up by the slope of the free surface were exactly cancelled by those created in the lower layer by the tilt of the thermocline. The wind-driven circulation would be confined to the upper layer, while the lower layer came to rest in the new configuration imposed by the steady wind. This situation should be contrasted with the unimpeded vertical circulation occurring when the lake is unstratified. The alignment of the long axis of Lake Ontario with the prevailing winds in summer is particulartly favourable for the creation of upwelling on the north shore, as these surface temperature maps derived from airborne infrared thermometer measurements demonstrate (Figure 13). The strong tendency for the Coriolis force to steer flows in such a way that the pressure gradients are balanced by the Coriolis force (geostrophic equilibrium) limits the upwelling and downwelling zones to narrow bands along the coast. A strong alongshore wind impulse may cause the thermocline on the left-hand side, looking downwind, to intersect the surface some distance offshore (Csanady, 1977).

Thus a wind impulse along the axis of Lake Ontario from west to east causes transient upwelling along the northshore and downwelling along the south shore with the transition between upwelling and downwelling zone taking place at the ends of the basin. Upon cessation of the wind, this initial, unbalanced configuration "relaxes" through the mechanism of internal Kelvin waves. Kelvin waves propagate alongshore in a counter-clockwise direction (northern hemisphere). In their direction of travel they propagate as long gravity waves, but pressure gradients and Coriolis force due to the alongshore component of motion balance in an offshore direction (Figure 14a). There is no motion perpendicular to the shoreline. Internal Kelvin waves are confined to a few km from the coast. The initial disturbances start out at the ends of the lake and propagate counterclockwise along the shore. Near-surface currents which moved downwind nearshore during the storm now reverse as the "end" disturbance passes by. The IFYGL coastal zone measurements contain some striking examples of this phenomenon (Csanady and Scott, 1974). The long-term average of currents through the 1982 cross-section for the summer months (Figure 12b) is consistent with a counterclockwise coastal circulation, a possible remnant of the current associated with the later stages of the thermal bar.

In their analysis of the 1982/83 Lake Ontario experiment, Simons and Schertzer (1985) set both the Kelvin wave (stratified response) and the topographic wave (homogeneous response) into an overall context. They point out that the topographic waves and the Kelvin waves both propagate along the shore in the same direction and generally exist together. A two-layer model is used to demonstrate the coupling between the two modes that arises from variable depth and from friction. Statistically derived response functions linking alongshore winds and currents in the time domain demonstrate that the currents respond to disturbances propagating from distant parts of the lake as well as to local winds. The effective "memory" of the lake does not exceed 20 days.

c) Inertial Frequency Motions.

The foregoing discussion of horizontal circulation has referred to large-scale, low frequency motions associated with the forced response of the basin to wind stress, and its subsequent relaxation via wave-like phenomena. These motions produce shore parallel coastal currents interrupted by periods of reversal, an ensemble that is of prime importance in distributing shore-introduced material through the lake. Current meter records made offshore during the stratified season are dominated by motions that have clockwise, nearly circular trajectories with radii of the order of a kilometre and periods close to the local inertial period (12/SIN(PHI) hours; PHI = latidude). Similar motions occur in the oceans, anywhere the water can move horizontally without interference from the shore or bottom topography, and without significant friction forces above and below. Marmorino (1978) has documented the existence of inertial currents in winter in Lake Ontario; these are more pronounced during the period of weak winter thermal stratification. The main features of the motion may be explained in terms of a balance between Coriolis force and the centrifugal force due to the turning. A parcel of fluid, free to move horizontally without restraint, given an initial velocity, and under the influence of the Coriolis force that acts at a right angle to that velocity, will move through a full circle in one inertial period. The radius of the circle is proportional to the speed.

The Great Lakes, with relatively shallow surface mixed layers, favour the generation of these motions; wind stress is rapidly communicated to the entire mixed layer within a small fraction of the inertial period, and the stable stratification allows the layer to slide freely over the subsurface waters. A sudden wind impulse, lasting less than one half of an inertial period is particularly favourable, as is a wind stress that turns in a clockwise sense at nearly the angular frequency of the inertial motion (Figure 15). The observations show that these motions are not confined to the surface layers but are also found below the mixed layer where they generally have the opposite direction to the surface oscillations. Moreover they appear essentially simultaneously through the water column. A careful estimate of their frequency shows it to be a few percent higher than the local inertial frequency. These motions do not appear at the shoreline because of the requirement for the motion to be shore-parallel (Blanton, 1974). Extending the concepts of internal seiches (standing internal waves) in small lakes where rotation is unimportant to large lakes where rotational effects dominate was first pioneered by Mortimer (1963, 1968). A theoretical standing wave solution that fits the boundary condition across the basin (no motion perpendicular to the shore at the shore) is that of standing internal Poincare waves (Figure 14b). These waves are a hybrid between pure inertial motion described above and gravity waves; the current vector rotates clockwise at a frequency close to but larger than the local inertial frequency, and in a two layer fluid, currents in the top layer oppose those in the bottom so as to maintain zero vertically-integrated transport. The currents are accompanied by vertical oscillations of the thermocline at the wave period. Thermocline displacements observed along a cross-lake transect would look like standing waves in a non-rotating basin. Because of the spatial uniformity of the wind stress, odd-numbered modes are favoured; and the transects should show evidence of nodes of greatly reduced verical motion of the thermocline (Mortimer, 1968, Boyce and Mortimer, 1977). Csanady (1973) proposed a simple model of cross-channel internal waves plus forced internal setup in a long channel in order to simulate the initial stages of a lake's response to wind (prior to the arrival of the Kelvin waves). Schwab (1977) used numerical techniques to calculate some of the internal modes of Lake Ontario and he is able to identify both Kelvin modes and Poincare modes. He points out that the peak in the current meter spectrum is very close to the local inertial frequency whereas the most energetic temperature fluctuations occur at slightly higher frequencies, closer to the calculated Poincare mode frequencies. This difference between the current meter spectra and temperature spectra is also observed in Lake Erie (Boyce and Chiocchio, 1987). The initial-value approach taken by Crepon (1969) was applied to the generation of internal fronts in Lake Ontario by Simons (1978) and a more general theory for continuous stratification was elaborated by Kundu et al. (1983). This argument proposes that the surface pressure gradients set up by flow moving towards a coastline accelerate the subsurface layers so as to nullify the vertically integrated transport. In a typical Great Lakes basin this would occur in the order of an hour. Thus pure inertial motion would arise in both the surface wind-driven layer and the subsurface layer until such time as the internal displacements at the shoreline propagated outwards as internal waves, a matter of several tens of hours, depending on the stratification and possibly the bottom slope where the thermocline intersects the shore. A simple model along these lines accounts for the essential features of inertial period motions in central Lake Erie (Boyce and Chiocchio, 1987), where the accompanying vertical motion of the isotherms is small compared with Lake Ontario. In Lake Erie, the vertical shear of the near-inertial currents contributes to vertical mixing and entrainment (Ivey and Patterson, 1984) and the bottom currents at the inertial frequency supply energy for a hypolimnetic mixed layer unique to that basin (Ivey and Boyce, 1982).

Horizontal Distribution of Materials entering the Lakes from the Shore: Interaction of Large-Scale Transport and Small-Scale Mixing. Harrington (1895) revisited.

The horizontal transport and distribution of materials into the lakes from the shore is controlled by a complex interaction of small-scale mixing and large-scale circulations. To illustrate this, we will consider the mixing of the Niagara River into Lake Ontario. With an inflow of 7000 m^3/s, the Niagara River is the largest single input of materials into Lake Ontario. In recent years, there has been much concern, in both the U.S. and Canada, about the transport, distribution, pathways,and fate of toxic chemicals entering the lake from the Niagara River.

Most of the discussion about large-scale circulation has been based on current meter data from fixed moorings. The flow field can also be inferred by tracking the motion of "marked" parcels of water. This second method, often referred to as a Lagrangian experiment, is well-suited for the study of the transport and distribution of materials entering a lake. The early experiments by Harrington (1895) were of this type but because the launch and retrieval times of the drift objects were months apart, and often separated in space by the length of the entire basin, only very general results about the mean surface drift can be inferred. The recent experiments described here use a small surface buoy to suspend a sail at a chosen depth (3m is often selected to measure surface currents). The drag forces exerted on the sail by the currents are assumed to be very much larger than the wind drag acting on the buoy so that the ensemble moves with water parcels of the dimensions of the sail and larger. The buoy carries satellite navigation equipment that allows its position to be determined every few hours.

Several experiments were carried out in 1983 and 1984. In each experiment, two Mini-TOD satellite -tracked drifters were released at the mouth of the Niagara River and their movements followed over periods of up to 5 weeks. The experiment intervals were 3 - 18 October, 1983, 20 October to 1 November, 1983, and 15 October to 20 November, 1984. The drifter paths are shown by the heavy and dashed lines in Figures 16, 17, and 18. For comparison, the thin solid lines show progressive vector diagrams of the wind stress from an arbitrary origin in the lake. Although the two drifters were released close together and simultaneously, their subsequent paths are different, especially those of experiments 1 and 3. This data provide a glimpse of the effects of small-scale turbulent motions in the lake and the resulting unpredictability of of water movements in a deterministic sense. The drifter paths also exhibit clear evidence of wind impulses and large-scale circulation features (see 9 October during experiment 1, 26 October during experiment 2, and 19 October during experiment 3). The drifters move in and out of the strong eastward flow along the south shore.

The Lagrangian experiments reveal the remarkable variability of the Niagara River plume. Results of extensive field studies have been published by Murthy (1969) and by Murthy et al. (1986). An important conclusion of these studies is that the traditional view of the plume as confined to the south shore and having little influence on the open lake is too limited (see above paragraphs on long-term horizontal circulations). On several occasions, the Niagara plume is observed to sweep across the Western Basin of the lake and this behaviour is reproduced in hydrodynamic model studies (Simons 1972, Simons et al. 1985). Note also the large along-lake displacements when the drifters are trapped in the eastward boundary current compared with the much smaller displacements observed when the dirfters move into the open lake.

It is clear that these observed features of the circulation correlate with the distribution in the sediments of contaminants known to have entered the lake via the Niagara River. Figure 19 shows the mercury distribution in the sediments published by Thomas (1983). The effect of the eastward boundary current along the south shore is apparent, as well as westward displacements of the plume.

Coastal Climatology

While the Lagrangian data vividly illustrate the interaction of the large and small scales of motion in the Lakes, a climatology of coastal events at a particular location is more readily obtained with moored, self-recording current meters. Starting in 1970, as a prelude to the International Field Year, nearshore current and temperature data has been collected along the north shore of Lake Ontario, and in later years at various locations throughout the rest of the Great Lakes (Murthy and Blanton 1975, Boyce 1976, Murthy and Dunbar 1981). These studies have been conducted between one and ten km from the shore where shore parallel currents respond to local wind forcing and large-scale circulations of the entire lake (see paragraphs above). During periods of shore parallel currents, contaminants may be carried tens of km along the shore, with relatively little onshore/offshore mixing, the latter being governed by small scale turbulence. Csanady (1970) points out that the turbulence appears not to be a unique function of the mean, alongshore flow, a serious difficulty for modelling nearshore dispersion. Large onshore/offshore motions are associated with upwellings and current reversals, effectively replacing the water in the nearshore zone. Very close to the shore, within the surf zone, alongshore currents are generated by the breaking surface waves, and this energetic zone is one of erosion and transport of coarse-grained sediments (Coakley and Skafel 1982, Schwab et al. 1984) (Figure 20).

SURFACE AND BOTTOM BOUNDARIES OF THE GREAT LAKES.

Surface Waves and Wind Stress.

The action of wind on the surface of the lakes has four major consequences: (i) The wind is the main driving force for the lake circulation; (ii) the wind causes the lake surface to tilt producing increases in water level (potentially dangerous in Lakes Erie and St. Clair) at the downwind shore; (iii) the wind excites surface waves which can be hazardous to navigation, and which are the main cause of shore erosion; (iv) the wind greatly increases the transfer of heat, moisture, and gases across the water surface.

When first generated by the wind, waves are small, but as they travel more or less downwind, they grow in height, become longer, and move faster. When the largest waves move as fast as the wind the wind can no longer add energy to them; the waves no longer grow as they travel and they are said to be fully developed. In these conditions, the largest waves are not steep and the wind stress exerted on the water is due in part to skin friction and partly to the drag induced by the shorter, slower waves in the ensemble. Conversely, when the wind has not been blowing for long enough, or because the upwind sea-room or fetch is limited by the shore or by the edge of the meteorological disturbance, the largest waves travel appreciably slower than the wind and continue to accept energy from it. These waves become steep and they add to the aerodynamic roughness of the water surface. Paradoxically, the roughest sea experienced by the navigator is not the wind's aerodynamically roughest sea. Starting from the upwind shore and moving lakewards, the waves grow continuously to full development, but the wind stress increases at first and then decreases as the waves approach full development. We assume in the present discussion that the wind, once "turned on" remains constant; wind stress is roughly proportional to the square of the wind speed.

Although the Great Lakes are large, the fetches they present to the winds ensure that for the most part, the waves are underdeveloped (except in light winds). Consequently, the average wind stress experienced by the lakes is higher than that experienced by the open ocean, for comparable wind speeds and air-sea temperature differences. The effect of surface waves on the wind stress was first documented on the Caspian Sea (Kitaigorodskii, 1968). Further work (Donelan, 1982) on the Great Lakes has confirmed the effect, and this knowledge has been applied in a numerical wave forecasting model now in routine use on all the Great Lakes (Donelan, 1977; Schwab et al., 1984). Anyone familiar with the history of Great Lakes shipping will welcome this development. Simons (1980) has discussed the simulation of lake circulation and storm surges using wave-modified stresses and he shows that the wave effects appear to account for the relatively high stresses (compared to oceanic measurements) required to simulate these phenomena realistically in the Great Lakes (Figure 21). The observed set-up (steady response of the lake surface to an imposed wind stress) has been used to infer the wind stress (Donelan et al. 1974; Simons, 1980; Schwab, 1982).

The earliest studies of waves on the Great Lakes were motivated by concern for navigational safety and shore protection, but the lakes themselves are particularly well-suited for the study of the characteristics of locally-generated waves (Liu, 1971; Donelan et al., 1985). The closed boundaries effectively eliminate "swell" (long waves propagating from distant storms). Among the interesting new results arising from work on the Great Lakes but universally applicable are: (i) When the fetch varies substantially about the wind direction, the largest waves tend to diverge from the wind direction towards the long fetch direction (Figure 22); (ii) very underdeveloped waves (at very short fetches) move faster than fully-developed waves of the same length; (iii) the longest waves in an undeveloped sea are much steeper than their fully-developed counterparts. This last finding helps to explain why the wind stress is larger over underdeveloped lake waves than over their fully-developed oceanic counterparts.

We must mention, although a full discussion is beyond the scope of this paper, the effects of the Great Lakes on local weather. The deep lakes in particular can absorb and release huge amounts of heat over an annual cycle. Thus they tend to moderate air temperature extremes in the surrounding area. The successful peach orchards of the Niagara region are protected from cold northerly winter winds by the open waters of Lake Ontario. Evaporation from the open waters of Lakes Erie and Huron causes the heavy snowfalls experienced in Buffalo, New York and London, Ontario. There is interest among meteorologists in improving the forecasting of local weather that depends on such local interactions (meso-scale meteorology). The Great Lakes region can experience severe local weather at times in the form of line squalls, thunderstorms, tornados and lake-effect snow storms. All of these may be affected by the lakes.

Bottom Boundary: Sediment Resuspension.

Suspended sediments may be either a source or a sink of nutrients and contaminants in the natural environment depending on the past history and the prevailing conditions. Sediment resuspension is perhaps the most important process in chemical recycling (Allan, 1986). Besides resuspension and sediment concentration, knowledge of particle size is required in order to quantify such processes as adsorbtion and desorption of conaminants, and to determine the sinking speed. The sinking speed is also needed to determine the time interval that the particle is exposed to the water column and can exchange products with it. Despite their importance, sediment resuspension studies in the Great Lakes are at an early stage of development. Pioneering work has been done by Sheng and Lick (1979), Eadie (1983), and by Rosa (1985). Laboratory experiments by Lee et al. (1981) have preceeded the more difficult field studies which are now underway (Boyce et al, 1986). A thorough review of the hydrodynamics of sediment resuspension with particular focus on Lake Erie has been contributed by Abdelrhman and Bedford (1987).

SUMMARY AND CONCLUSIONS

The foregoing discussion suggests that the physical behaviour of the Great Lakes, although complex, is comprehensible in terms of phenomena that have counterparts in the coastal oceans. The interchange between coastal oceanography and large lake physical limnology has been valuable; it has not been a one-way street. Individual scientists, the authors and their colleagues, for example, have no difficulties in formulating further research proposals to clothe or to extend what appears to be a reasonable framework of understanding. The interaction of many scales of motion, not only in the lakes, but also in the atmosphere above them, induces a spatial and temporal variability that often obscures cause and effect relationships. The development of time-dependent models and their verification against long and variable sets of input data has helped immeasurably in the interpretation of that data as well as increasing the confidence in the modelling techniques (see, for example the work of Lam et al. (1983) in confirming the dependence of late summer oxygen conditions in the Lake Erie hypolimnion upon the cumulative effects of surface heat flux and wind stress during the heating season). The question has frequently been raised as to how much farther this research needs to continue. Since the notion that he who pays the piper, calls the tune has general currency, we can expect to be asked how these studies contribute to the practical management of the Lakes.

The problem of eutrophication of the Great Lakes may no longer be one of controlling a blatant overload of nutrients, thanks to major investments in sewage treatment facilities, but rather one of attaining an optimum balance, particularly in view of apparent interactions between nutrients and contaminants and recognition that net productivity may be strongly influenced by fish populations (top-down control). The role of stratification in limiting the pool of available nutrients to those in the epilimnion is well known. An examination of the details of light penetration and vertical turbulence (effectively controlled by stratification) may indicate that the succession of algal species is influenced by these processes. Since most external sources of nutrients input at the shore, it is quite possible that the nearshore zone be eutrophic while the offshore zone be oligotrophic. The historical onset of eutrophication from the nearshore zone outwards confirms this idea (Beeton, 1969). Thus knowledge of the rates of lakeward transport of nutrients from the shore during periods of alongshore currents, upwelling/downwelling, and flow reversals is valuable and applicable.

The other prime concern is that of toxic contaminants. A major source of contaminants is fall-out or wash-out from the atmosphere, but inputs from the shore (runoff, industrial and municipal outfalls, etc.) are important too, and the same physical processes mentioned above affect their distribution through the lake. The assessment of probable contaminant concentrations at nearshore municipal water intakes has well-defined physical components. Bacterial contamination of bathing beaches is also influenced by water movements and temperatures. Since many organic contaminants have an affinity for suspended materials, the physical behaviour of fine-grained sediments will mediate the removal (sedimentation and burial) and the reintroduction (resuspension) of some contaminants (see discussion above). These too are physical processes. Finally, it is considered that some volatile organic contaminants may evaporate from the water surface, a process strongly governed by turbulent mixing in the atmospheric boundary layer.

The management of commercial and sport fisheries must deal with the biological implications of both the eutrophication problem and the presence of toxic contaminants together with their essential physical components. Many examples exist of the preference for or sensitivity to temperature exhibited by different fish species (Haynes et al. 1986, Boyce and Roach, 1983).

Water quantity is also an important management issue. The present record-high water levels have caused extensive damage to shore properties through flooding and erosion (Bruce, 1984). At the same time schemes for diverting "excess" freshwater south from the Great Lakes Basin to areas requiring irrigation and now experiencing water shortage are being considered. Substantial changes to the flow of water through the system would be most acutely felt in the interconnecting channels and would also effect the bulk flushing times of the affected basins. Large scale circulations and thermal structure within the basins themselves would be almost unaffected by the changes likely to occur.

The importance of suspended material as a substrate for chemical recycling has focussed attention on the associated physical processes of transport, settling, and resuspension. Given the great experimental difficulties, one of which is to sample and record currents fast enough to measure surface wave orbital velocities, and another is to measure sediment concentrations at similar rates, it is doubtful if much progress could have been made before the development of low-powered, microcprocessor-controlled instrumentation. These studies are being taken up vigourously by oceanographers, and once again we can anticipate useful scientific exchanges between the limnological and oceanographic community.

While we have mentioned from time to time the advantages of working in the Great Lakes compared with oceanic studies, none should think that the resources needed to make progress with Great Lakes studies are small. There has been a long tradition of joint, inter-agency, and frequently international studies, starting with the fisheries-motivated work of the late 20's (Fish and associates, 1960) and including Project Hypo (Burns and Ross 1972), the International Field Year on the Great Lakes (Aubert and Richards, 1981), the IJC intensive surveillance program on Lake Erie (Rathke, 1984; Boyce et al. 1987), and the recent Upper Great Lakes Connecting Channel Study (1986). The pooling of resources, equipment, and talents and the inclusion of many limnological disciplines have yielded scientific results beyond those which could be achieved by the isolated efforts of individual laboratories. We hope that this tradition will be maintained.

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Table 1.

Selected physical data for the Great Lakes (Robertson and Scavia, 1984; Schertzer, 1981).

	Superior	Michigan	Huron	St. Clair	Erie	Ontario
Elevation above sea-level (m)	183	176	176	174	173	74
Length (km)	563	494	331	42	388	311
Width (km)	259	190	294	39	92	85
Area ($1000\ km^2$)	82.1	57.8	59.5	1.1	25.7	19.0
Mean depth (m)	149	85	59	3	19	86
Maximum depth (m)	407	282	229	6	64	245
Residence time (years)	165	69	11	0.03	2.5	7.5
Bedrock (1)	PC	SED	PC/SED	SED	SED	SED
Mean air temperature (°C) July	18.1				21.8	
January	-11.2				- 3.8	

(1) PC - Precambrian rocks; SED - Sedimentary rocks

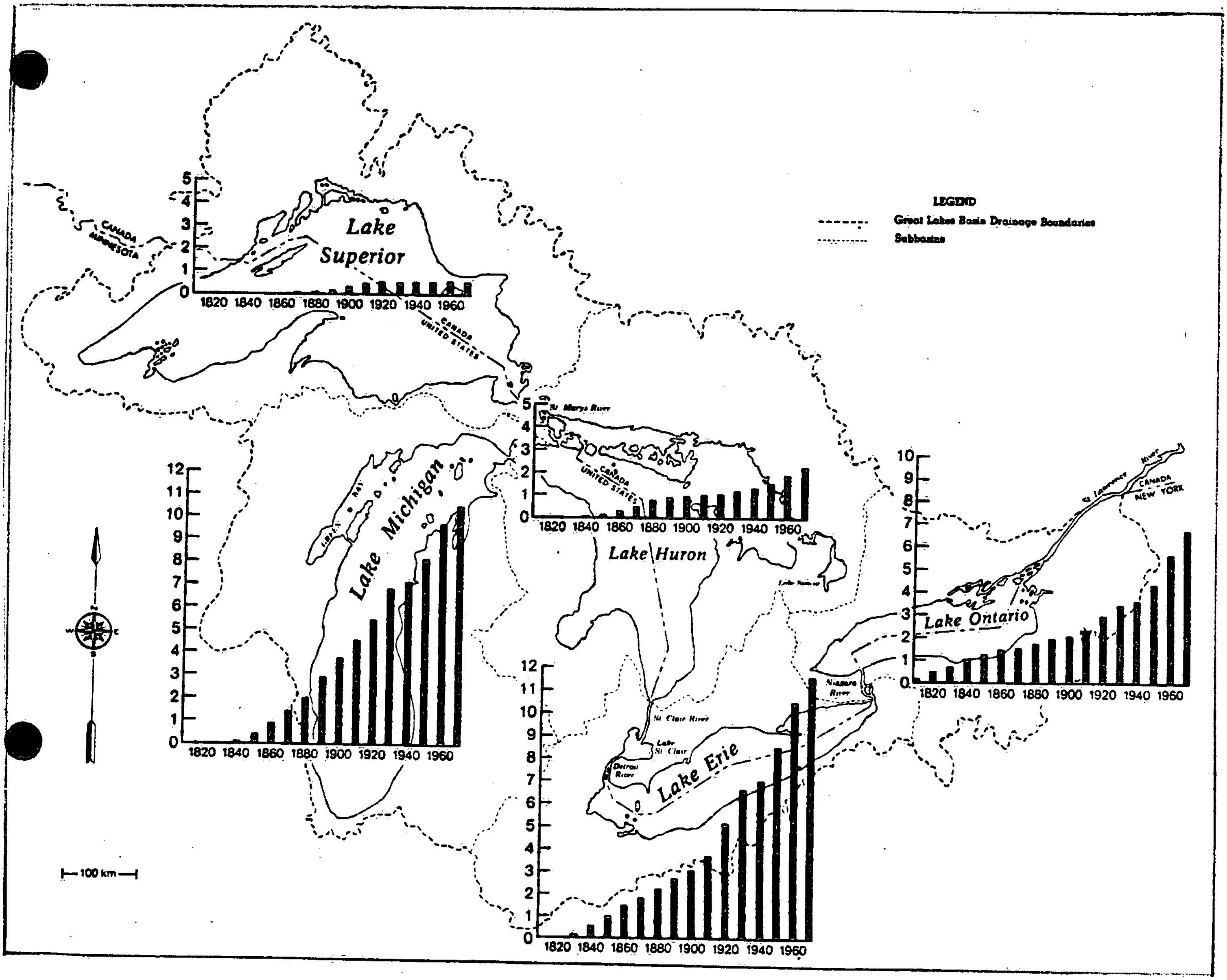


Figure 1.
Map of the Great Lakes and their drainage basins showing the human population (millions) for each decade from 1800 to 1970. (Robertson and Scavia, 1984, Fig. 6.2)

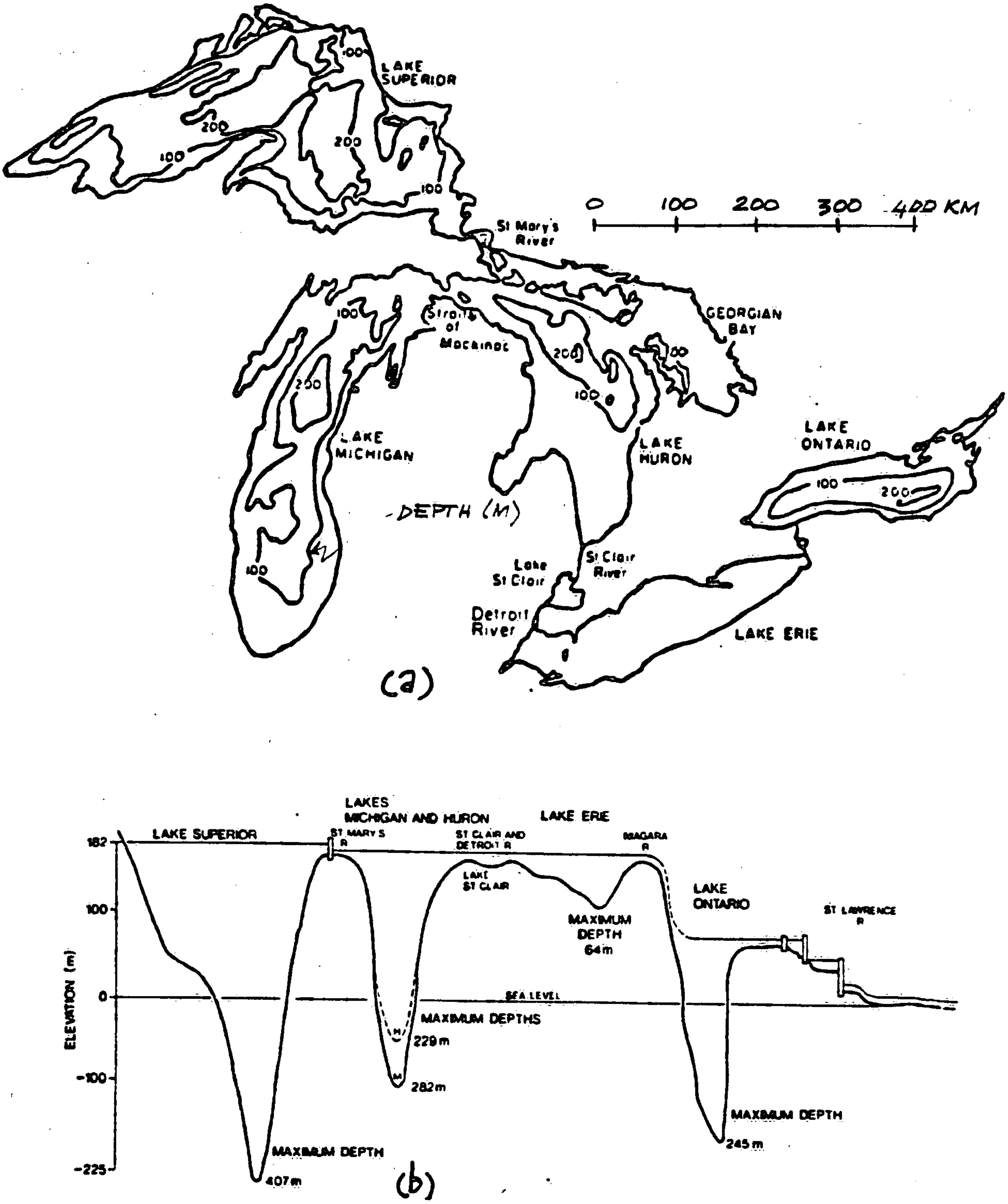


Figure 2.
a) Map of the Great Lakes showing major bathymetric features.
b) Cross-section of the Great Lakes (not to horizontal scale) showing basin elevations and depths (Schertzer, 1981).

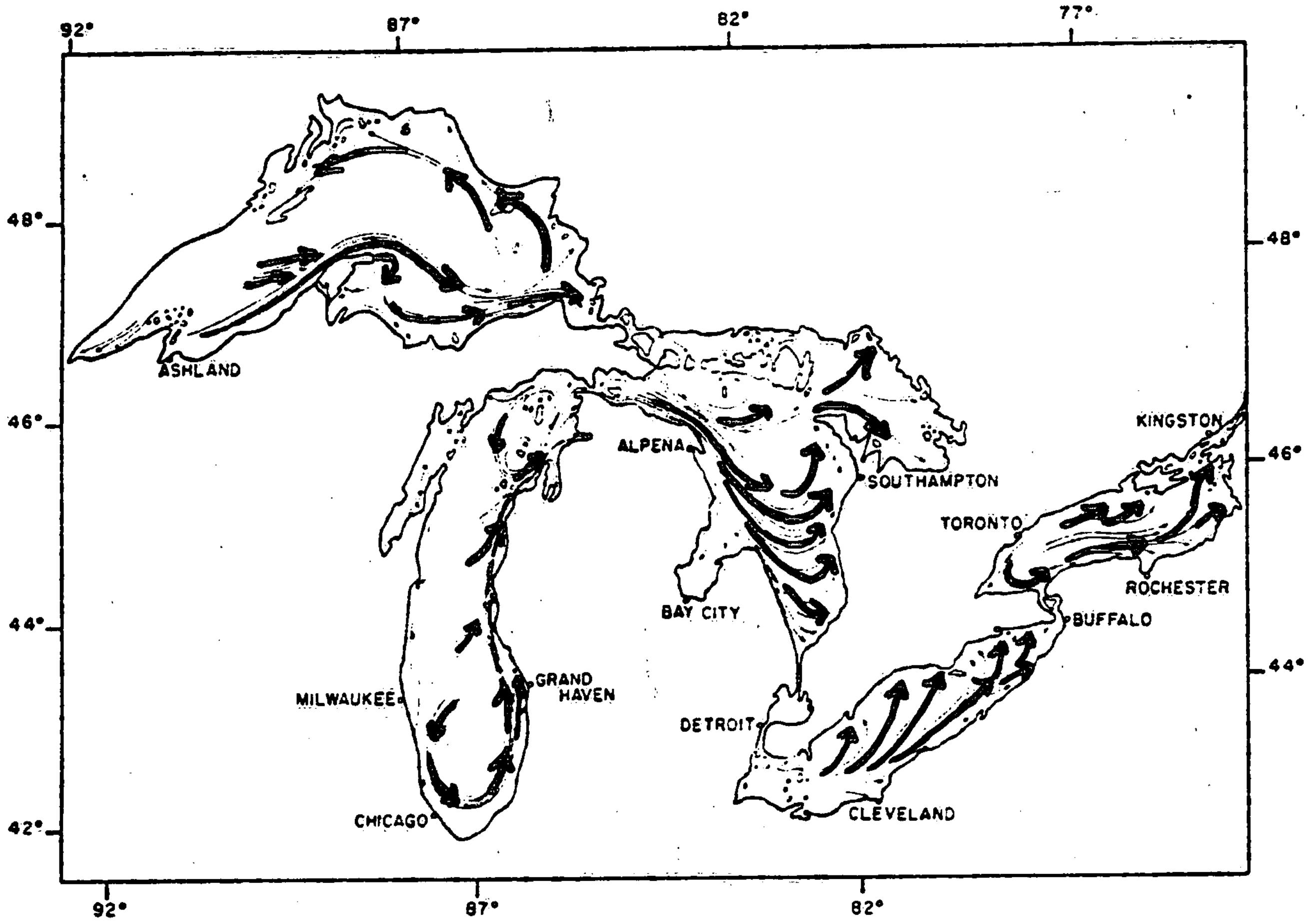


Figure 3.
Map of the Great Lakes summarizing Harrington's (1895) surface drift studies. Redrawn from Hutchinson (1957).

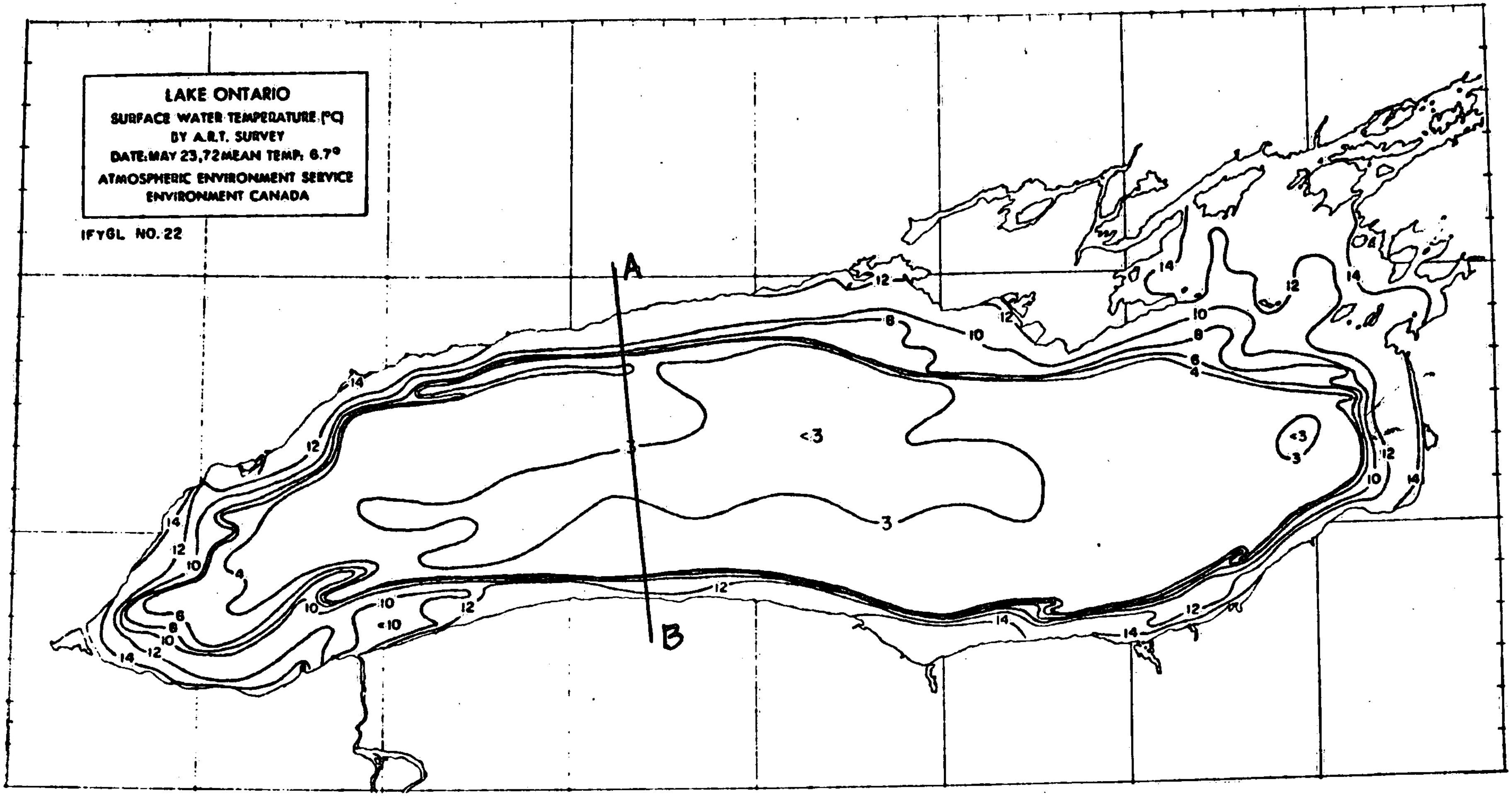


Figure 4.
Surface temperature map of Lake Ontario for May 23, 1972, made with an airborne infrared thermometer (A.R.T.) (Irbe and Mills, 1976). This distribution is typical of the intermediate phase of the thermal bar (geostrophically balanced counterclockwise flow of the warm, inshore water).

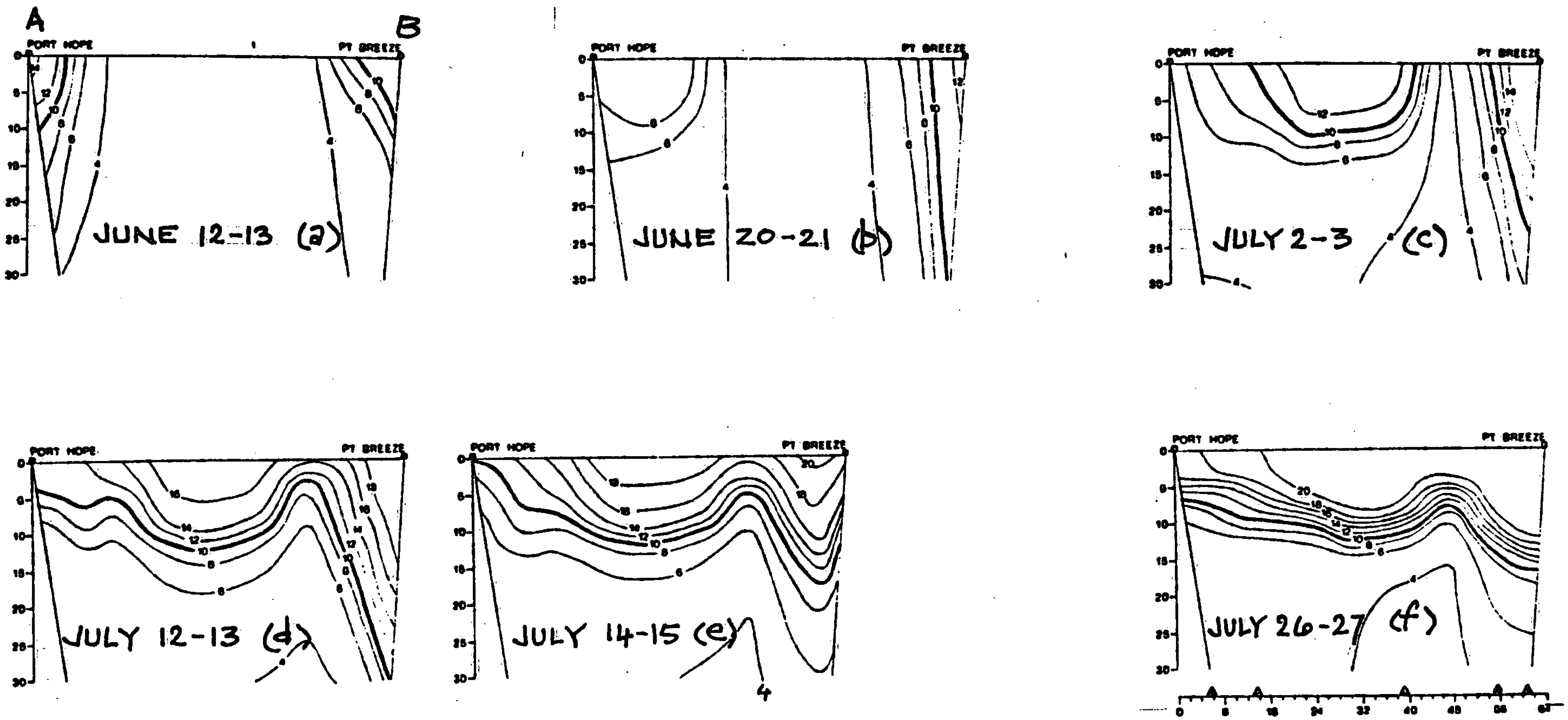


Figure 5.
Distribution of temperature on a cross-section of Lake Ontario from Port Hope, Ontario (A) to Point Breeze, New York (B) (Simons and Schertzer, 1985). The location of the section is indicated on Figure 4. The cross-sections are assembled from time-series data collected at the mooring locations; each section represents a 48-hour average. Section (a) shows the intermediate phase of the thermal bar, roughly corresponding to the situation depicted in Figure 4. Under the influence of strong winds from the west, upwelling pushes the band of warm water on the north shore into mid-lake (sections b and c). By mid-July, stratification is established across the whole lake. Note the strong downwelling on the south shore and its subsequent relaxation 48 hours later (sections d and e).

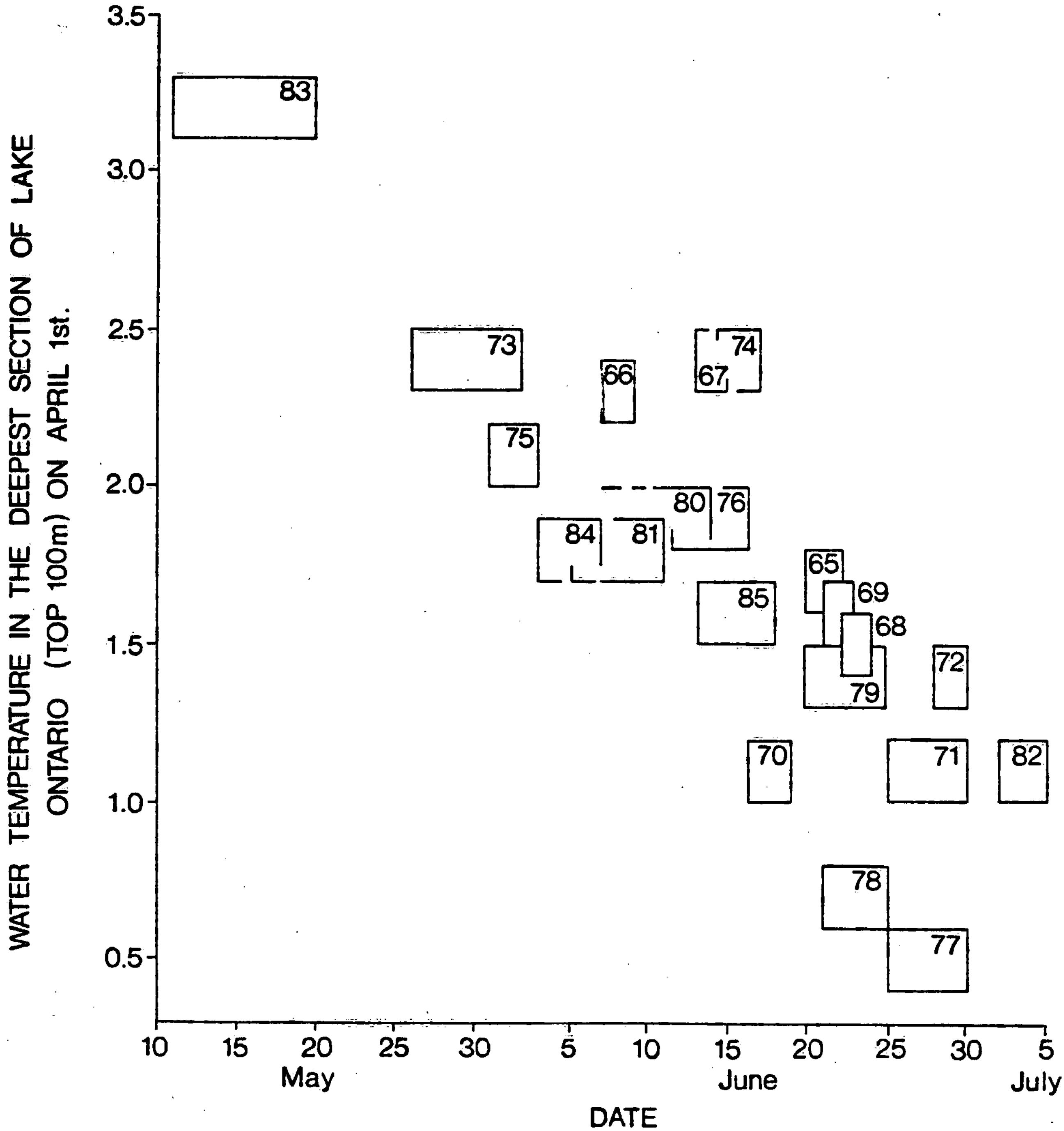


Figure 6.
Date of full stratification or disappearance of the surface 4°C isotherm as a function of April 1st water temperature (Deep region east of 77 45'W longitude in Lake Ontario). (Rodgers, 1987).

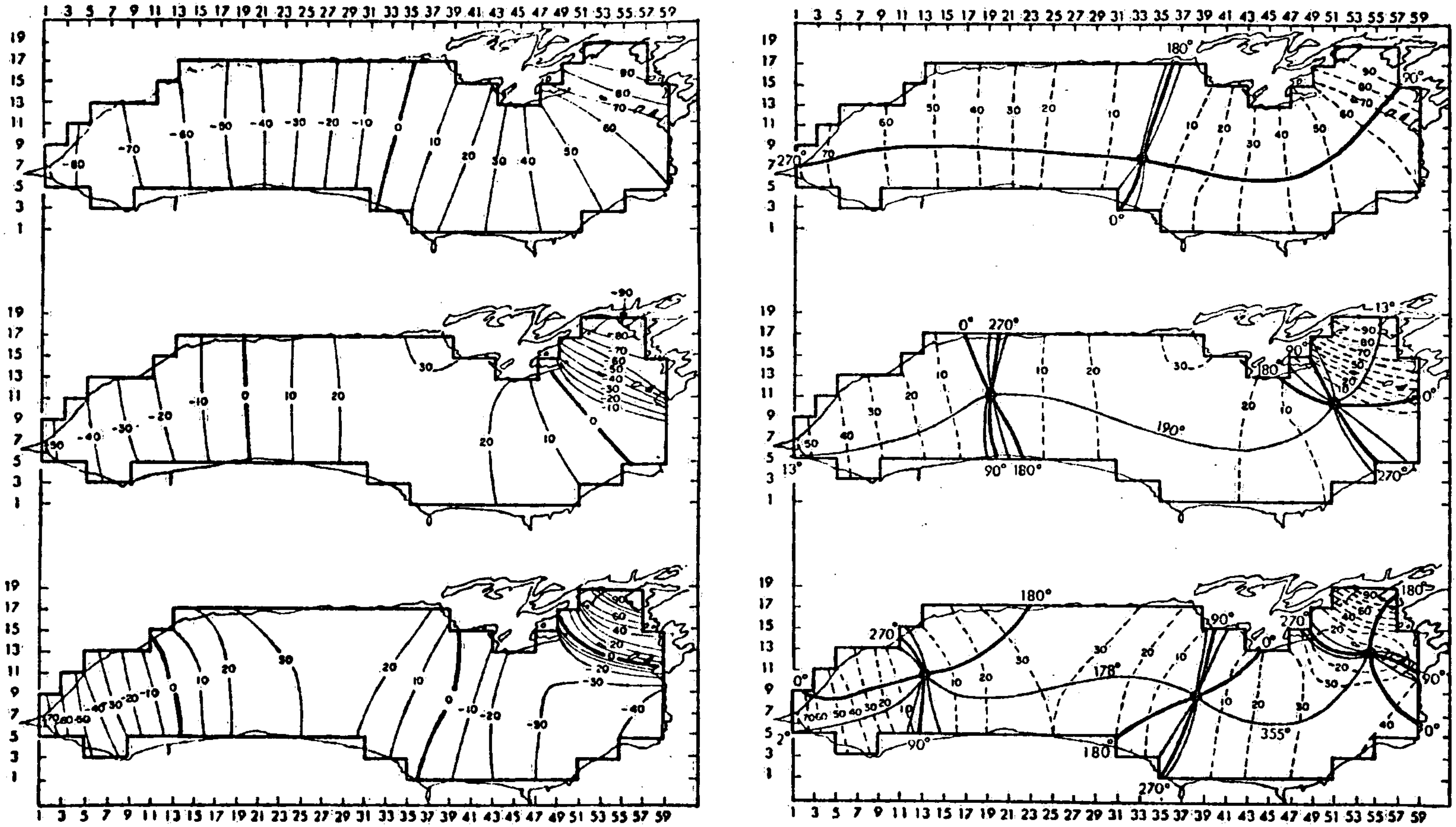


Figure 7.
Computed co-tidal lines and co-phase lines for the first three modes of the free-surface seiches of Lake Ontario neglecting the earth's rotation (left panel) and including the earth's rotation (right panel). (Rao and Schwab, 1976).

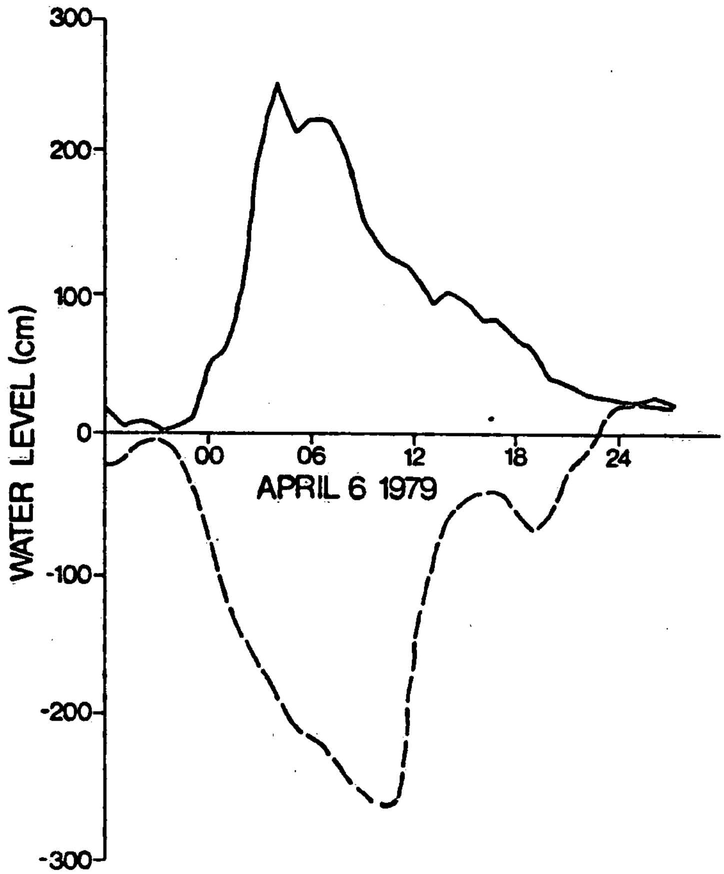


Figure 8.
Water levels recorded at Buffalo, New York (solid line) and Toledo, Ohio (dashed line) during the storm surge of April 6, 1979. At the peak of this event, the water level difference from one end of the lake to the other is almost 6 metres (Hamblin, 1979).

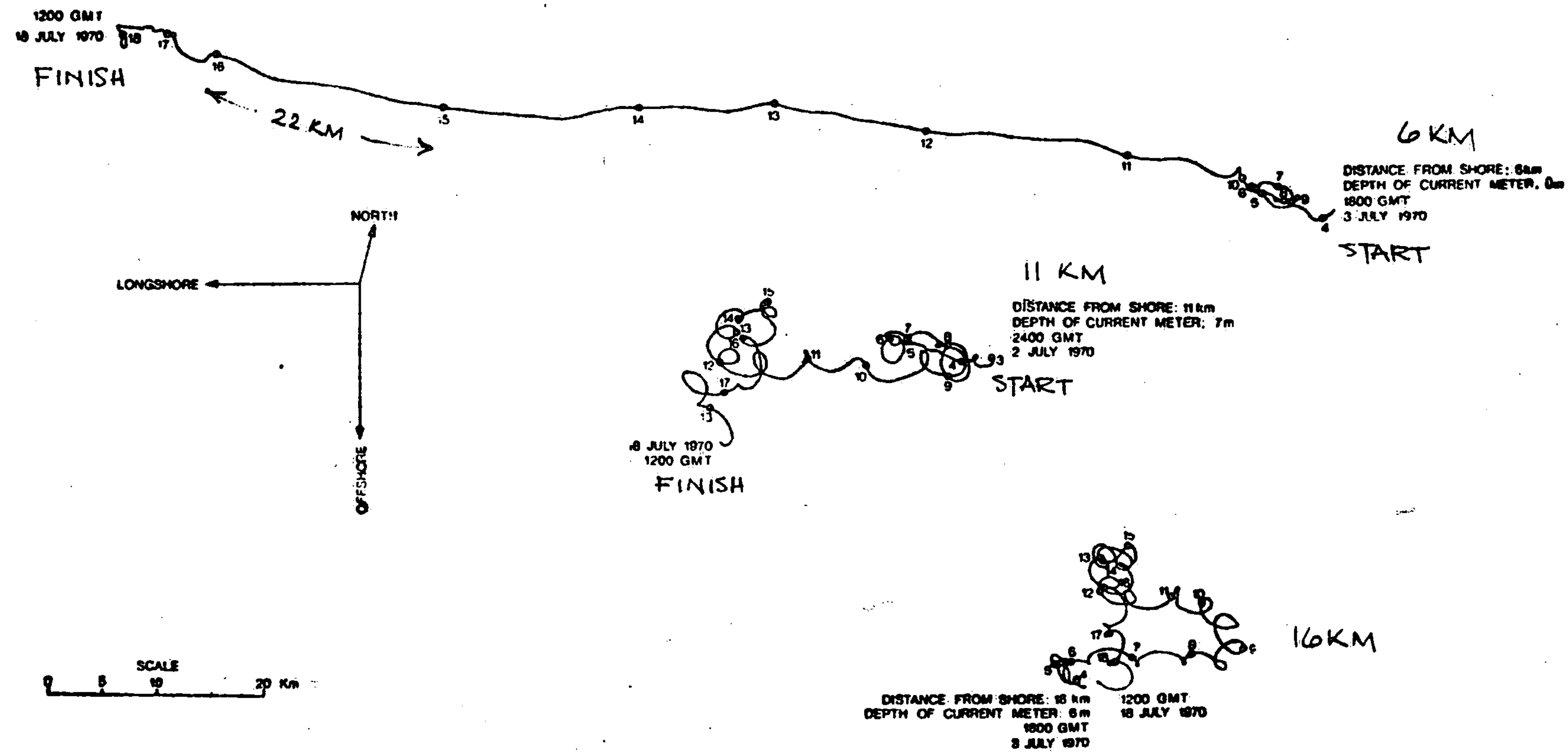
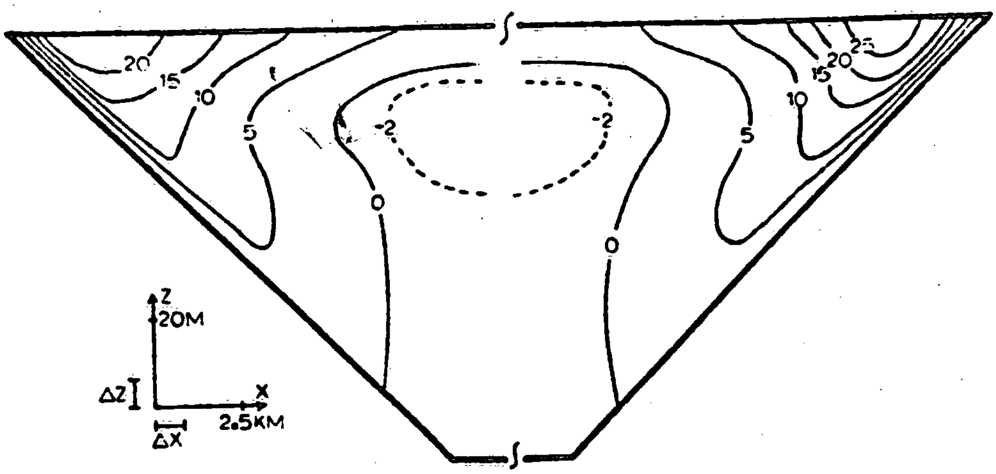
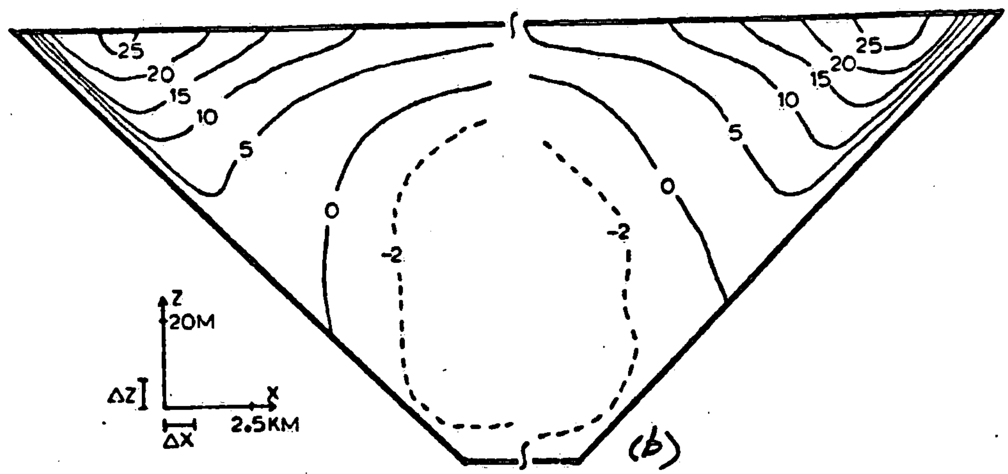


Figure 9.
Progressive vector diagrams constructed from near-surface current meter records at distances of 6, 11, and 16 km from the north shore of Lake Ontario over the time interval July 3 to July 18, 1970. (Murthy and Blanton, 1975).



(a)



(b)

(c)

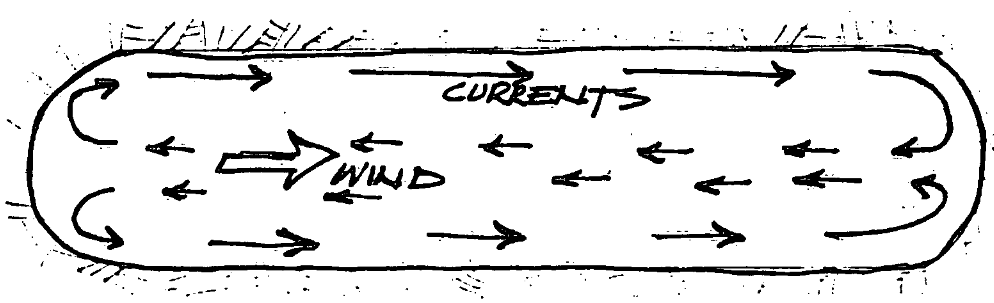


Figure 10.
Theoretical current distribution after application of a constant wind stress for 10**5 seconds in the channel model of Bennett (1974). Figure 10a shows the distribution for a homogeneous water column, Figure 10b is that of a stratified water column. The diagrams do not show a 30 km, flat bottomed mid-section. Note the general similarity of the flow in both cases, downwind "jets" near the shore and broad upwind return flow in mid lake. A plan view of the circulation is sketched in Figure 10c.

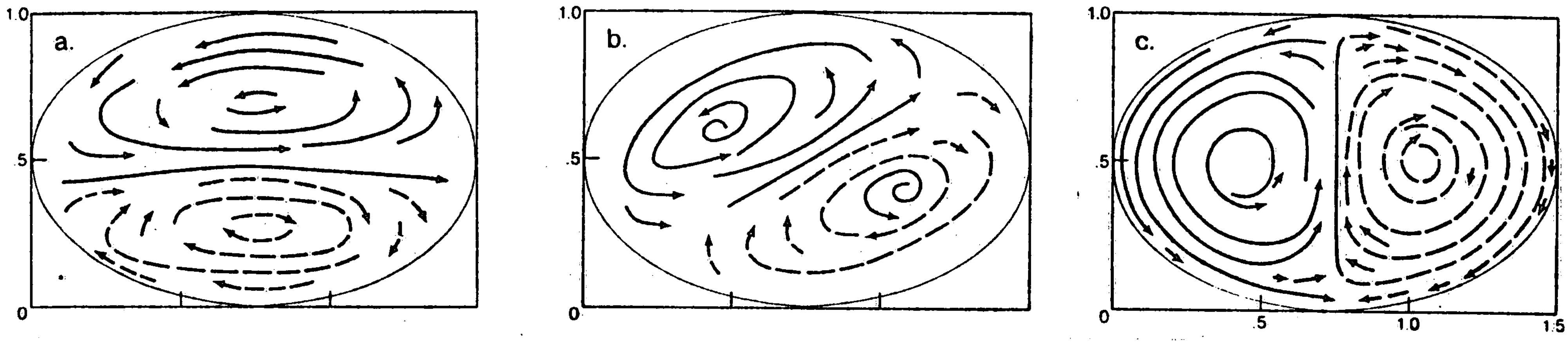


Figure 11.
Schematic streamline pattern of the two-cell vortex rotational mode in an elliptical basin with a paraboloidal cross-section. Figure 11a represents the initial, wind-forced pattern (wind blows from left to right along the axis of the basin). Figures 11b and 11c represent the flow at successively later times (1/8 and 1/4 period). (Saylor et al., 1980).

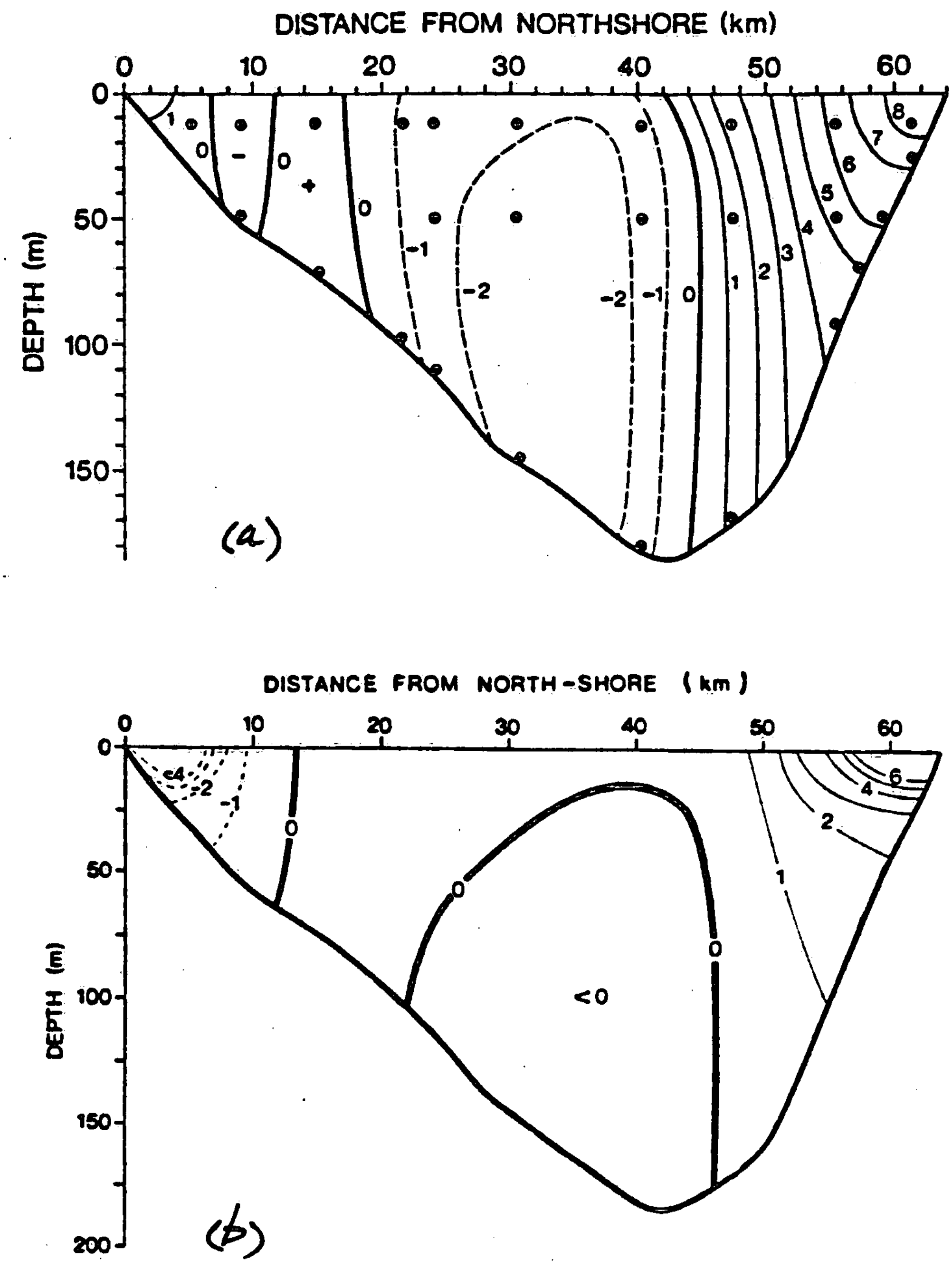


Figure 12.
Time-averaged currents along the axis of Lake Ontario at the Port Hope Point Breeze cross-section (see Figure 4; north is to the left). Figure 12a shows the winter circulation (November, 1982 through March, 1983); note the strong eastward flow on the south shore with the broad return current in mid-lake. Figure 12b shows the summer circulation (May to August, 1982). The nearshore currents indicate a counter-clockwise circulation around the basin. (Simons and Schertzer, 1985).

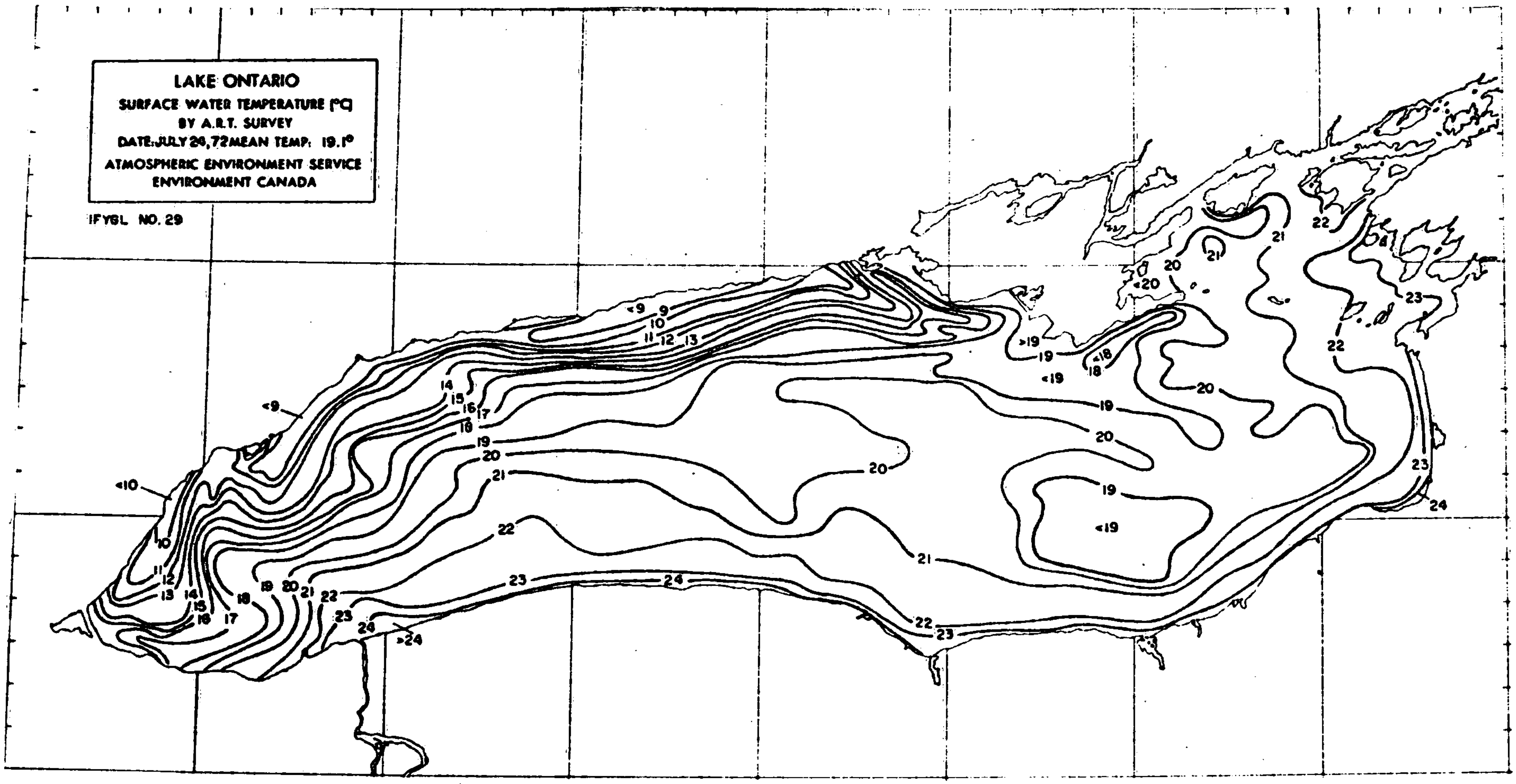


Figure 13.
Surface temperature map of Lake Ontario for July 23, 1972 made with an airborne infrared thermometer (A.R.T.) (Irbe and Mills, 1976). This distribution shows upwelling of thermocline water along the northwest shore in response to winds blowing from west to east.

Figure 14.
Illustrations of two gravity wave motions in the presence of rotation. Figure 14a (Mortimer, 1965) depicts a Kelvin wave, a coastally "trapped" mode that travels with the shore on its right hand side in the northern hemisphere. In a Kelvin wave, the Coriolis force resulting from motion in the plane of the wave's travel is balanced by pressure gradients arising from the slope of the surface in a direction at right angles to the direction of travel. Figure 14b (Mortimer, 1968) depicts a standing Poincare wave. Waves of this kind appear to account for prominent near-inertial frequency currents and isotherm displacements observed offshore in the stratified season. This pictures can be viewed as motions in the hypolimnion; an oppositely directed current would be observed in the epilimnion.

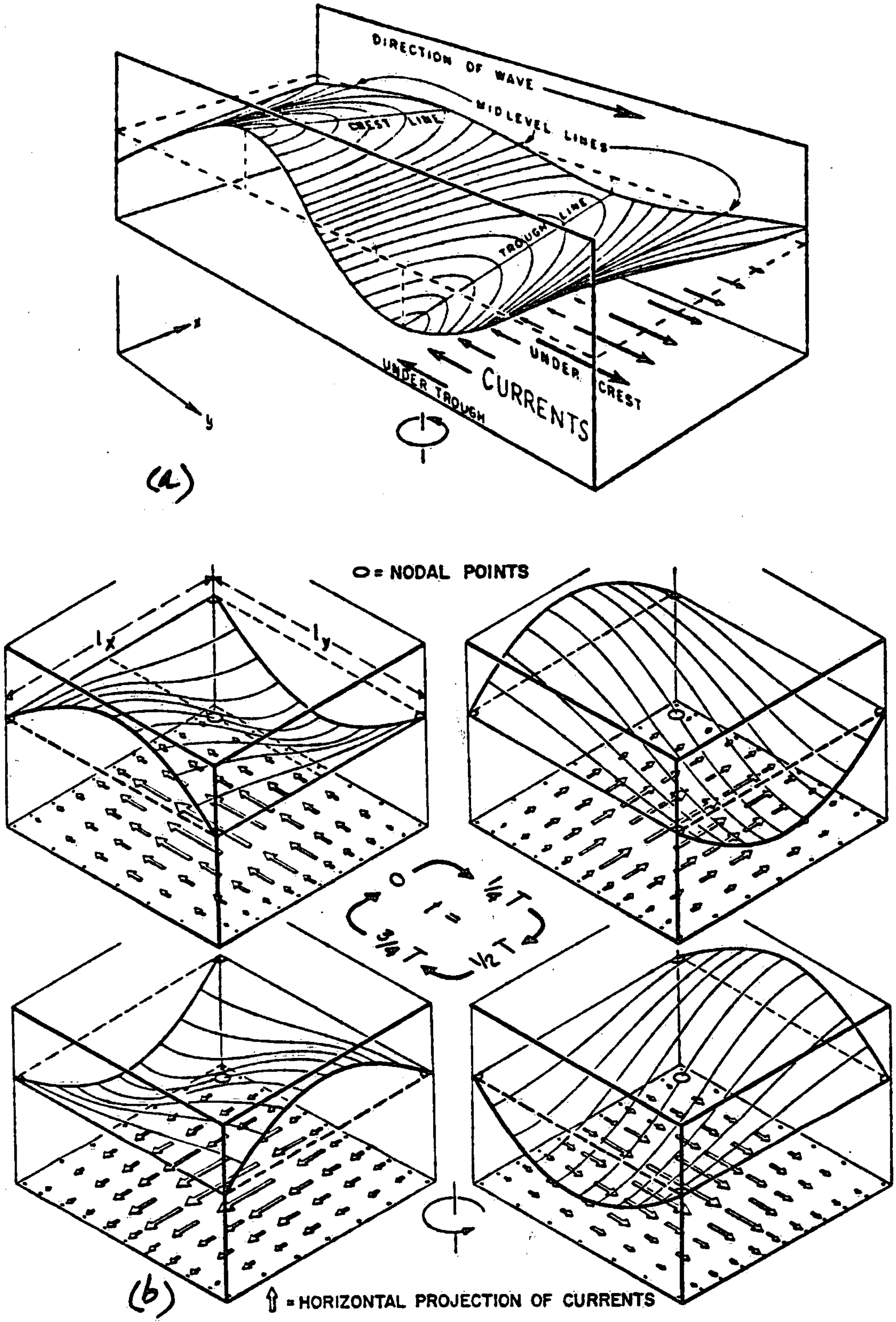


Figure 14.
Illustrations of two gravity wave motions in the presence of rotation. Figure 14a (Mortimer, 1965) depicts a Kelvin wave. Figure 14b (Mortimer, 1968) depicts a standing Poincare wave.

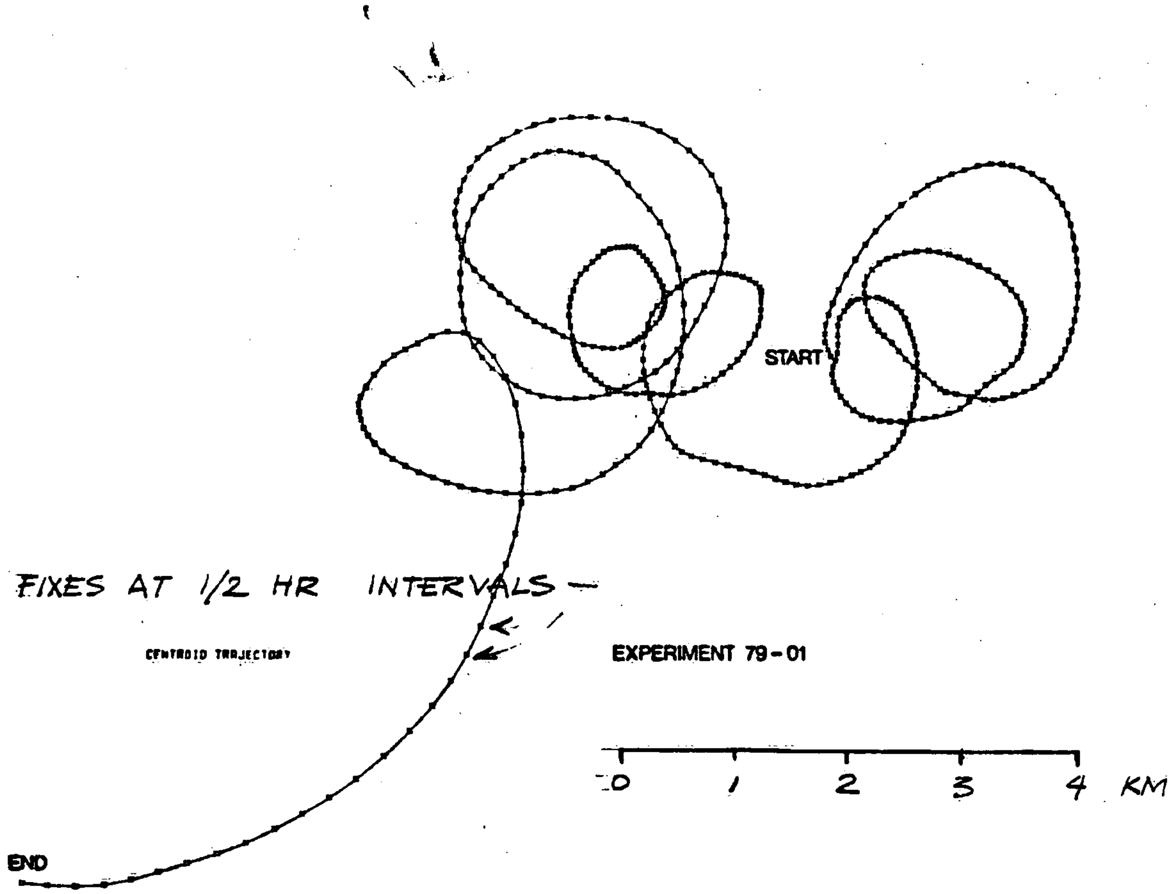


Figure 15.
Path of a 3m drogue released in the Central Basin of Lake Erie in early July, 1979. During this episode, winds were light and a shallow mixed layer of less than 5m thickness was in place above the seasonal thermocline. Circular, near-inertial period motions dominate most of the record. (Sanderson et al. 1983)

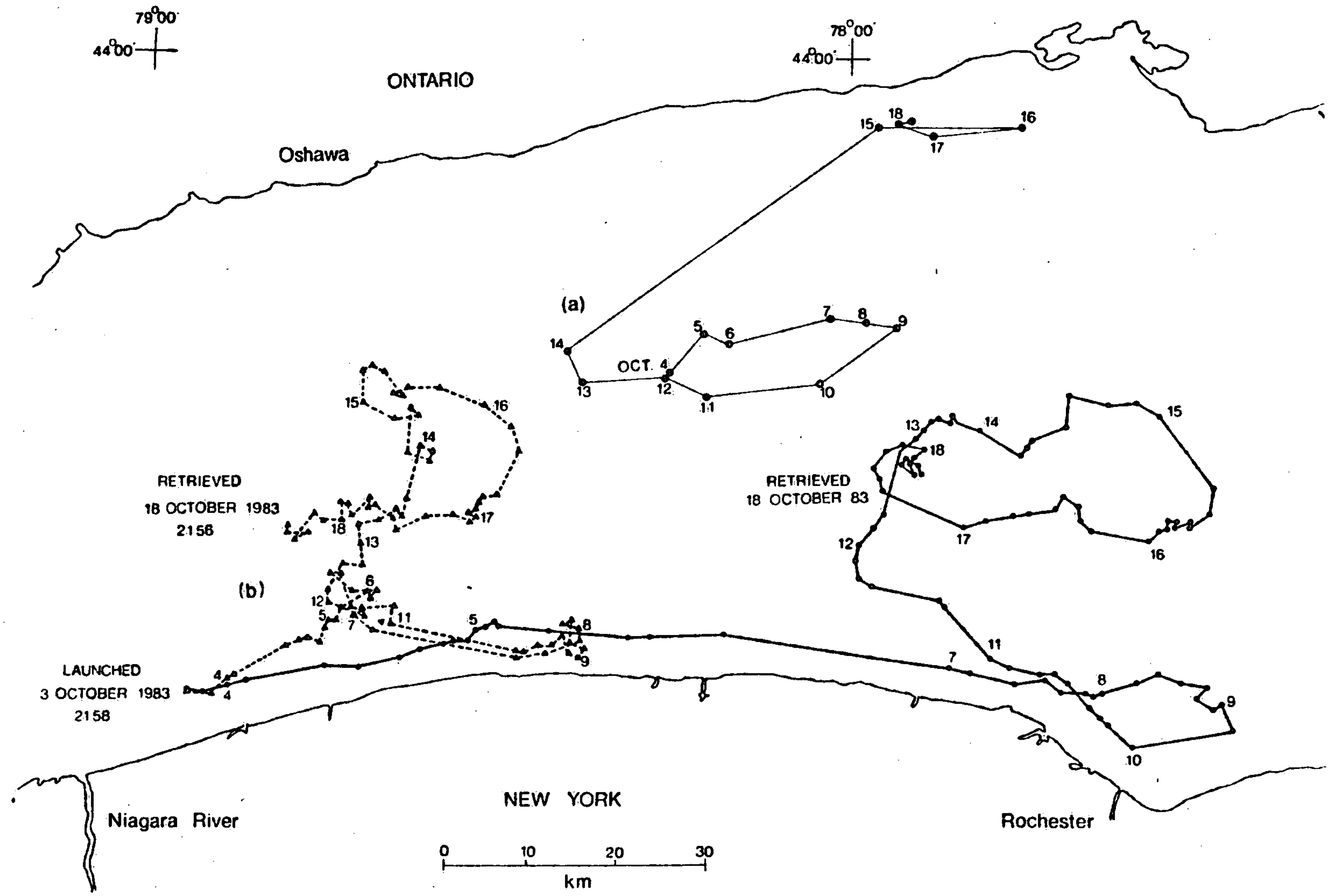


Figure 16.
Lagrangian drifter experiment 3 - 18 October, 1983 in Lake Ontario. The paths of two satellite-tracked drifters released to the northeast of the Niagara River mouth are shown. The wind-track during the experiment is plotted to the north (a). (Murthy et al. 1986)

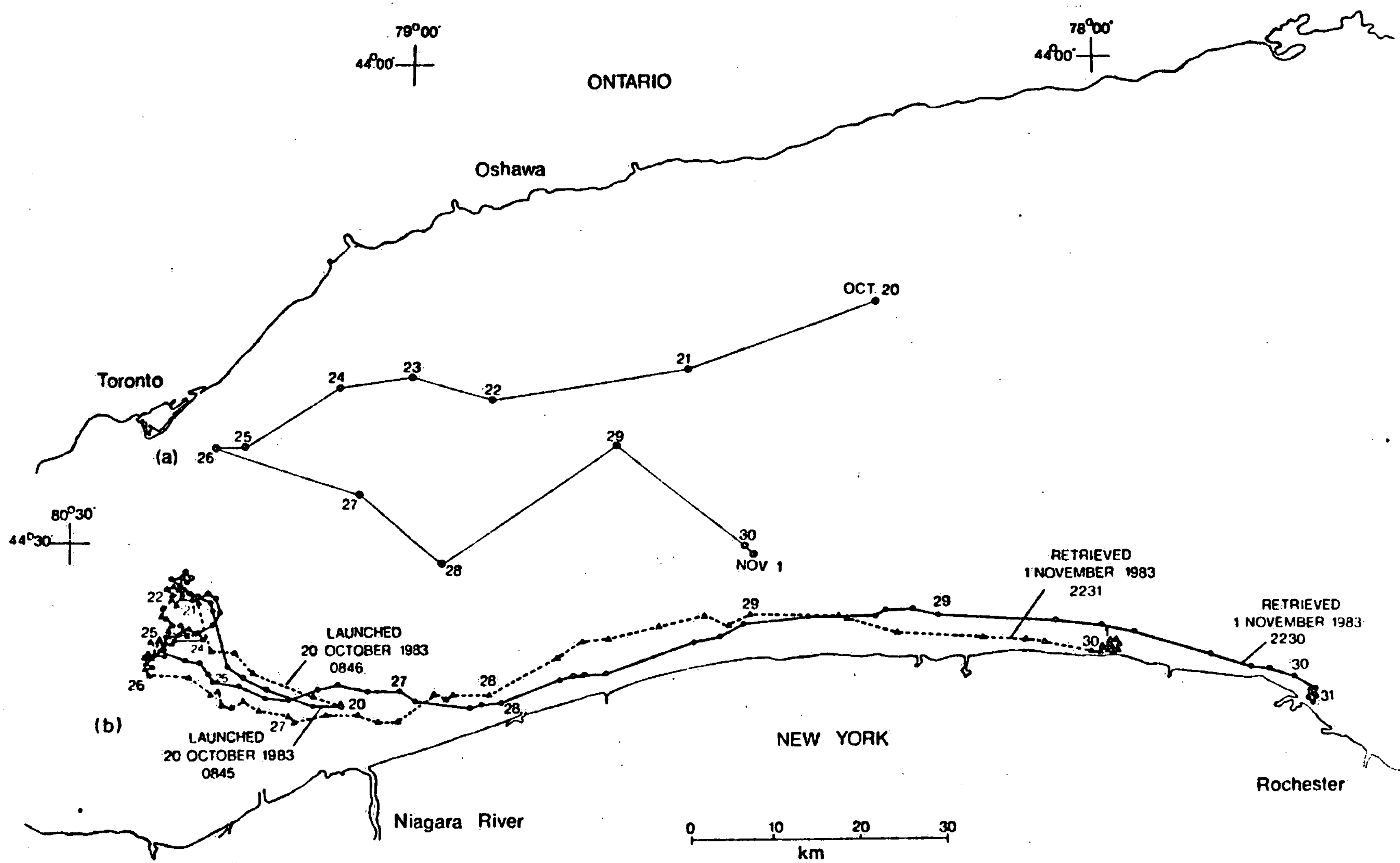


Figure 17.
Similar to Figure 16 but showing the drifter experiment of 20 October to 1 November, 1983. (Murthy et al., 1986).

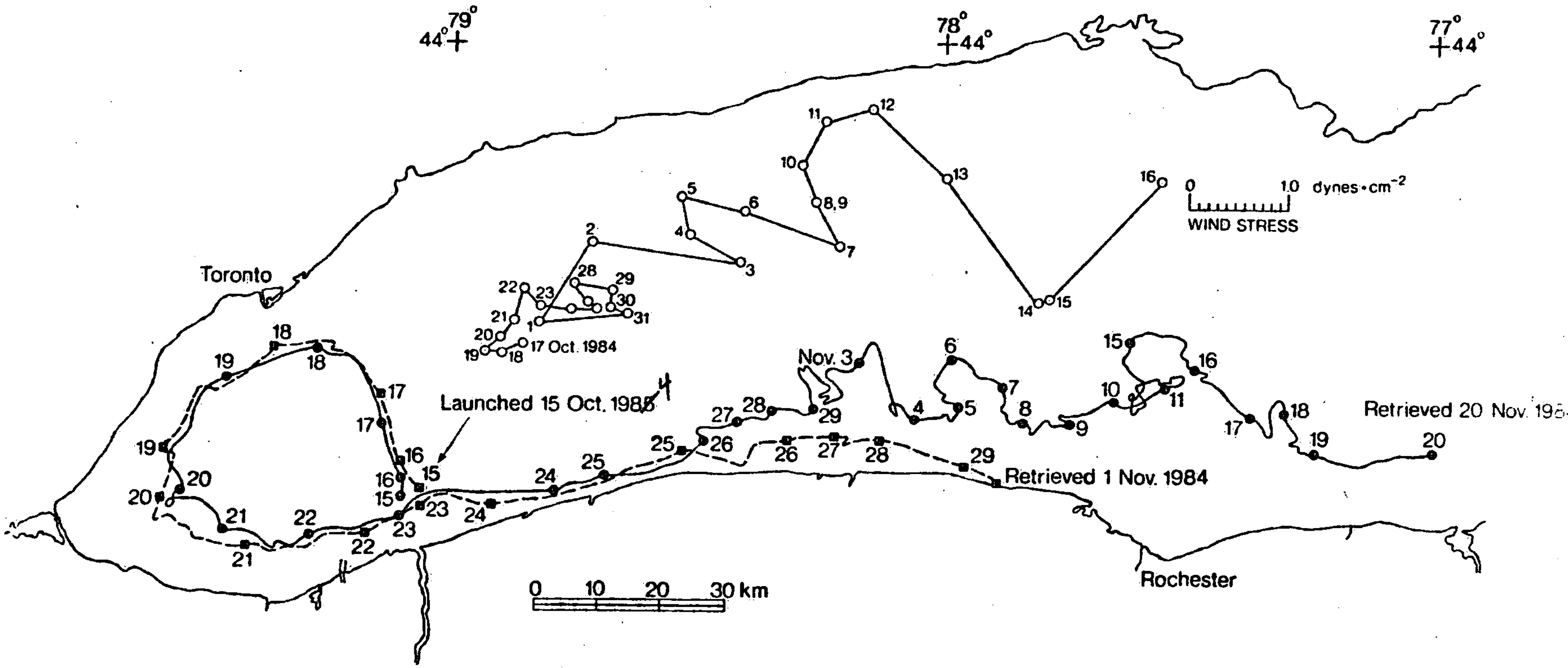


Figure 18.
Similar to Figures 16 and 17 but showing the drifter experiment of 15 October to 20 November, 1984. (Murthy et al., 1986).

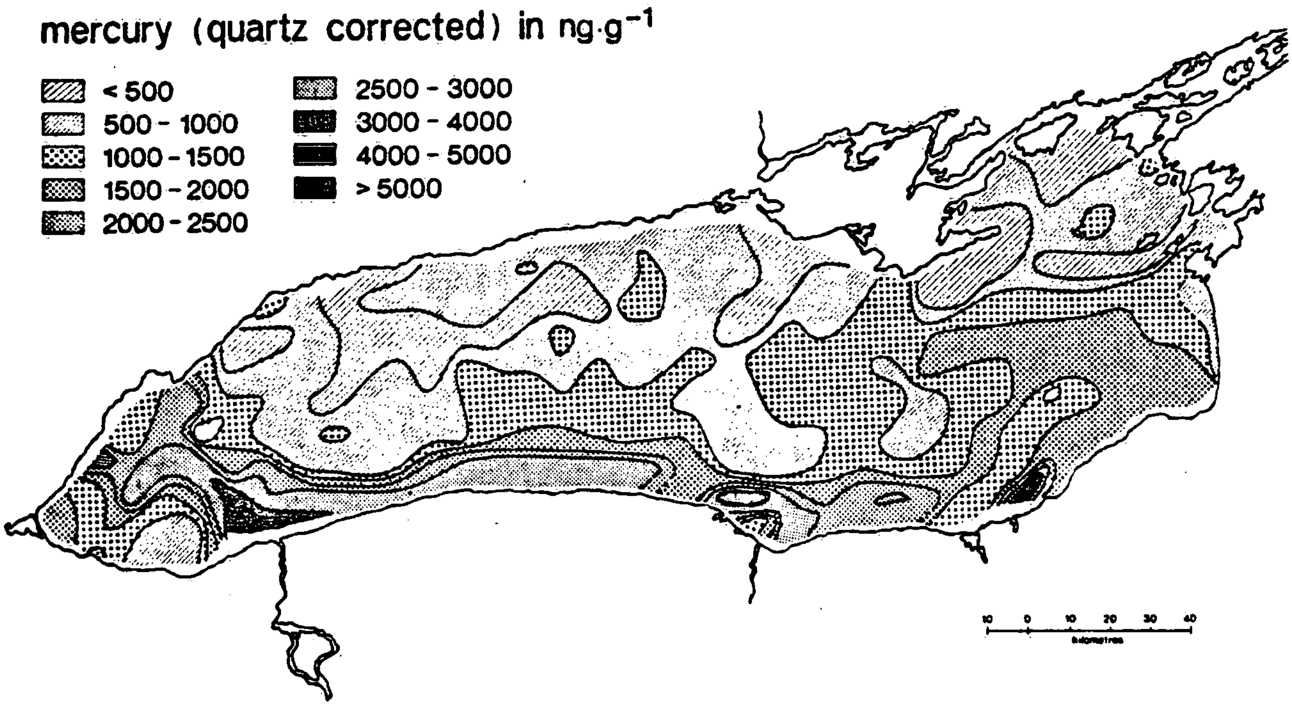


Figure 19.
Distribution of mercury (corrected for the presence of quartz) in the surficial sediments of Lake Ontario. This distribution is consistent with a source in the Niagara River and a persistent eastwards flow along the south shore. (Thomas, 1983).

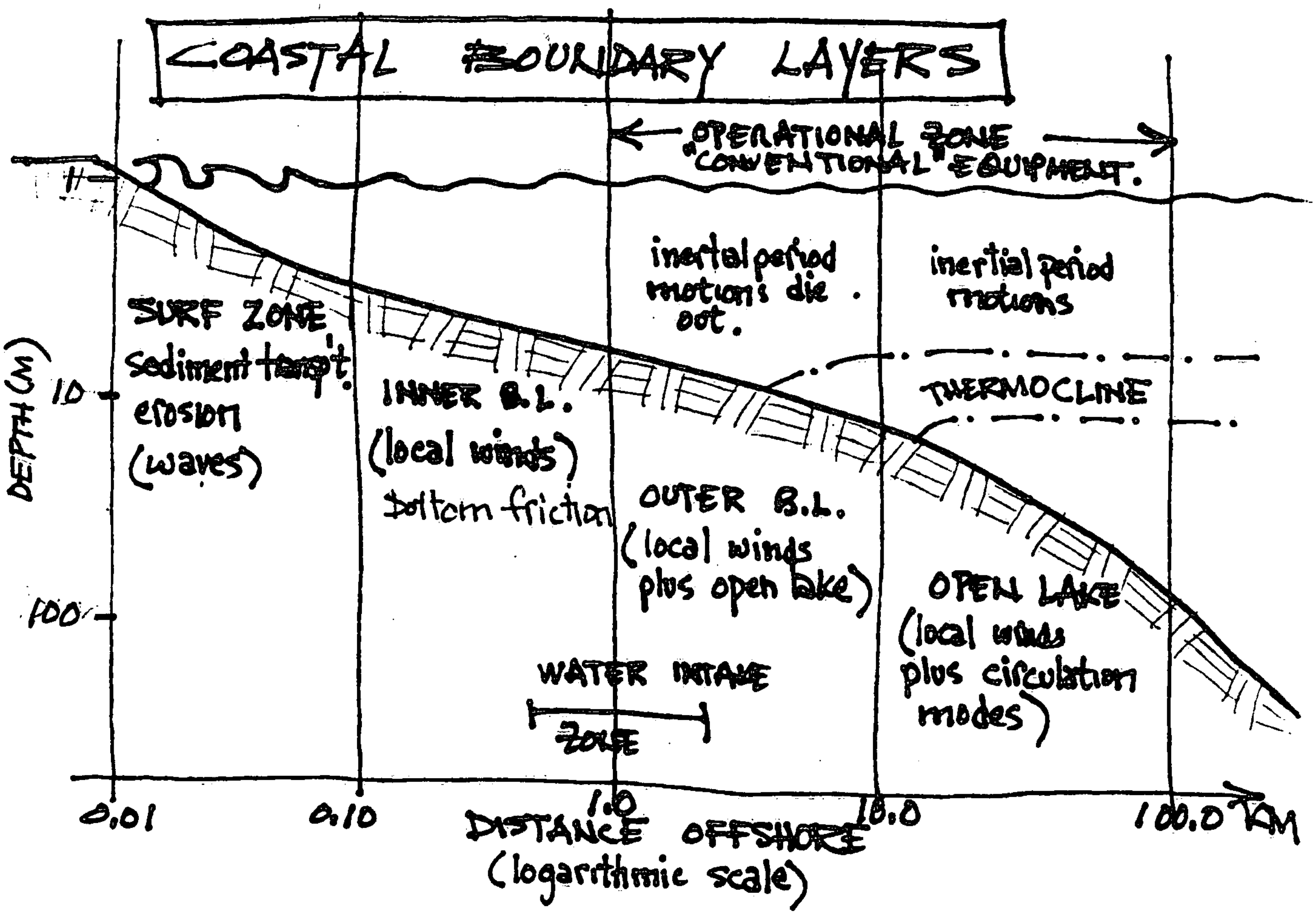


Figure 20.
Diagram depicting coastal boundary layer regimes.

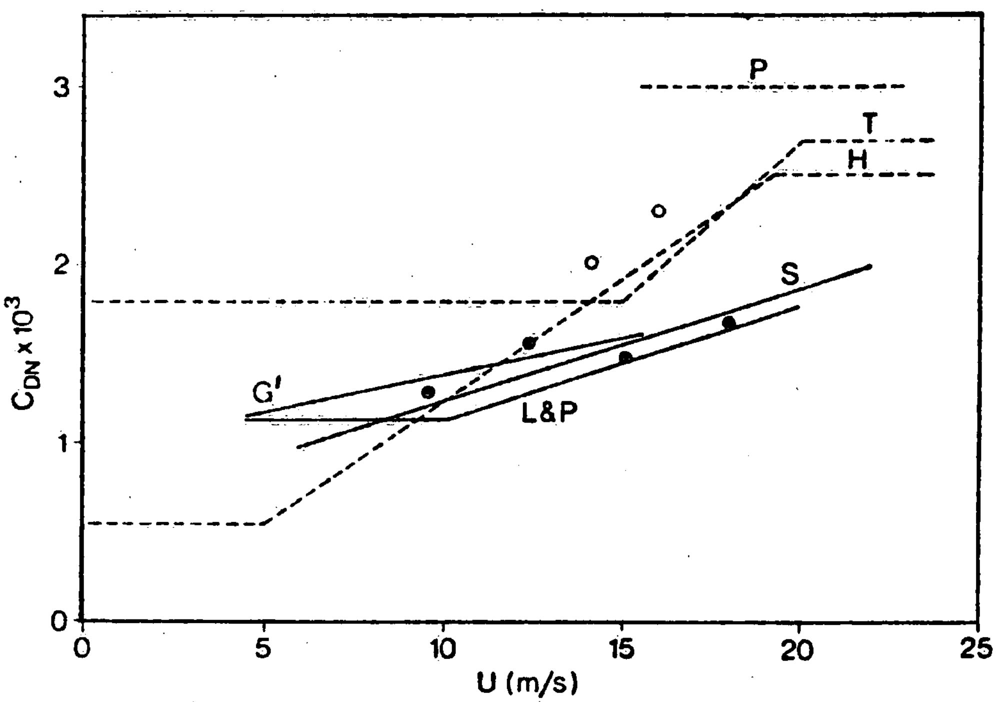


Figure 21.
The neutral drag coefficient (CDN) versus wind speed U. Solid lines are regressions from eddy correlation estimates. Dashed lines are formulae adopted by three storm-surge modellers. Solid circles are derived from water level fluctuations over several months (Schwab, 1982), open circles are derived from the peak storm surge for two months (Simons 1974 and 1975). (Donelan, 1982).

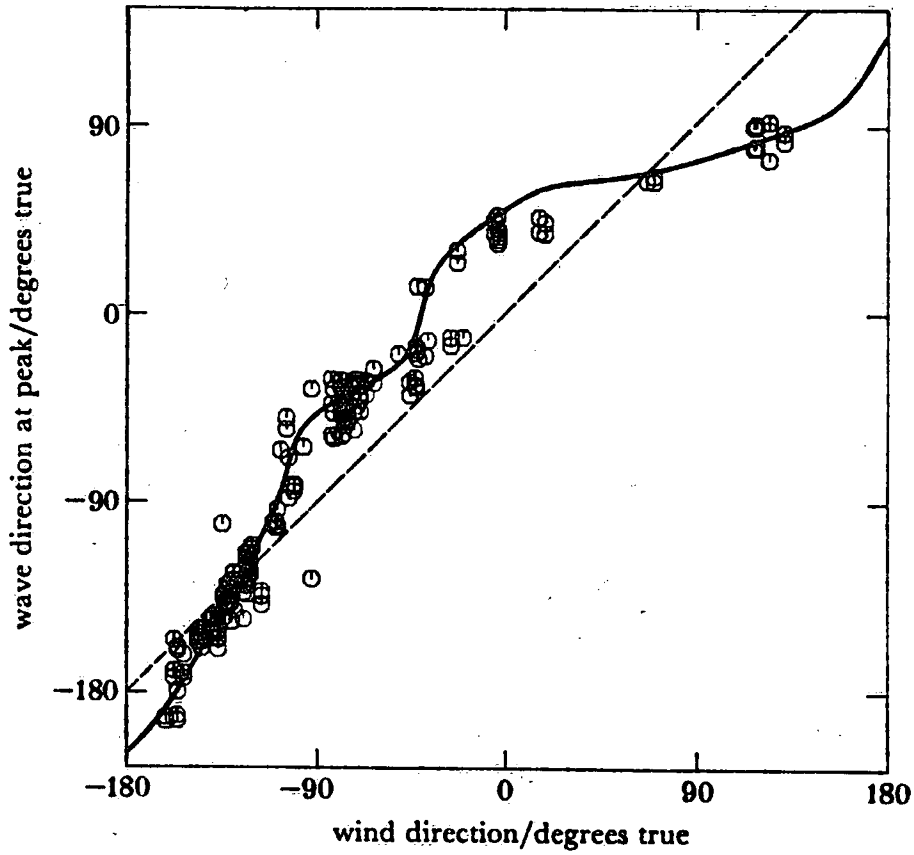


Figure 22.
Mean direction of waves at the spectral peak against wind direction for a platform in the western end of Lake Ontario. In the absence of fetch effect, the two directions should agree (points lie on the dashed line). (Donelan et al., 1985).