THERMAL STRUCTURE AND CIRCULATION IN THE GREAT LAKES

F.M. Boyce, M.A. Donelan, P.F. Hamblin
C.R. Murthy and T.J. Simons

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Lakes Research Branch
National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario L7R 4A6
Canada

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ABSTRACT

Thermal Structure and Circulation in the Great Lakes. F.M. BOYCE, M.A. DONELAN, P.F. HAMBLIN, C.R. MURTHY, T.J. SIMONS (National Water Research Institute, Environment Canada)

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 thermally 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. F.M. Boyce, M.A. Donelan, P.F. Hamblin, C.R. Murthy et T.J. Simons (Institut national de recherche sur les eaux, Environnement Canada)

Assez grands pour se prêter à de nombreux phénomènes océaniques, les Grands Lacs sont très justement qualifiés de mers intérieures. À l'exception du bassin ouest, peu profond, du lac Érié, les lacs présentent une stratification thermique en été, sont homogènes en hiver, avec des températures moyennes passant par la température de densité maximale de l'eau douce (4°C) au printemps et à l'automne. La circulation y est surtout due au vent, mais est fortement modifiée par la stratification thermique et la géométrie du bassin. Les effets de la rotation de la Terre se manifestent dans tous les flux à grande échelle. Les vitesses des courants sont de l'ordre de 10 cm/s; elles sont trop faibles, sauf rares exceptions, pour créer des difficultés à la navigation, mais la connaissance des configurations du mouvement de l'eau est essentielle pour

interpréter le comportement de ces lacs, qui sont des écosystèmes de grande valeur. Cette présentation passera en revue des études physiques des Grands Lacs couvrant plus d'un siècle.

INTRODUCTION

The combined surface area of the Laurentian Great Lakes is slightly larger than the United Kingdom (245,000 km) (Robertson and Scavia, 1984) and they contain enough water to flood the entire North American continent to a depth of 1 m. 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 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 rehabilitate 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 mediate the responses of the lakes to imposed environmental stresses. It would be incorrect, however, to suggest that the only reason for studying physical processes on the Great Lakes was because of the implications of the above processes 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, and they share a large, overlapping literature (Simons, 1980, Csanady, 1982, 1984). Moreover, these magnificent lakes contain their own intrinsic interest and beauty that makes their study a pleasure. This article is dedicated to the memory of the late T.J. (Joe) Simons (1939 - 1987) of the National Water Research Institute whose numerous and substantial contributions in the areas of numerical hydrodynamics, lake systems modelling, and the theory of large lake circulations have added significantly to our insight.

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 consequences of thermal 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 occurrence a density maximum of fresh water at 4° C leads to some physical phenomena unique to the Lakes. Aside from vigorous tidal currents, the major physical difference between the Great Lakes and the coastal oceans is the nature of the boundaries, open on one side in the case of the coastal ocean, but closed in the Great Lakes.

We will briefly review the historical development of Great Lakes physical limnology and then describe the main 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 more complete information on those lakes. The reader will be aware of a natural bias of the authors to discuss 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 and their students together toured the North Shore of Lake Superior by canoe (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 and 1893, M.W. Harrington of the U.S. Weather Bureau (Harrington, 1894) 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 the study 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). An extensive bi-national study of Lake

Erie, a follow-up of the 1970 study, was undertaken in the years 1979 and 1980. Results of this effort have recently appeared in a special issue of the Journal of Great Lakes Research (13(4), 1987), and they document the connections between physical and biochemical variability. In Lake Ontario, a major dynamical experiment led by T.J. Simons in 1982 - 83 has produced new and valuable insights reported below. Our colleagues at the Great Lakes Environmental Laboratory in Ann Arbor, Michigan, have likewise made good use of their extensive investigations on Lake Michigan.

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 (Aubert 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. (1985). 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 depth of stratification (Pollard, Rhines, and Thompson, 1973; Gorham and Boyce, 1989). The major difference between the 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 (1963) studies of the spring warming of Lake Lagoda, 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 occurring 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 1971). A more refined model has been proposed by Zilitinkevich and Terzhevik (1987). The vertical circulations arising from the non-linear equation of state of water near 4°C have been studied by Hamblin and Ivey (1984) and by Marmoosh et al. (1986).

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 geostrophic equilibrium (Bennett, 1971). Because of the stability 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 seasonal 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 $4^{\circ}C$ 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 vertical circulation. 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). 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 increased 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 special Lake Erie issue of the Journal of Great Lakes Research mentioned above (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; it will be discussed more fully below.

CIRCULATION IN THE GREAT LAKES

Seiches and storm surges.

The phenomenon reported by Father Andre in 1672 was undoubtedly a co-oscillation of Green Bay with Lake Huron, although nearly three hundred years were to pass before these particular oscillations were explained (Mortimer, 1965; Heaps et al., 1982). Such mass oscillations or seiches 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). When the natural period of the oscillation is comparable to or greater than the local inertial period, the latter given by the formula 12/sin(φ) hours (φ = latitude), the motions are affected by the earth's rotation (Rao and Schwab, 1976) (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 opposition to the wind stress, and for the duration of the wind. These changes in water level observed in response to extremely vigorous 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 damage and risk to human lives. During periods of high mean water level, 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 move initially in the direction of the component of wind parallel to the shore and then, over time scales measured in days, reverse direction before dying out. In certain locations, nearshore currents may persist in one direction over many days. 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). 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).

a) Winter Isothermal Period.

With the exception of the circulation associated with the intermediate phase of the thermal bar and the hydraulic component of flow in shallow basins or narrows, 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 environmental 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 of stress 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, 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 (section 20), 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 theoretical 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. These motions 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 (1983, 1984). 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 and Richards (1975) and by Pickett (1977) based on the 1972 IFYGL experiment confirmed the presence of gyral motion, but the horizontal separations of the current meter network were too large at that time for unequivocal interpolation of the current patterns. Particularly interesting results, therefore, were obtained from a closely-spaced 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 eastward 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.

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 (Figure 12 b). 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 accommodate 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 particularly favorable 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 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. When the wind stops, 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 with effective periods measured in days. 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 ($12/\sin(\varphi)$ hours; φ = latitude). 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.

The Great Lakes, with relatively shallow surface mixed layers, favour the generation of these circular 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 favorable to the creation of inertial motions, as is a wind stress that turns in a clockwise sense at nearly the angular frequency of the circular 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. 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. Theoretically, 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 vertical 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 outward 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 (1894) 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, 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 tributary to 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.

While most of the discussion about large-scale circulation has been based on current meter data from fixed moorings, several Lagrangian experiments were carried out in 1983 and 1984. In each experiment, two Mini-TOD satellite -tracked drifters with sails set at 3 m depth were released at the mouth of the Niagara River and their movements followed over periods of up to 5 weeks. These measurements constitute an update of Harrington's (1894) pioneering efforts. The experiment depicted in Figure 16 ran from 15 October to 20 November, 1984. The drifter paths are shown by the heavy and dashed lines. 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 differ. 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.

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 drifters 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 17 shows the mercury distribution in the sediments (Thomas 1972, Edgington and Robbins 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 1977, 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 kilometres 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. 1984b).

SURFACE AND BOTTOM BOUNDARIES OF THE GREAT LAKES.

Wind Stress and Surface Waves

The results of wind stress on the water surface, storm surges, set-up, large scale circulations, have already been discussed under the assumption that the distribution of wind stress in time and space was known. The truth is that inaccuracy in the estimation of surface wind stress over the lakes in terms of the wind field and the actual boundary conditions (air-water temperature differences, surface waves) is still a major source of error in numerical storm surge or circulation models (Schwab and Morton 1984). The wind stress is strongly modified by surface waves.

The wind excites surface waves which can be hazardous to navigation, and which are the main cause of shore erosion. When first generated by the wind, surface waves are small, but as they travel more or less downwind, the waves 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. 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.

Although the Great Lakes are large, the fetches they present to the winds ensure that 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., 1984a). 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 18). 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).

Many studies of waves on the Great Lakes have, and continue to be motivated by concern for navigational safety and shore protection, but the lakes themselves are particularly well-suited for basic research 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 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 19); (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 the effects of the Great Lakes on local weather, although a full discussion is beyond the scope of this paper. 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. In addition to fluxes of heat and momentum, winds and waves strongly influence the transfers of gases and volatile contaminants across the air-water interface.

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 adsorption and desorption of contaminants, 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. A significant fraction of the particles eroded from the shoreline or carried to the lake by tributaries move eventually to the deepest parts of the basin where they accumulate, this process, often called sediment focussing, is episodic; an individual particle may settle out and resuspend many times before final burial. 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 et al (1982), and by Rosa (1985). Laboratory experiments by Lee et al. (1981) have preceded the more difficult field studies which are now underway (Boyce et al, 1986; Hamblin et al. 1987). A thorough review of the hydrodynamics of sediment resuspension with particular focus on Lake Erie has been contributed by Abdelrhman and Bedford (1987).

THE CONTRIBUTION OF PHYSICAL LIMNOLOGY TO THE ONGOING "MANAGEMENT" OF THE GREAT 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) (Scavia and Fahnenstiel 1987). The role of stratification in limiting the pool of available nutrients to those in the epilimnion is well known. Lam et al. (1983) demonstrate convincingly how interannual variablity in the oxygen depletion within the hypolimnion of Lake Erie's Central Basin is dominated by physical processes. 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; similar arguments have been proposed by Harris (1983) to explain the lack of productivity in nutrient-rich Hamilton Harbour. Since most external sources of nutrients input at the shore, it has been observed that portions of the nearshore zone are eutrophic while the offshore zones are oligotrophic. The Bay of Quinte region of Lake Ontario is one of several examples (Minns et al. 1986). 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 (see the recent multidisciplinary study of such processes on the north shore of Lake Ontario (Lean, 1987)).

Another 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 (Bell and Eadie, 1983). 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. These studies are being taken up vigorously by limnologists and oceanographers (Lesht and Hawley (1987), Simons and Shertzer (1986), Bedford et al. (1983), Hamblin et al. (1987)), and once again we can anticipate useful scientific exchanges between the two communities.

A significant warming of the climate will produce changes in the Great Lakes that may be important to anticipate. If, for example, the winter temperature of Lake Ontario remains above 4°C, convective instability will no longer add to the wind stirring of the lake and thorough vertical mixing in the fall may not always occur. Dissolved oxygen levels in the deep waters could move substantially lower than present autumn minima with potential implications for fish. The lake's capacity to absorb nutrient inputs could be affected and management strategies would have to be altered. Water supply to and evaporation from the lakes would be changed with potential ramifications for shoreline uses, power generation, and shipping. An attempt to list possible effects of climate change on the Great Lakes Basin has been published by Meisner et al. 1987. Computer simulations of the impact of climate warming on water levels of the Great Lakes form the basis of a recent report by the Great Lakes Environmental Research Laboratory in Ann Arbor (Croley and Hartmann 1988).

Whether or not lake system models are the managerial tools some people claim them to be, they represent our best efforts to synthesize our knowledge of lake behaviour into a coherent whole. As a means of interpretation and analysis of field data, they are invaluable. Simons, more thoroughly than most, has studied the limitations of systems modelling (Simons and Lam, 1980) based on numerical hydrodynamical models. He recognized that the parameterization of vertical turbulent fluxes in terms of mean field variables was a weak point in the system (Simons, 1974). It still is. The inclusion of sediment-water interactions is a formidable challenge (Simons and Schertzer (1986)).

CONCLUSIONS

It is clear, from "management" considerations alone, that there is no lack of challenging physical problems to be investigated. While we have mentioned from time to time the advantages of working in the Great Lakes compared with oceanic studies, no one 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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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, reprinted with the authors' permission)

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. Figure contributed by W.M. Schertzer, National Water Research Institute.

Figure 3.

Map of the Great Lakes summarizing Harrington's (1894) surface drift studies.

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, reprinted with the authors' permission). 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, reprinted with the authors' permission). 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 or the surface $4^{\circ}C$ isotherm as a function of April 1st water temperature (Deep region east of $77^{\circ}45'$W longitude in Lake Ontario). (Rodgers, 1987, reprinted with the author's permission).

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 (a) and including the earth's rotation (b). The distance between tick marks is 5 km (Rao and Schwab, 1976, reprinted with the authors' permission).

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, reprinted with the author's permission).

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, reprinted with the authors' permission).

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. Figures 10a and 10b are reproduced from Bennett (1974) with the author's permission.

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, reprinted with the authors' permission).

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, reprinted with the authors' permission).

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, reprinted with the authors' permission). 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 picture can be viewed as motion in the hypolimnion; an oppositely directed current would be observed in the epilimnion. Both Figures 14a and 14b are reproduced with the permission of C.H. Mortimer, University of Wisconsin at Milwaukee.

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 1987, reprinted with the author's permission)

Figure 16.

Lagrangian drifter experiment 15 October to 20 November, 1984, 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, reprinted with the authors' permission)

Figure 17.

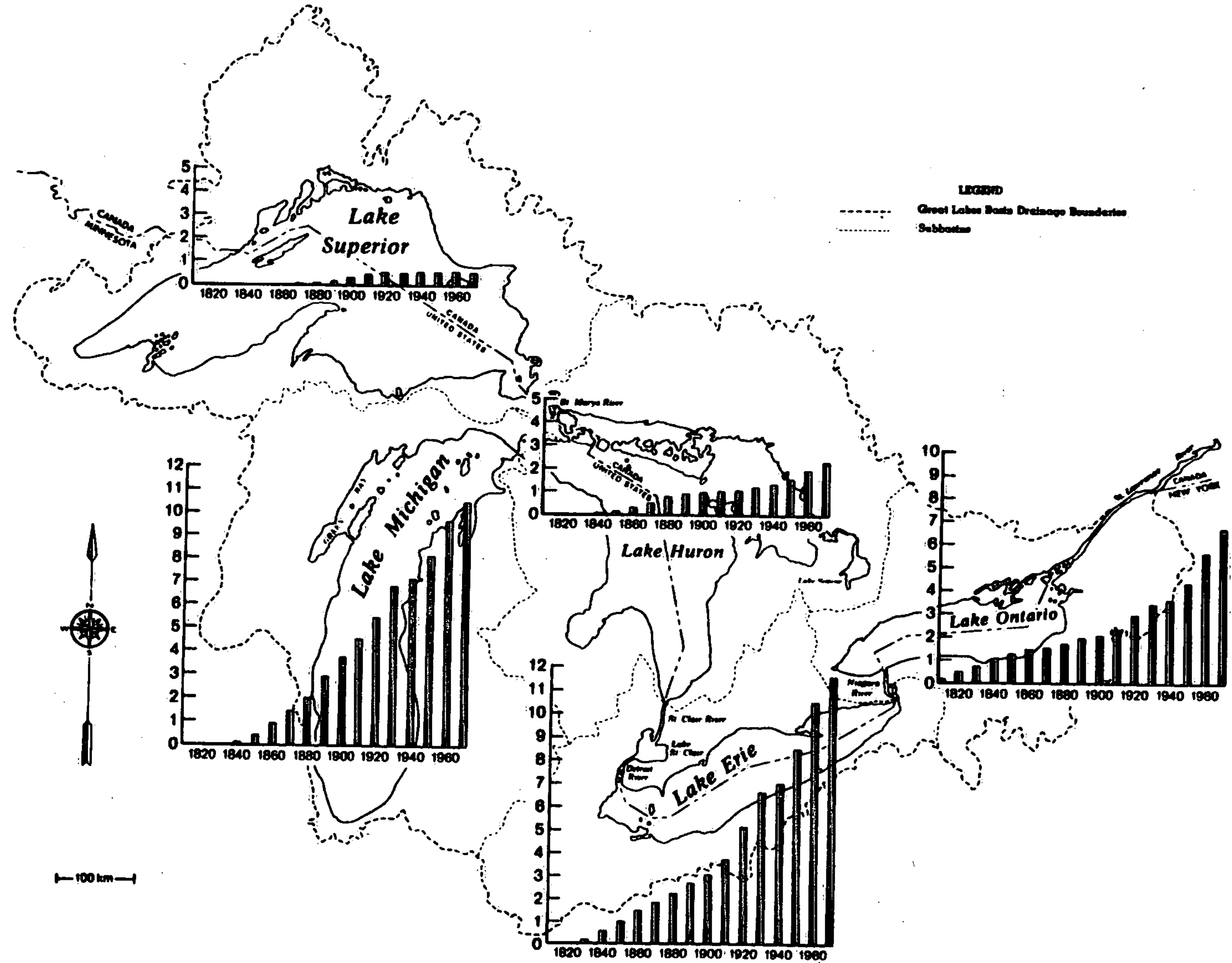
Distribution of mercury (corrected for the presence of quartz) in the surficial sediments of Lake Ontario. This distribution is consistent with a source in the Niagara River and a persistent eastwards flow along the south shore. (Thomas, 1972, reprinted with the author's permission).

Figure 18.

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, reprinted with the author's permission).

Figure 19.

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, reprinted with the authors' permission).


Lake Superior
Lake Michigan
Lake Huron
Lake Erie
Lake Ontario
CANADA
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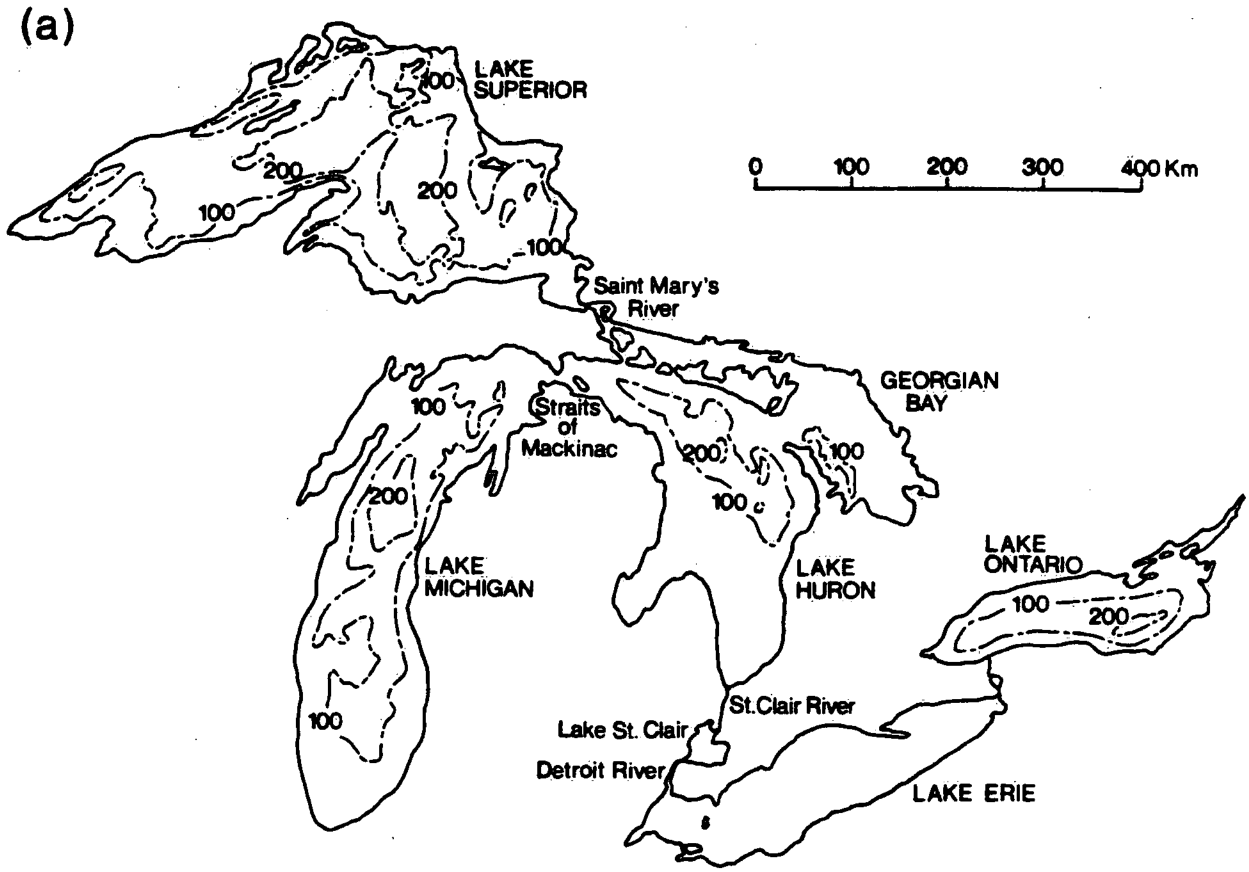
UNITED STATES
CANADA
NEW YORK
St. Marys River
St. Clair River
Lake St. Clair
Detroit River
Niagara River
1820 1840 1860 1880 1900 1920 1940 1960
LEGEND
Great Lakes Basin Drainage Boundaries
Subbasins
100 km

F1

F2


(a)
LAKE SUPERIOR
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Saint Mary's River
GEORGIAN BAY
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Straits of Mackinac
200
100
200
100
LAKE MICHIGAN
LAKE HURON
LAKE ONTARIO
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200
100
St.Clair River
Lake St. Clair
Detroit River
LAKE ERIE

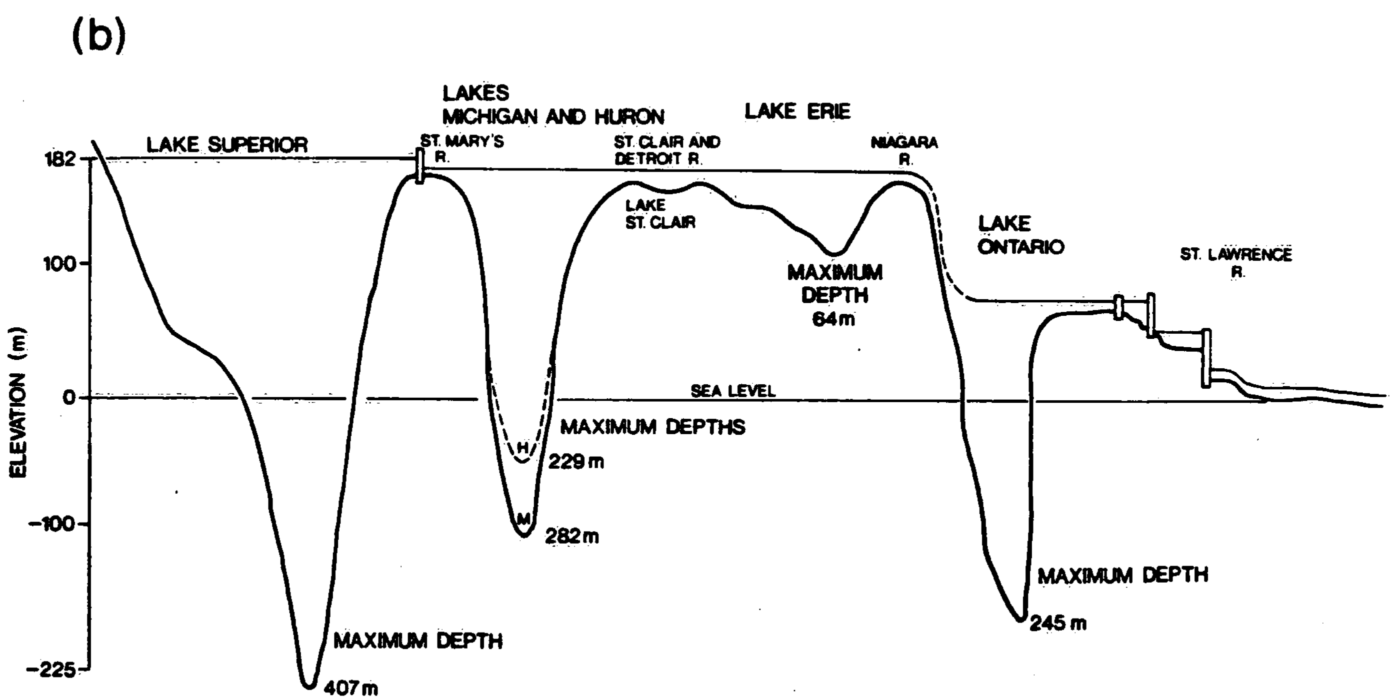
(b)
LAKES MICHIGAN AND HURON
LAKE ERIE
LAKE SUPERIOR
ST. MARY'S R.
ST. CLAIR AND DETROIT R.
NIAGARA R.
182
LAKE ST. CLAIR
LAKE ONTARIO
100
MAXIMUM DEPTH 64m
ST. LAWRENCE R.
ELEVATION (m)
0
SEA LEVEL
MAXIMUM DEPTHS
H
229m
-100
M
282m
MAXIMUM DEPTH
245m
MAXIMUM DEPTH
-225
407m

Fig 3


Ashland
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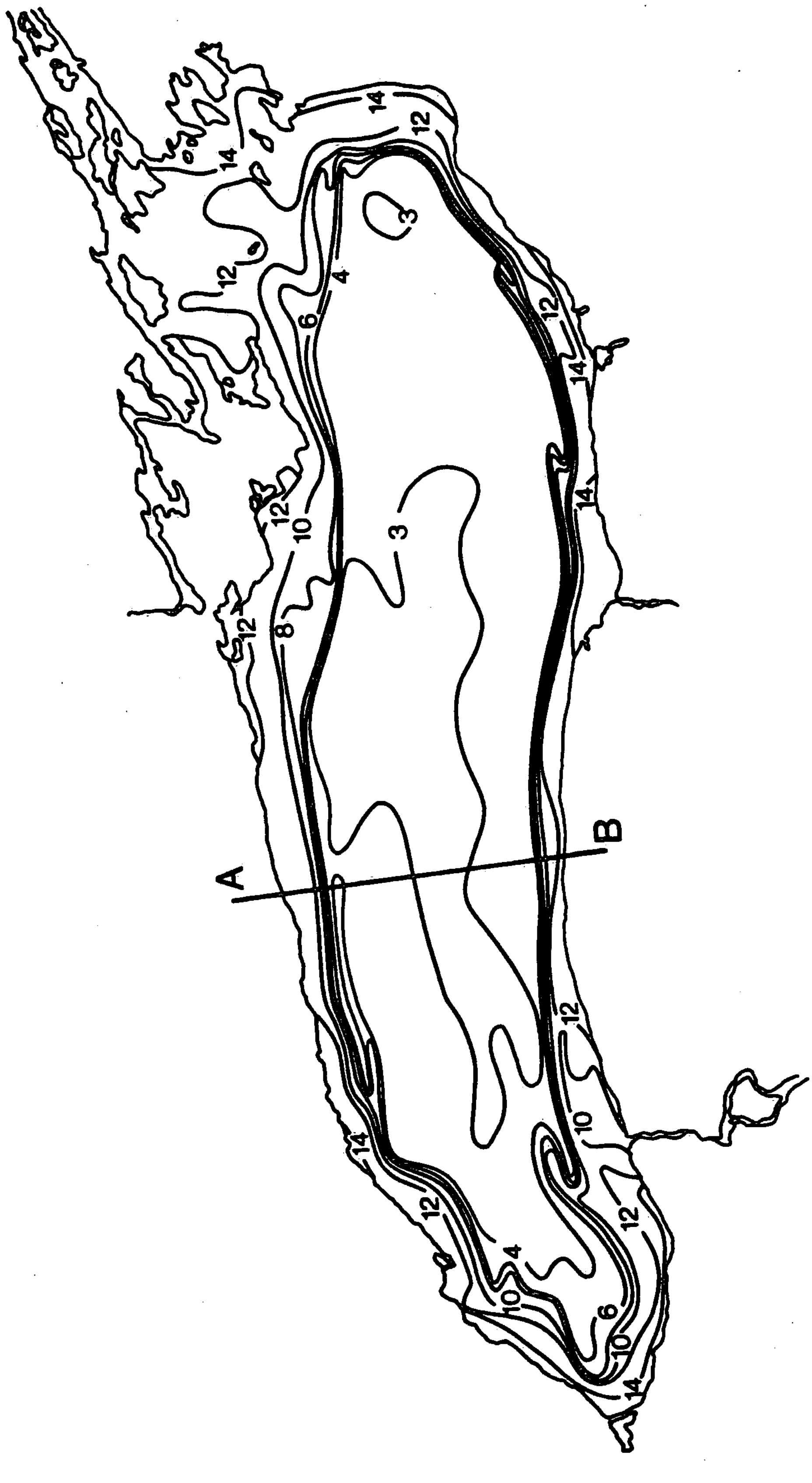
Southampton
Kingston
Toronto
Rochester
Bay City
Grand Haven
Milwaukee
Buffalo
Detroit
Chicago
Cleveland

Fig 4



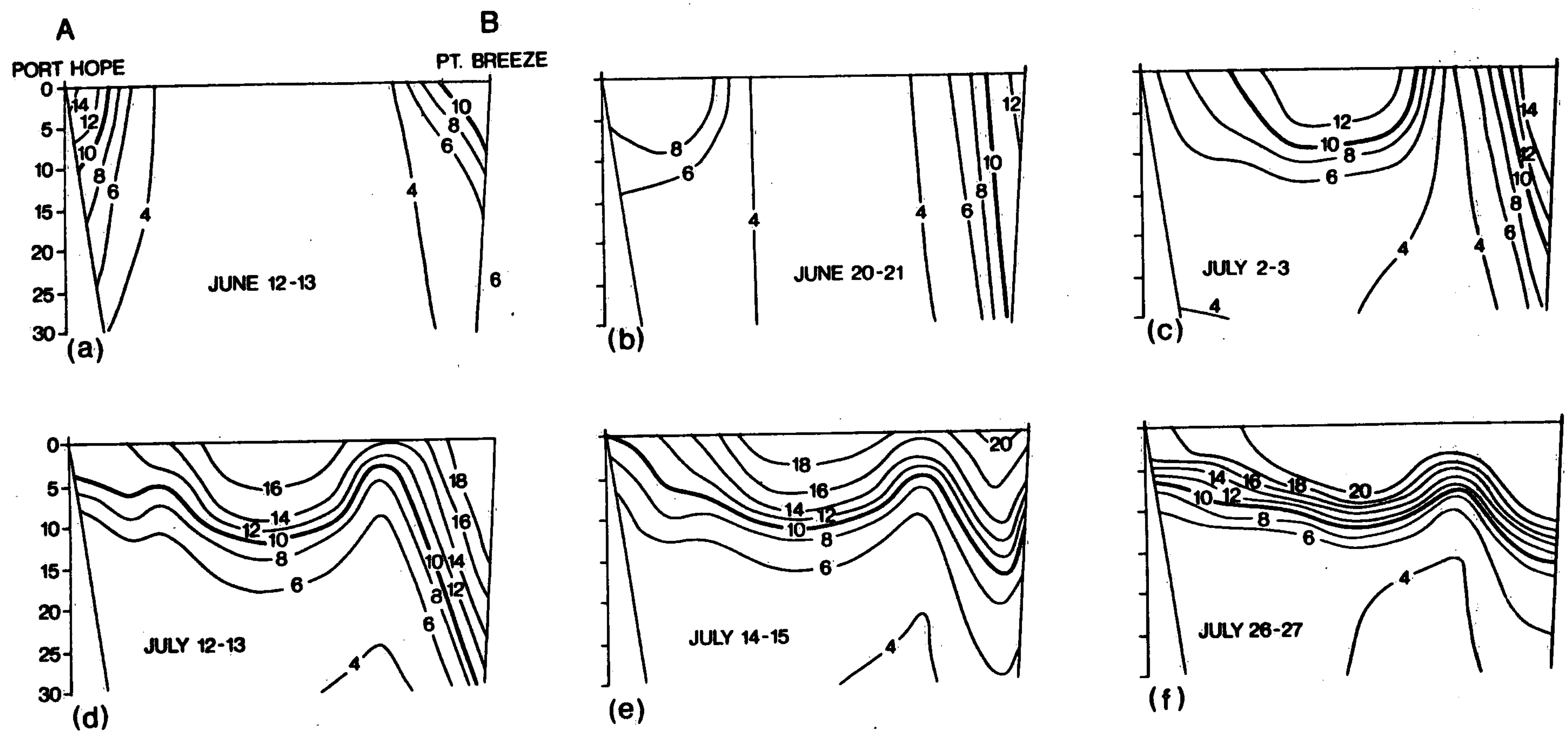

A
B
PORT HOPE
PT. BREEZE
JUNE 12-13
JUNE 20-21
JULY 2-3
JULY 12-13
JULY 14-15
JULY 26-27
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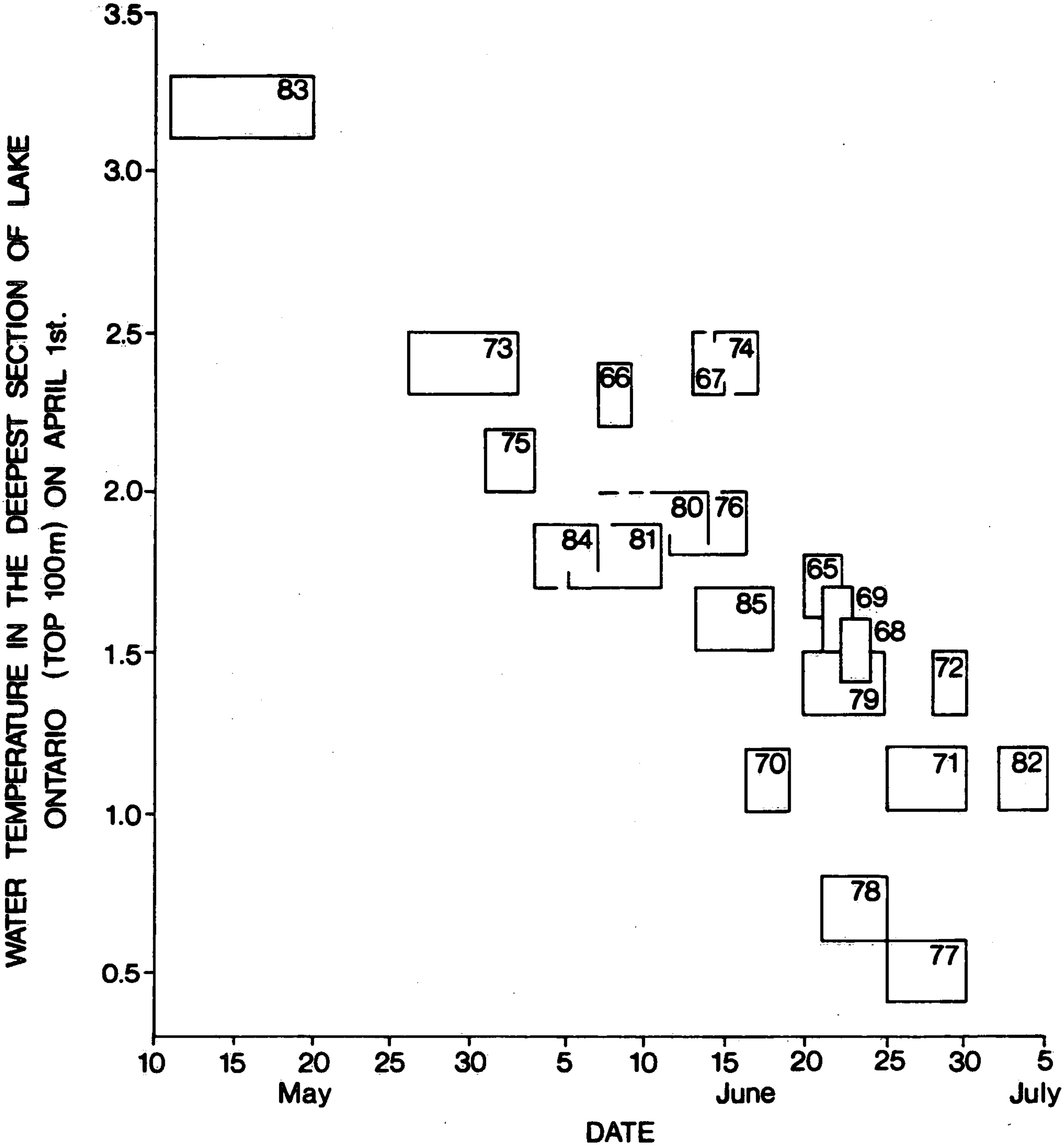
Fig 5

Fig 6



DATE OF FULL STRATIFICATION OR DISAPPEARANCE OF THE SURFACE 4°C ISOTHERM AS FUNCTION OF APRIL 1st WATER TEMPERATURE (Deep region east of 77°45'W. longitude in Lake Ontario)

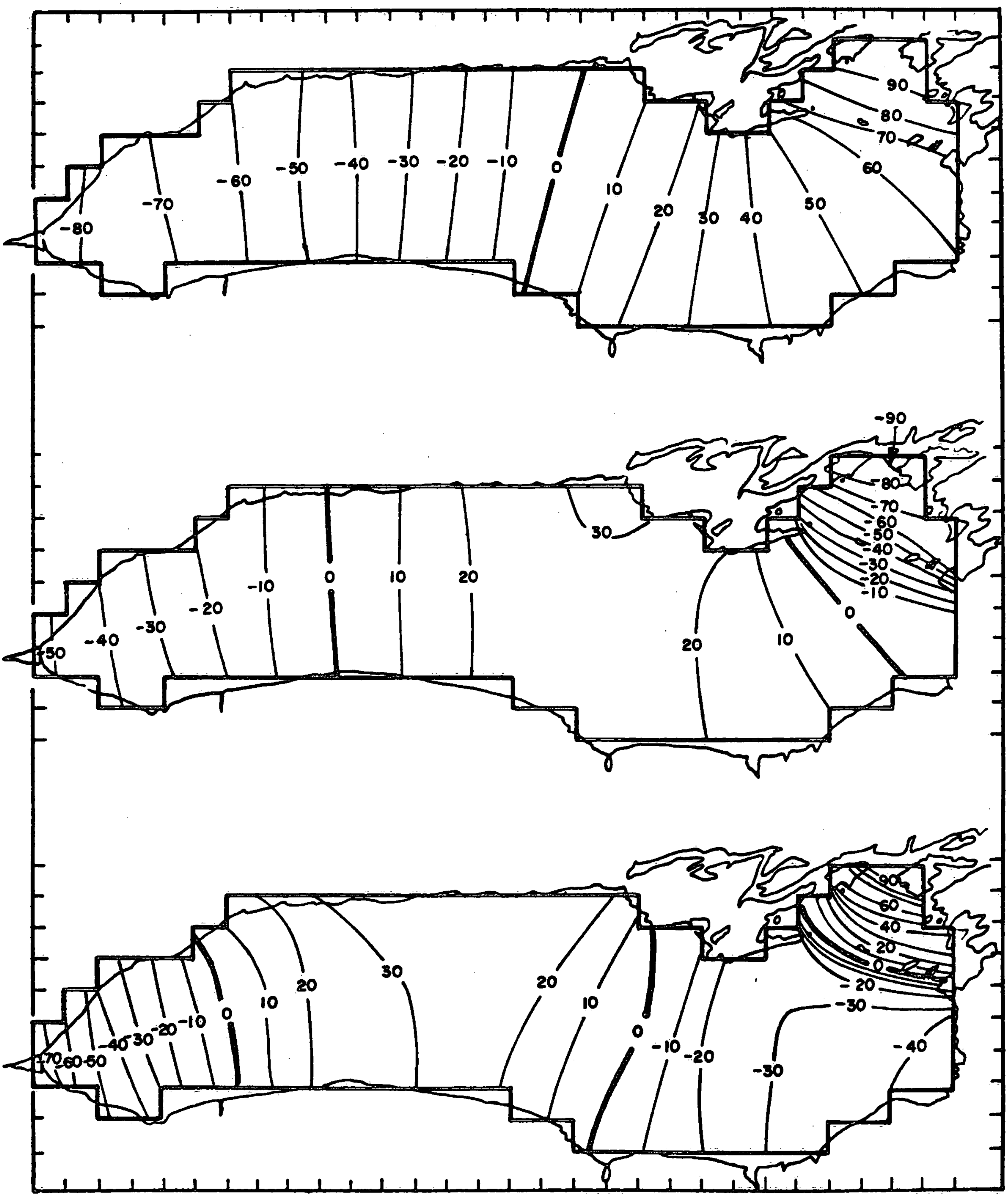


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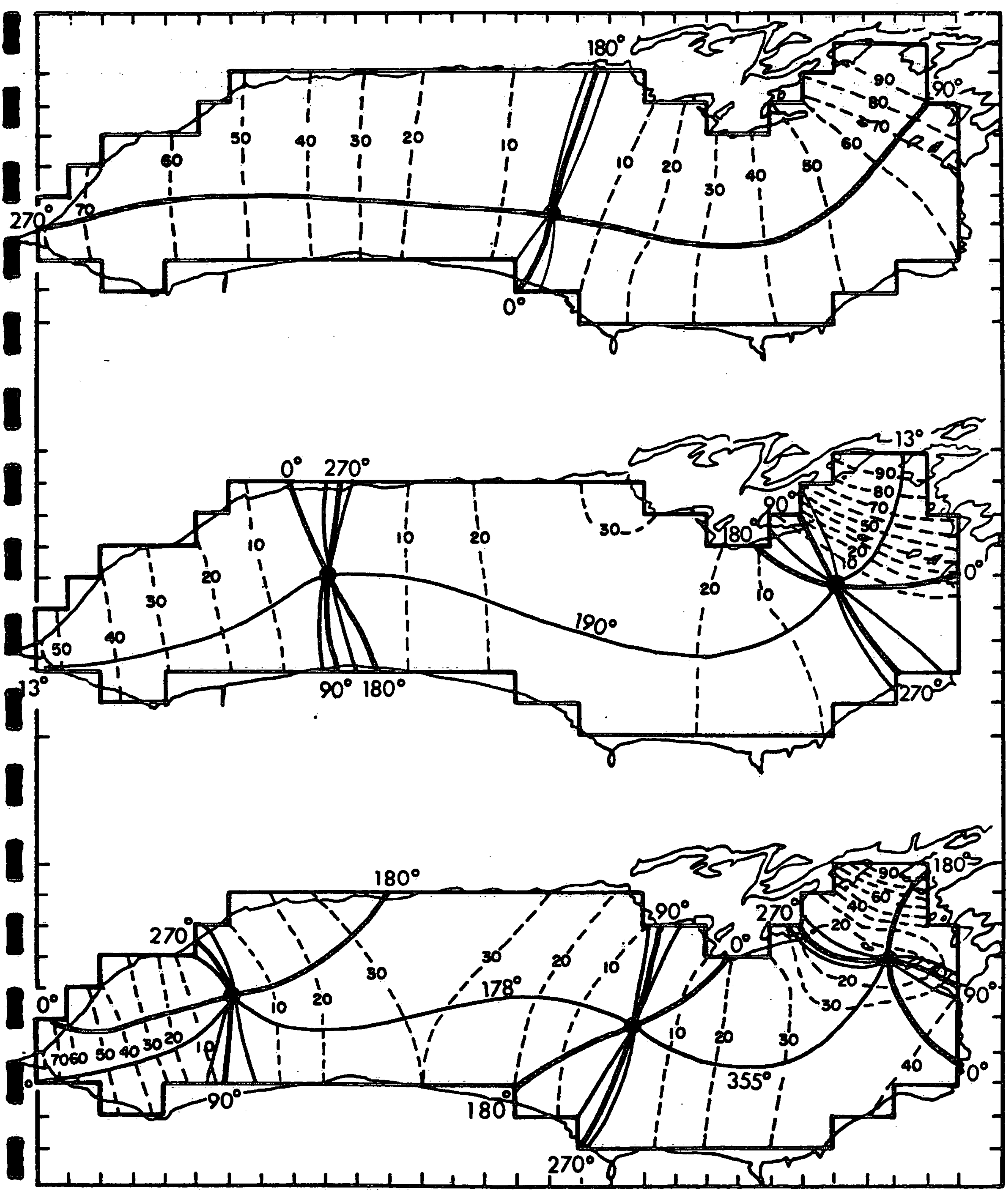
Fig 7a

Fig 7b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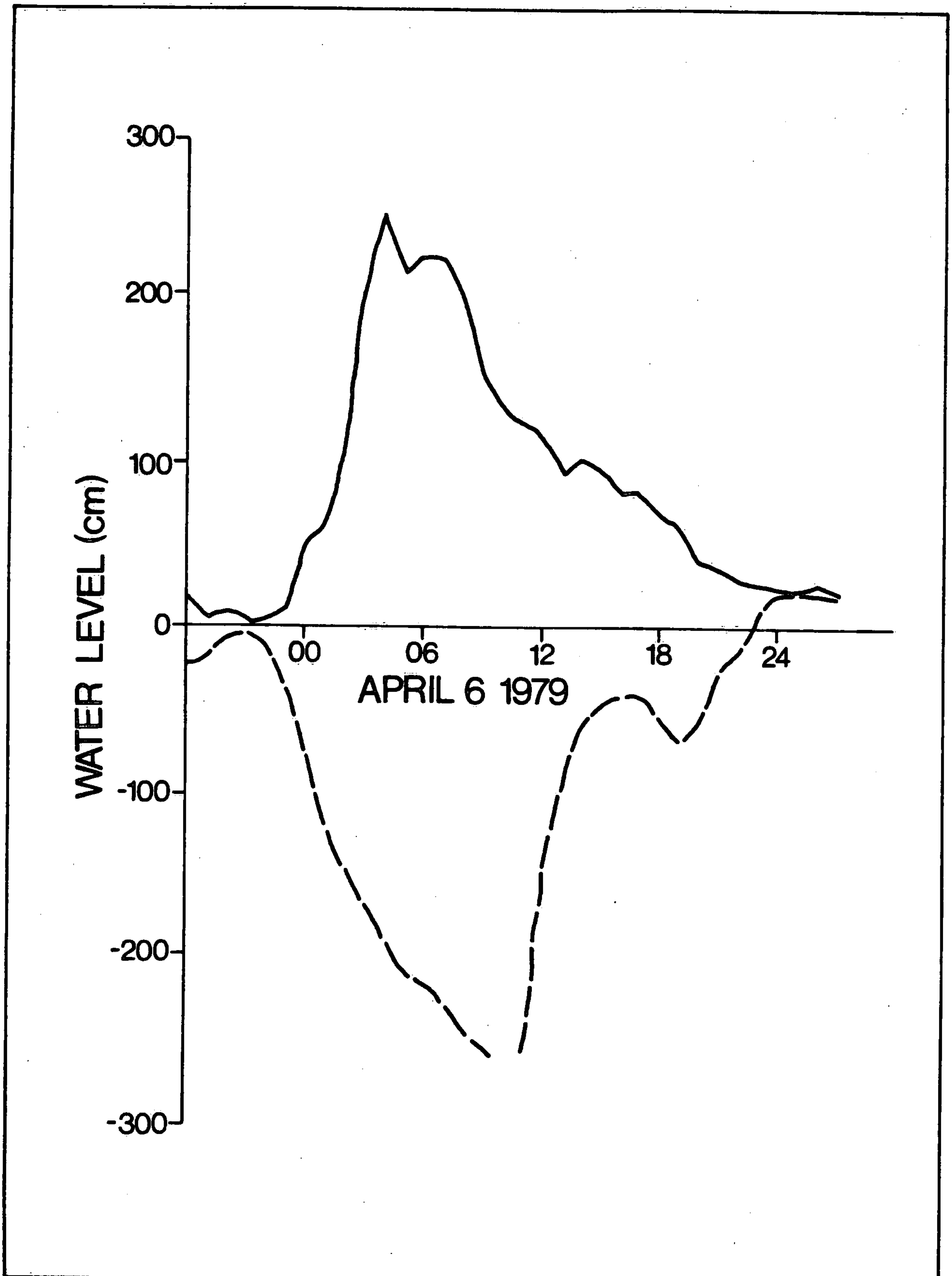
178°
355°
270°

Fig 8



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-100
-200
-300
WATER LEVEL (cm)
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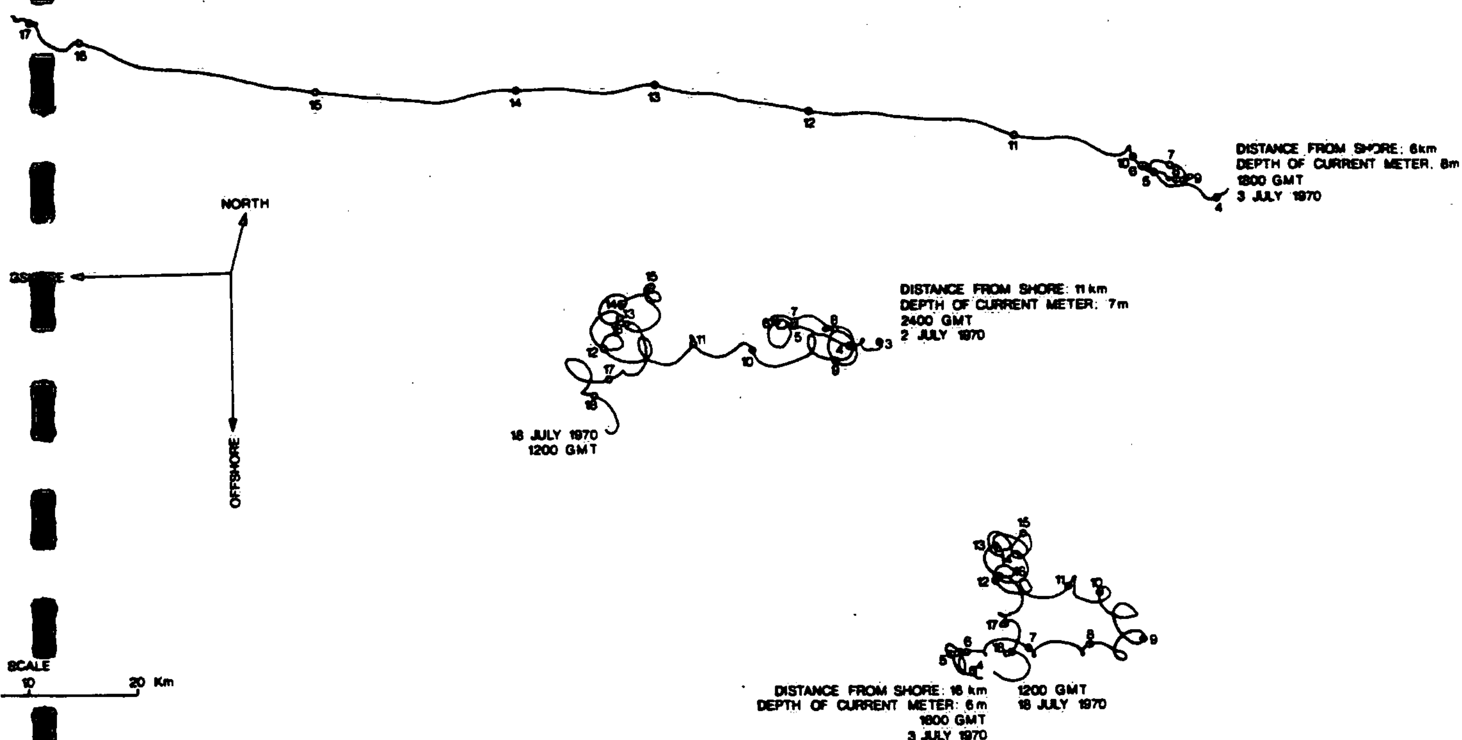
12
18
24
APRIL 6 1979

Fig 9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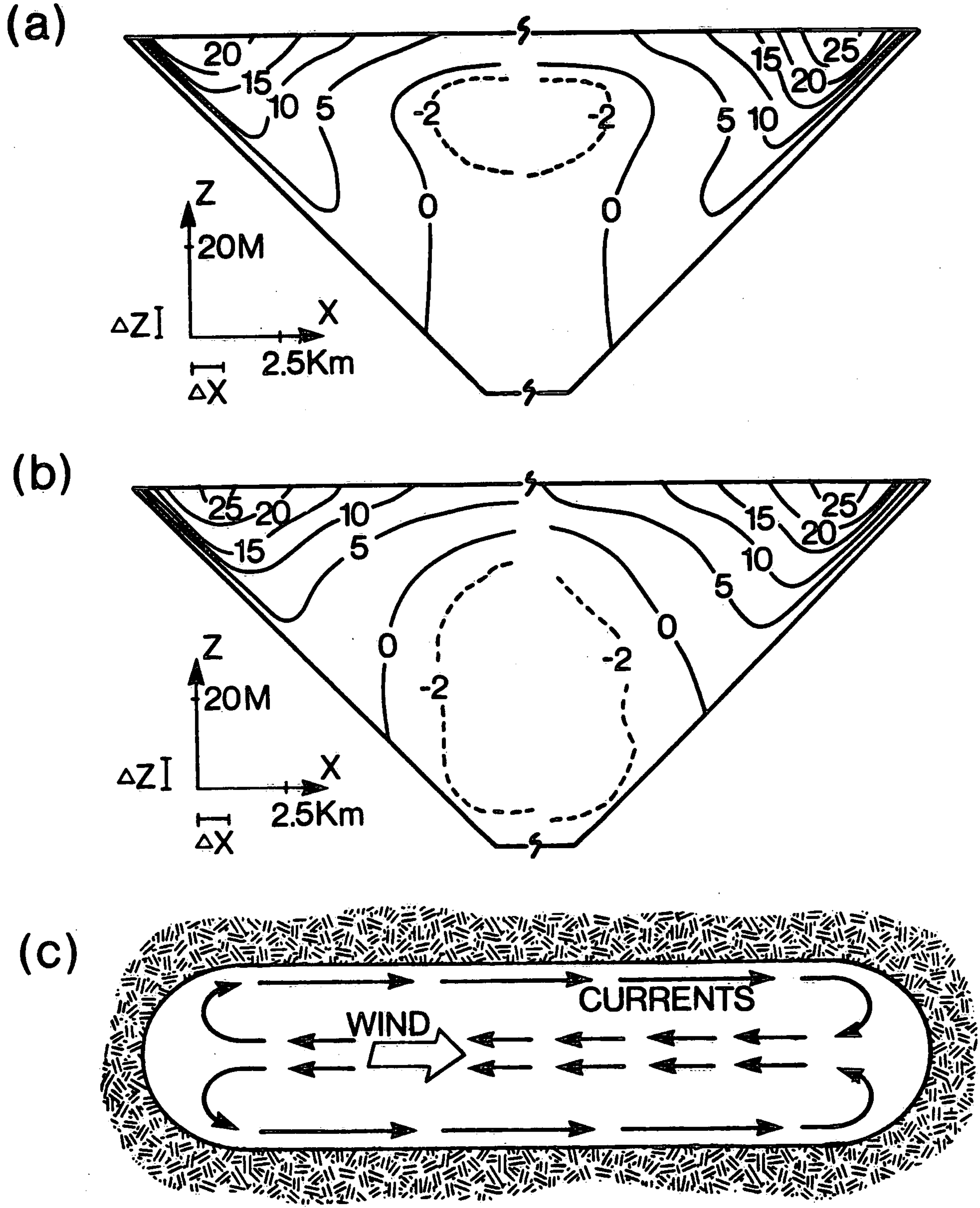
DEPTH OF CURRENT METER: 8m
1800 GMT
3 JULY 1970
NORTH
OFFSHORE
DISTANCE FROM SHORE: 11 km
DEPTH OF CURRENT METER: 7m
2400 GMT
2 JULY 1970
18 JULY 1970
1200 GMT
SCALE
10
20 Km
DISTANCE FROM SHORE: 16 km
DEPTH OF CURRENT METER: 6 m
1800 GMT
3 JULY 1970
1200 GMT
18 JULY 1970

Fig 10



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2.5Km
ΔX
(b)
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20
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5
15
25
20
10
5
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0
-2
-2
Z
20M
ΔZ
X
2.5Km
ΔX
(c)
CURRENTS
WIND

Fig 11

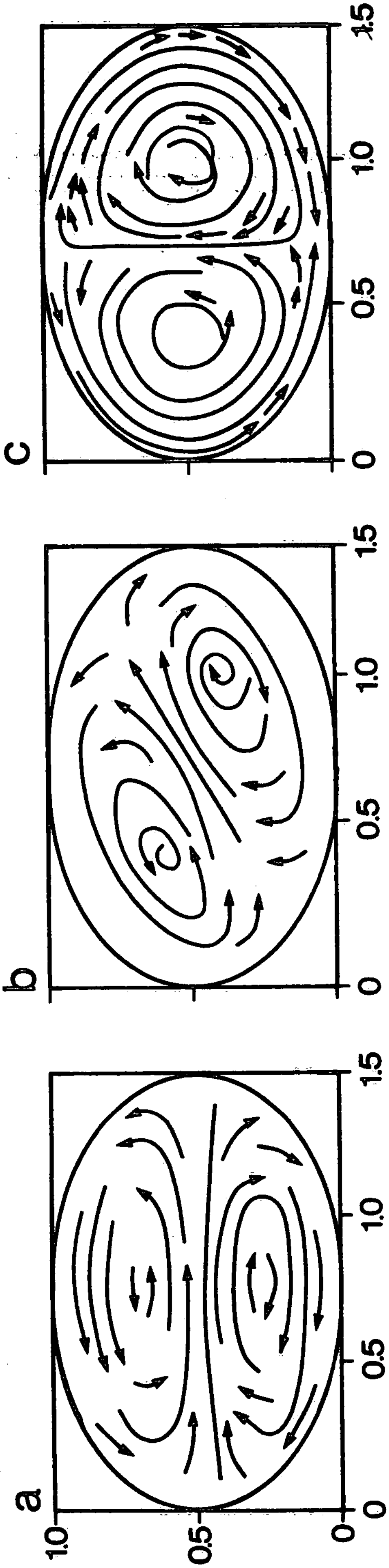
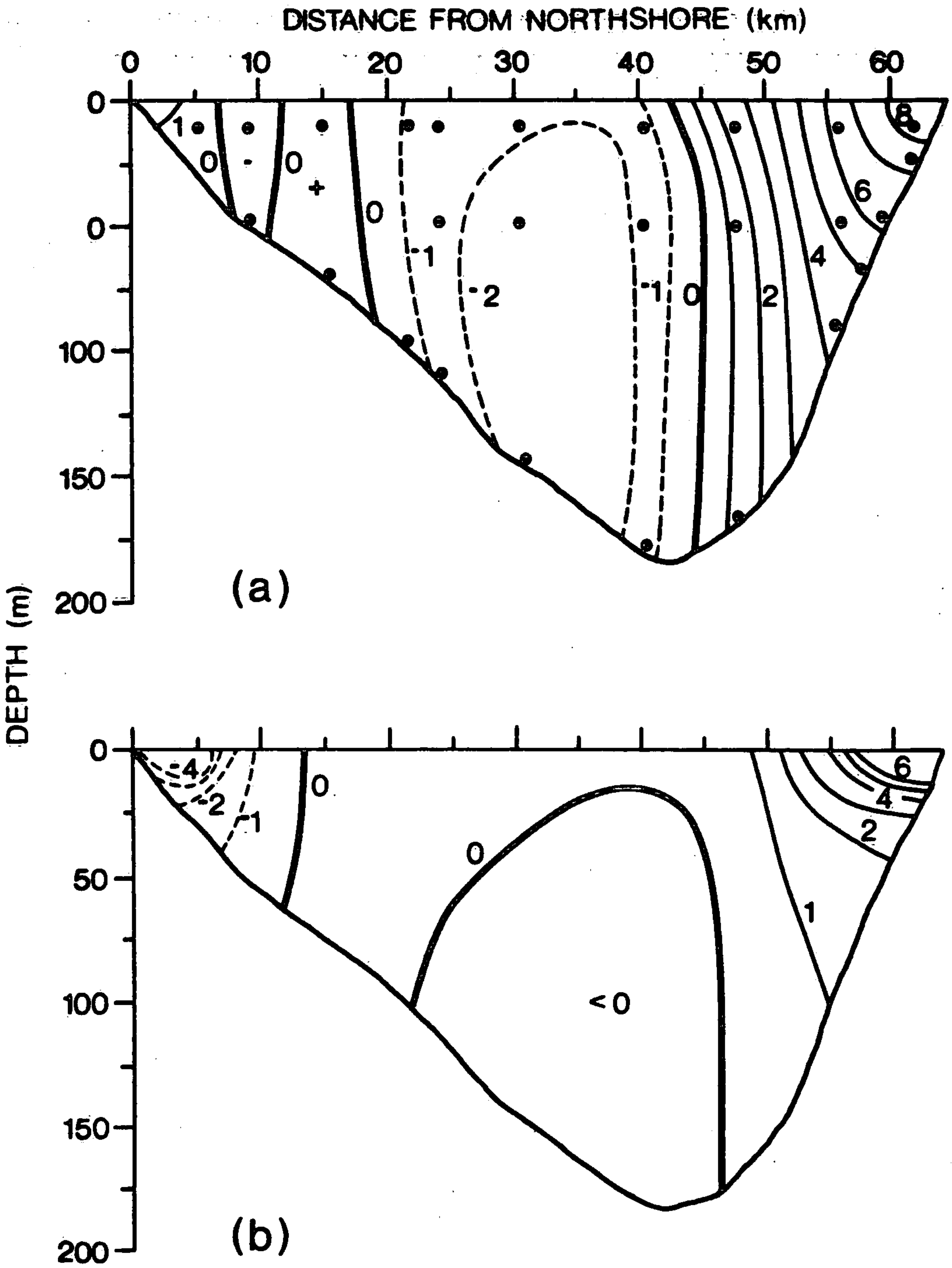


Fig 12



DISTANCE FROM NORTHSHORE (km)
0
10
20
30
40
50
60
DEPTH (m)
0
50
100
150
200
(a)
(b)
<0

Fig 13

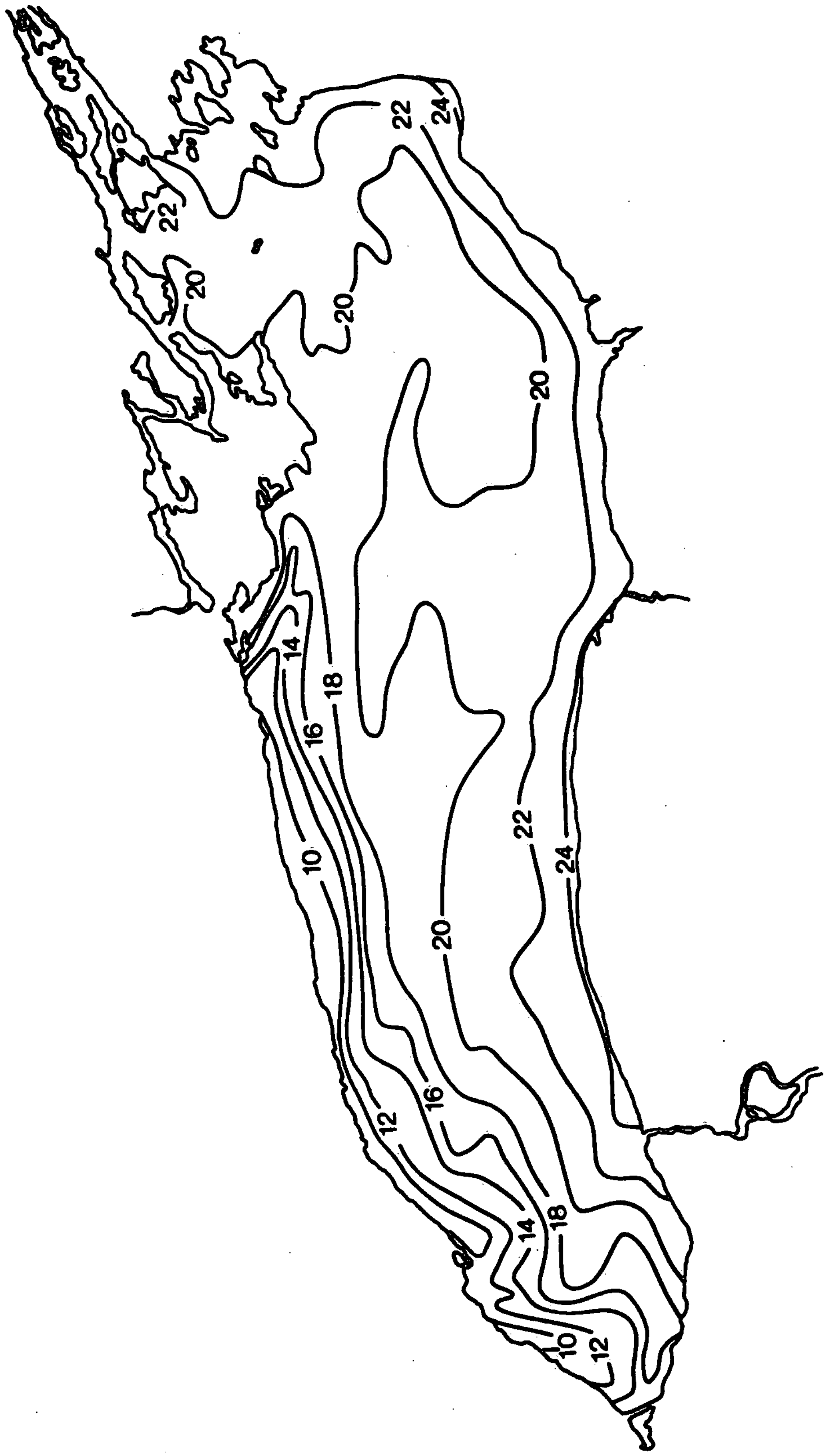


Fig 14 a

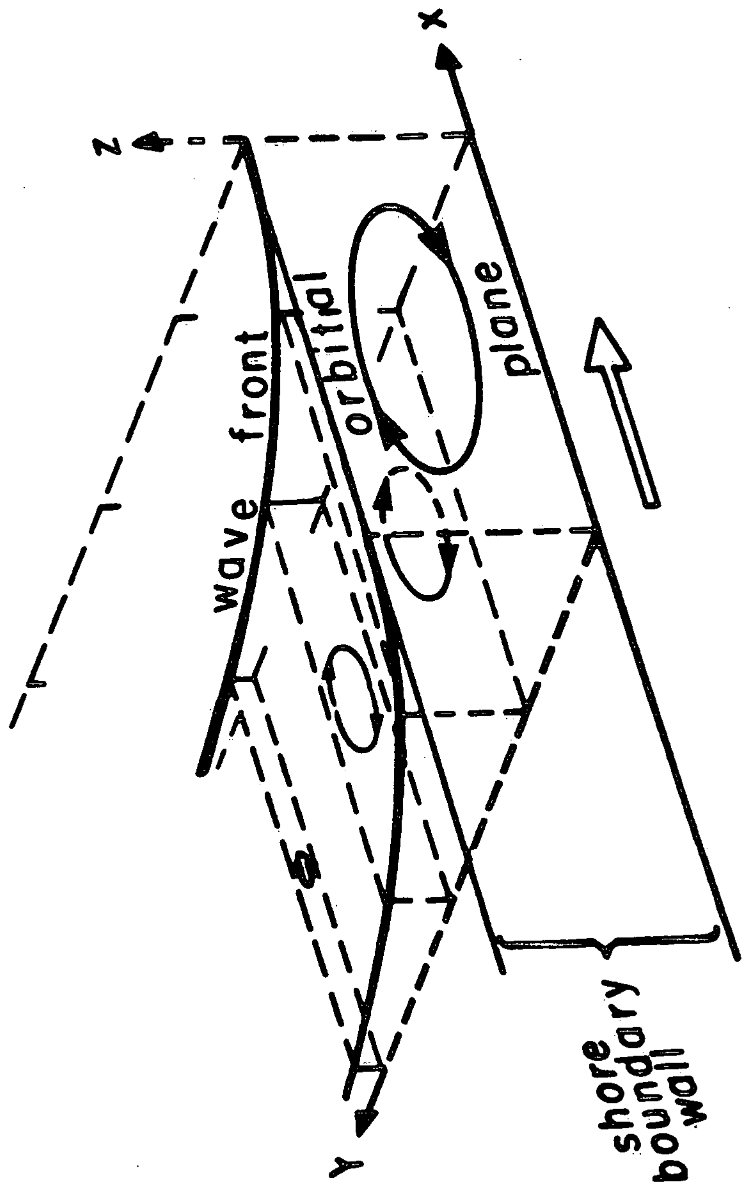
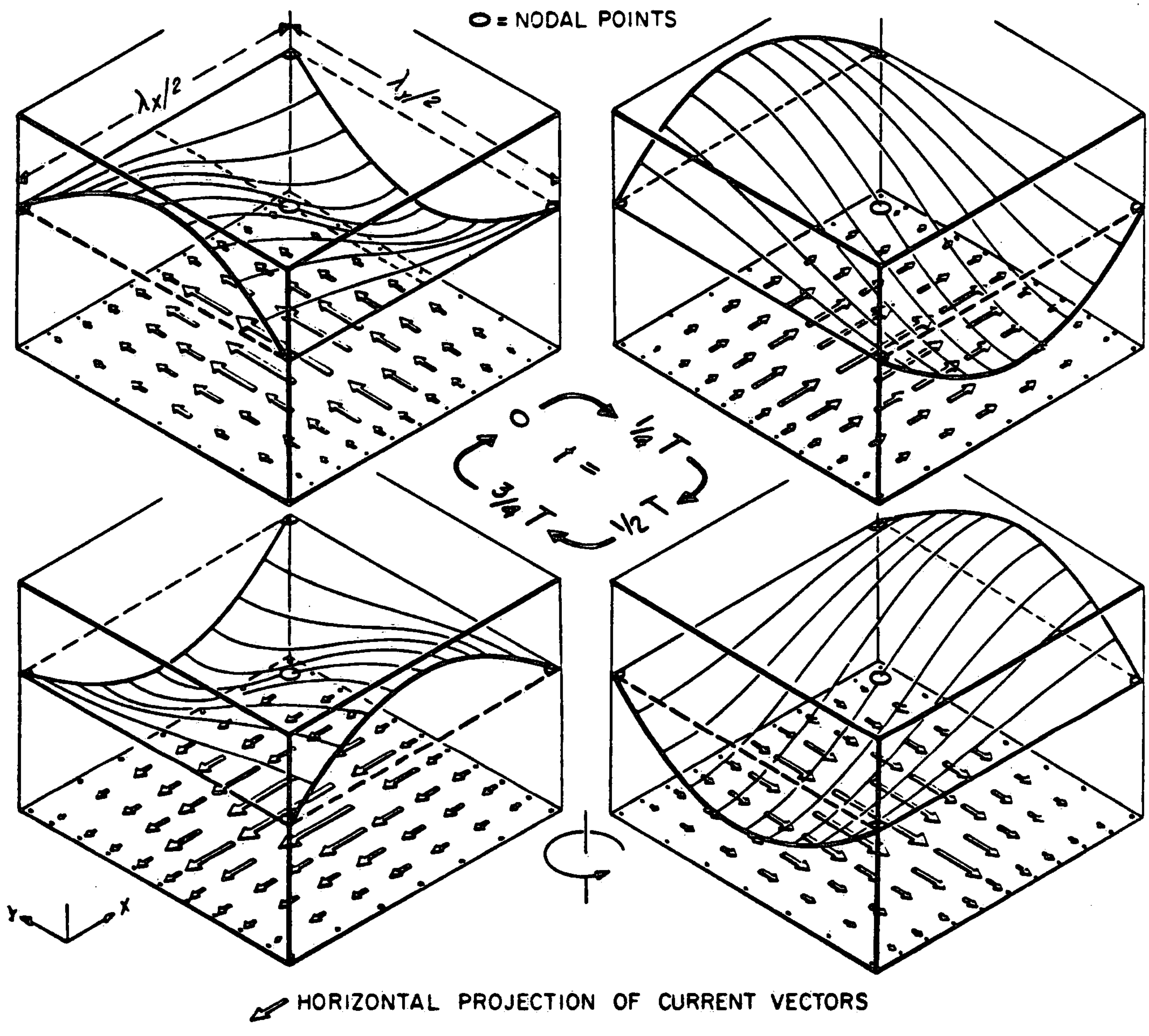
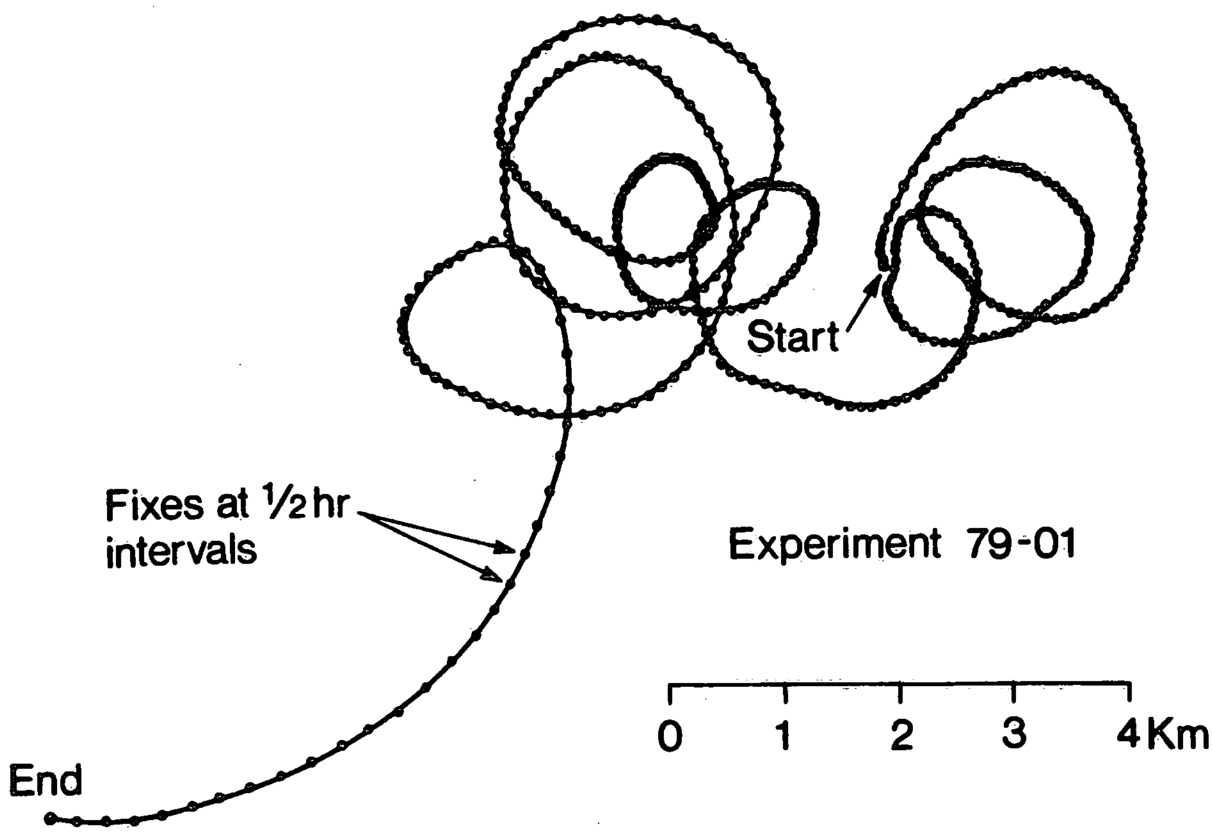


Fig 14b



HORIZONTAL PROJECTION OF CURRENT VECTORS

Fig 15



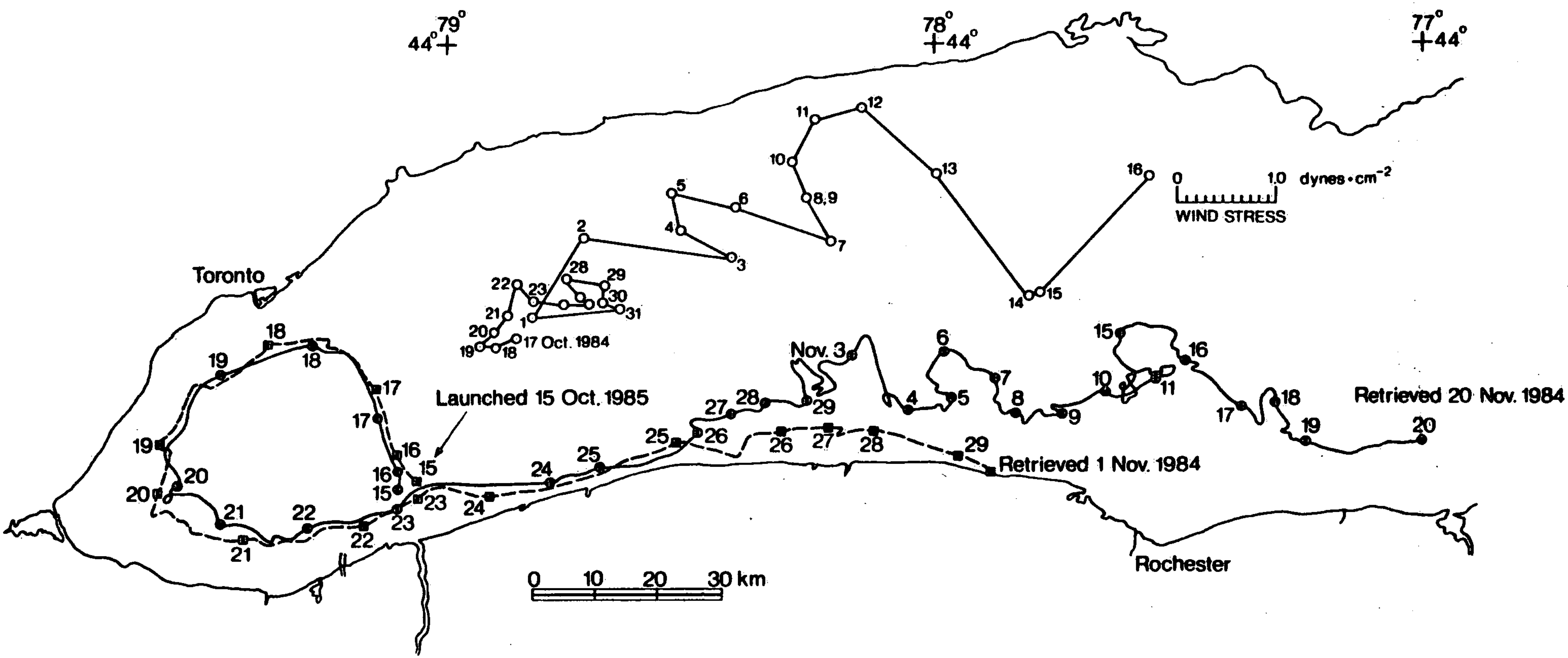

79°
44°
78°
44°
77°
44°
Toronto
Rochester
WIND STRESS
0
1.0
dynes • cm^{-2}
0
10
20
30 km
Launched 15 Oct. 1985
17 Oct. 1984
Nov. 3
Retrieved 1 Nov. 1984
Retrieved 20 Nov. 1984

Fig 16

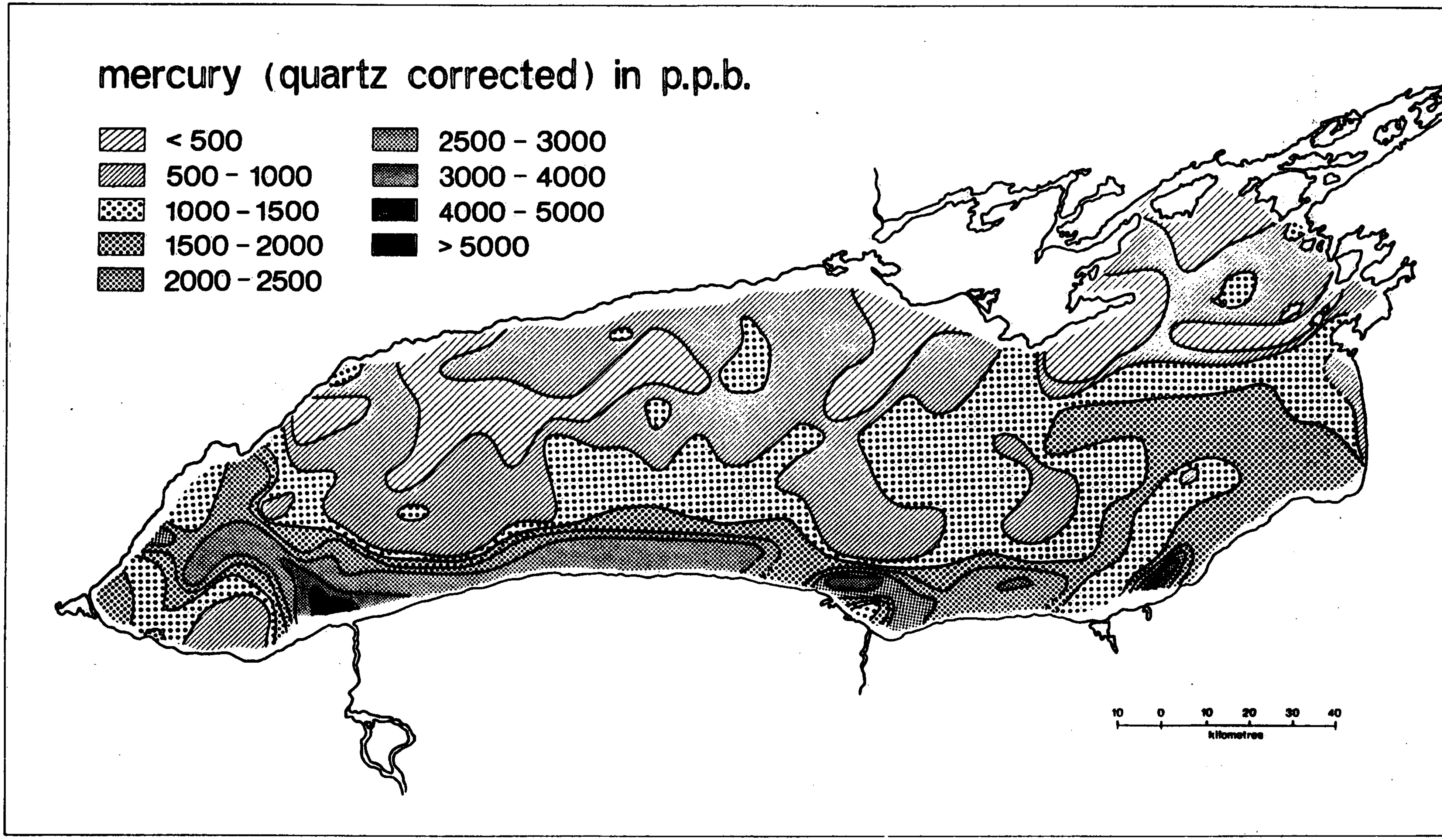

mercury (quartz corrected) in p.p.b.
< 500
500 - 1000
1000 - 1500
1500 - 2000
2000 - 2500
2500 - 3000
3000 - 4000
4000 - 5000
> 5000
10 0 10 20 30 40
kilometres

Fig 17

Fig 18

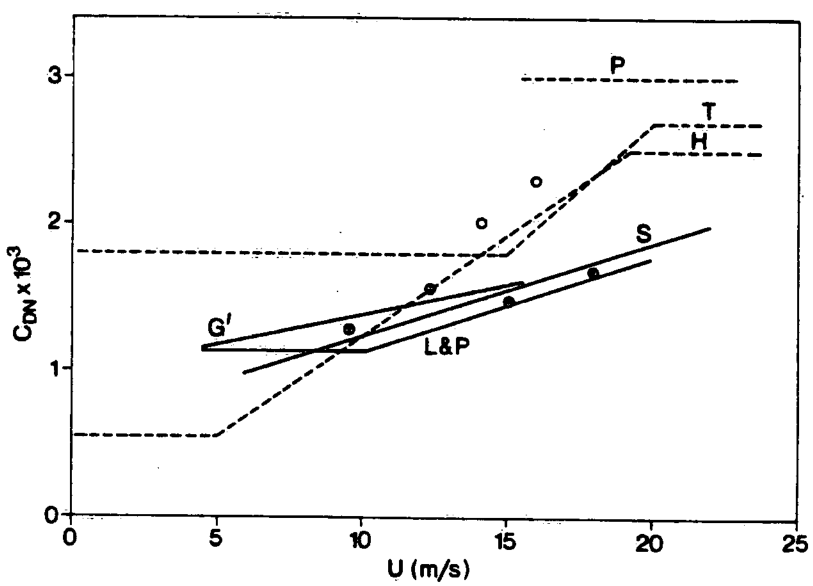
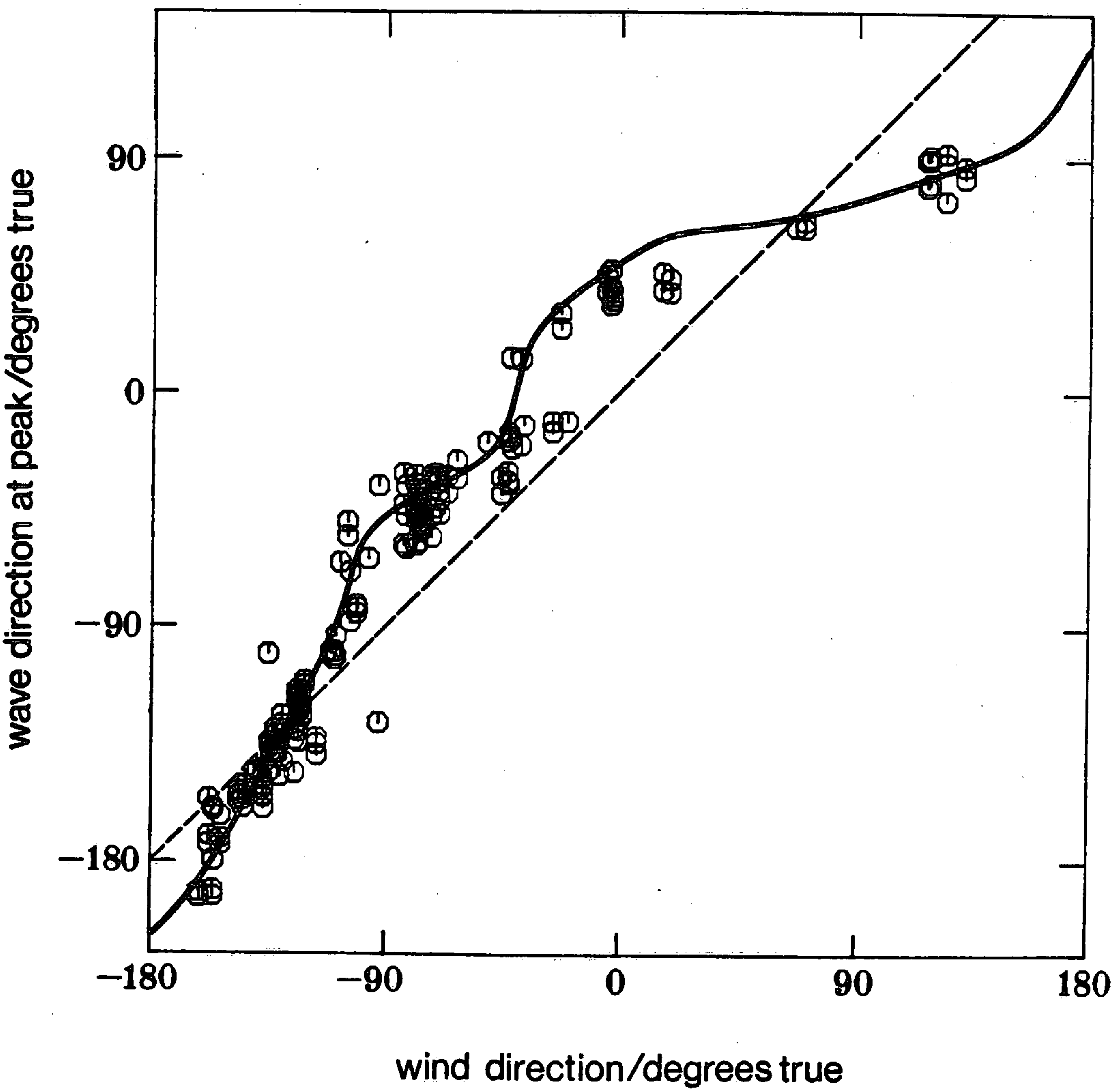


Fig 19



wave direction at peak/degrees true
90
0
−90
−180
−180
−90
0
90
180
wind direction/degrees true