# AN ASSESSMENT OF CURRENT UNDERSTANDING OF THE PHYSICAL BEHAVIOUR OF LAKE ONTARIO WITH REFERENCE TO CONTAMINANT PATHWAYS AND CLIMATE CHANGE

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# ABSTRACT

Current understanding of the physical behaviour of Lake Ontario is assessed. In particular, the role of water movements in the distribution and fate of contaminants is discussed, and a state- of-the-art survey is given of our ability to anticipate the results of global climate warming on the Great Lakes. In the past two decades, the general features of large lake circulation and mixing have been successfully delineated, although detailed studies of a climatological nature will be required for particular sites of interest or concern. More sophisticated models of thermal structure will be needed to assess the potential consequences of climate warming particularly in the matter of convective overturning. The process of "sediment focussing", so strongly linked to the fate of many organic contaminants is only recently amenable to study with instruments that respect the time and space scales of resuspension and settling. The rates of transfer of gases and contaminants across the air-water interface are known to depend on wind and wave conditions; this dependence is being explored. Experience over the past 20 years has consistently shown that large-lake studies of chemical and biological processes are far more readily interpreted if there is an adequate base of concurrent physical measurements.

## RÉSUMÉ

Cette étude évalue l'état actuel des connaissances relatives à la physique du lac Ontario. En particulier, elle examine l'effet des mouvements de l'eau sur la distribution et le devenir des contaminants et fait une présentation détaillée des moyens dont nous disposons pour prévoir les effets du réchauffement de la Terre sur les Grands Lacs.

Au cours des vingt dernières années, les caractéristiques générales de la circulation et du mélange des eaux dans les lacs de grandes dimensions ont été déterminées avec succès, mais des études climatologiques détaillées s'avéreront nécessaires dans le cas de certaines zones qui présentent un intérêt particulier ou qui sont sources de préoccupations. Des modèles plus sophistiqués de structure thermique des lacs seront nécessaires pour évaluer les conséquences éventuelles du réchauffement du climat relativement, en particulier, au mélange des eaux par convection. En outre, ce n'est que depuis peu que nous pouvons étudier le processus de la concentration des sédiments, très étroitement relié au devenir de

plusieurs contaminants organiques, avec des instruments qui permettent de respecter les échelles de temps et d'espace relatives à la remise en suspension et à la sédimentation des contaminants. On sait, par ailleurs, que les conditions de vent et les vagues ont un effet sur le taux de transfert des gaz et des contaminants à travers l'interface air-eau. Cette relation est aussi examinée dans le présent article.

Les recherches effectuées ces vingt dernières années ont montré que l'interprétation des études portant sur les processus chimiques et biologiques dans les lacs de grandes dimensions est toujours grandement facilitée quand de bonnes données physiques concommitantes sont disponibles.

## Introduction

Recent advances in the understanding of both large and small scale physical processes in the Great Lakes have been reviewed (Boyce et al., 1989; Csanady, 1984); monographs by Simons (1980) and Csanady (1982) summarize the relevant theory. A critical review of the lake system modelling (biology plus chemistry plus physics) carried out under the leadership of T.J. Simons has been published (NWRI, 1988). These documents provide a concise and current summary of both the application and theory of large-lake physics.

This paper provides an overview of the central themes of physical limnology as they relate to the concerns of biology and chemistry reported elsewhere in this volume. We present first a brief statement of the consequences of the simultaneous presence of phenomena operating over a continuum of time and space scales. Next we describe the thermal structure of Lake Ontario because of its importance in defining or controlling ecological niches. Then we present an overview of wind-driven water movements, the agents of internal redistribution of dissolved and suspended materials. In the remaining two sections of the paper, we discuss the physical components of two major environmental concerns, the pathways and fate of toxic contaminants, and the response of the lake to the anticipated global warming. The paper points out that large lake measurements unsupported by appropriate physical insights and data may be impossible to interpret and thereby argues for a multidisciplinary approach.

## Time and Space Scales; Numerical Simulations

Lake systems operate in a continuum of time and space scales. Time scales of concern to the study of Lake Ontario range from the geological (10000 - 100000 year ice-age cycles) to a scale of seconds associated with small-scale turbulence. Prominent in this large range are the seasonal or annual cycles, the average time between major meteorological events (several days) and the daily cycle. It is not always possible to disassociate the effects of one cycle or time scale from those of another. In this present review, we are particularly concerned with "long-term" trends in lake behaviour extending over many years where the annual increment of change associated with the trend is very much smaller than the changes imposed by the annual cycle or indeed by the substantial year-to-year variability in the annual cycles themselves. Reliable detection of trends or other long-term variations in "noisy" data requires a minimum length of record that depends both on the sampling methods and on the variability of the data. Unless the sampling methods and subsequent interpretations allow properly for all possible sources of variability, trends may be wrongly inferred (Charlton, 1980).

Spatial scales of water movements range from centimetre-scale turbulence to the dimensions of the basin itself, and even larger scales are associated with weather systems. At any point in the lake, the controlling spatial dimensions are those of the basin itself and the distance of the point from each of several important boundaries (shore, bottom, surface, thermocline). For most problems having to do with the whole lake, horizontal variations taking place over kilometers and vertical variations over 5-10% of the water depth would be of most interest, but smaller scale motions cannot be ignored since they may contribute significantly to mixing processes. Moreover, the small scale motions appear random in nature, and although their mean properties are usually assumed to be related to the large scale flow and to rates of energy loss to "friction", the nature of such "parameterizations" is still a subject for research and debate.

Because the "laws" of fluid motion are generally known and expressible as a set of partial differential equations that can be solved for the flow field in both time and space, much effort has been expended in developing computer-based models that simulate fluid motion in terms of boundary conditions, externally applied forces, and the initial state of motion. Despite the enormous computing power of today's machines, practical realities limit the models to relatively coarse resolution in both time and space. The problem of parameterizing the influence of smaller scale motions on the scales of motion resolvable by the model limits the accuracy of such simulations. Numerical simulations have nevertheless been extremely useful in developing and confirming physical insight. It is natural to turn to such models as a tool for predicting the future behaviour, but here an even more fundamental difficulty limits the length of time a prediction or forecast can be projected into the future (Lorenz, 1969). The initial conditions specified as input to the model are an approximation to the "true" initial conditions by virtue of measurement errors and the filtering imposed by the model structure. The difference between "true" and imposed initial conditions constitutes an unknown "error" signal, and work pioneered by Lorenz (1969) shows that this error signal is invariably amplified by the model and eventually drowns out the predicted changes. This effect is well-known to meteorologists but its consequences do not seem to have been taken to heart in other related disciplines. Our concern, however, is less with the hour-by-hour prediction of detailed flow fields and more with the development of what might be termed a climatology of lake behaviour for which the limitations described by Lorenz may be less severe but present, nevertheless. A recent article by Tennekes (1988) describes this quandary and recommends a more realistic philosophy for the making or using of forecasts of the behaviour of multi-scaled systems.

## Annual Thermal Cycle in Lake Ontario

Lake Ontario stratifies regularly and reliably each year and exhibits two periods of convective overturn, one in spring and one in autumn during which it is thought that the lake is at least partially mixed from top to bottom. However, the details of the thermal cycle, such as the dates of onset and disappearance of stratification, thicknesses of the upper mixed layer and the thermocline region through the stratified season, are subject to significant spatial and temporal variation. Since nutrient availability and biological productivity are closely tied to both absolute temperature and thermal structure, physical effects must be accounted for before biochemical effects can be deciphered in the observational record (Simons and Schertzer, 1987). The prospect of significant global increase in the earth's surface temperature in the coming decades has motivated substantial and increasing efforts to develop plausible scenarios of the lake's responses, particulary those affecting its thermal structure. This will be more fully discussed later.

## Lakewide effects - whole basin approach

One of the principal scientific goals of the International Field Year on the Great Lakes (1972-73) was to evaluate all possible terms in the annual heat and water budgets of Lake Ontario in order to define the lakewide evaporative heat flux with greater precision. During this experiment, Lake Ontario served as a huge calorimeter. The results of this study are summarized in the IFYGL synthesis volume (Aubert and Richards, 1981). The IFYGL data set, the most complete at the time, greatly stimulated the development of lake simulation modelling (Simons, 1974, 1975, 1976). Despite the appeal of fully three-dimensional models with many biological and chemical compartments, it has been found that the greater accuracy promised by more realistic simulations was not fully realized because the transfers across the growing number of interfaces were not generally known and had to be parameterized often in arbitrary ways (Simons and Lam, 1980). Relatively simple "box" models of whole lake basins are more suitable for the level of knowledge we now possess and the physical armature for these models is a one-dimensional thermodynamic model. In addition, these more simple models are computationally more economical than the more complex three-dimensional approaches, a distinct advantage for climatological studies.

Modern thermodynamic modelling of lakes may be classified into two approaches, empirically-based models, and integral models. A good example of the empirical approach is provided by Baba's (Baba, 1974) study of the thermal cycle of Lake Ontario in which he derives eddy mixing coefficients from field measurements of thermal structure and introduced tracers that are subsequently used to "predict" evolving thermal structure. A more recent example of the empirical approach is found in the work of Henderson Sellers (1985). In small lakes and in shallow lakes, the arbitrary specification of eddy diffusivities was successful, since in these water bodies, the thermal structure is dominated by vertical convection, and less by vertical diffusion. In contrast, the thermal properties of larger, deeper lakes are more strongly influenced by diffusion processes (Harleman, 1986). In these situations the performance of ad-hoc thermocline models has not been satisfactory and this has led to the development of a more exacting parameterization of thermal diffusion based on both turbulence theory and on field and laboratory experiments.

Eddy diffusivities are often specified as the product of a mixing length scale and a turbulent velocity scale characteristic of the flow. A review of various formulations for these scales is given by Blumberg (1986). One approach, the so-called k-e turbulence model, has been applied to the seasonal development of thermal stratification by Svensson (1978). The simulation of thermal structure was acceptable for the epilimnion, but in obvious error within the hypolimnion since, in the model, that portion of the water column remained at winter temperatures throughout the year. Clearly, the weak, but important mixing processes within the hypolimnion were not properly simulated.

The integral approach is also semi-empirical and it is based on the temporal evolution of the vertical integral of the turbulent kinetic energy budget. Details of the energy transfers in the mixed layer have been adapted from the oceanographic literature (Pollard et al. 1973). A major improvement of the integral models, as applied to lakes, was the parameterizing of the shear-induced mixing at the thermocline powered by internal waves (Spigel and Imberger, 1980). Ivey and Patterson (1984), in simulating the thermal structure of Lake Erie's

Central Basin, further improved the model by accounting for the turbulent energy generated by bottom friction in a bottom mixed layer. In this special case, the bottom generated turbulence is derived from observations of bottom currents and an estimated bottom drag coefficient. In other situations a limited turbulent energy budget is formulated for the subsurface waters in order to simulate the observed vertical mixing. Hamblin _et al._ (1986) has compared the approach of Fischer _et al._ (1979) where the dissipation rate of turbulent kinetic energy is assumed to be independent of depth with that of Harleman (1986) who considers the dissipation to depend on the local stability of the water column. Hamblin _et al._ (1986) find that the second approach leads to more accurate simulations, especially during periods of weak stratification in the spring and fall seasons. Improved understanding of the vertical diffusion of heat and dissolved or suspended materials is a valid goal for further research.

The inclusion of the effects of snow and ice cover represents another significant advance in the thermal modelling of lakes. Patterson and Hamblin (1988) have developed and tested formulations for snow and ice cover on data from large, deep lakes in British Columbia and in the Yukon Territories. These formulations should be verified in the Great Lakes.

Another important effect in deep, high latitude lakes is that of the compressibility of water. Remarkable consequences on thermal structure evolve from the fact that warm water is more compressible than cool water; these are explored in the modelling study of McCrimmon and Hamblin (1988). A sample temperature profile from their study (Figure 1) shows a situation that might occur after the mixing of two horizontally adjacent water masses initially at two temperatures below the temperature of maximum density. Because of compressibility effects there exists a depth at which both initial water masses have the same density (the compensation depth). Mixing occurs both above and below this depth and the resulting temperature profile possesses an extremum near the compensation depth.

Thermal modelling concepts dealing with small but important changes in water density imposed by pressure or dissolved or suspended materials are usefully extended to water quality concerns such as total and dissolved solids (Wei and Hamblin (1986); Hollan etal. (1989)). All of these processes are at various times and places important in Lake Ontario. Incorporation of them into, for example, a simulation of the Lake's response to anticipated climatic change remains high on the agenda of work to be done.

## Nearshore effects

Whereas for practical purposes, thermal energy both enters and leaves the lake at the air-water interface, mechanical mixing processes allow a much larger thickness of the water column to participate in the daily cycle of heating and cooling. In the nearshore, shallow regions of the lake, the "zone of participation" often extends to the bottom. This is also true for the transfer of the momentum of the wind to the water as will be discussed later. In the early spring, prior to whole lake stratification, when the lake is at temperatures close to 4°C (temperature of maximum density of fresh water) density-driven horizontal water movements are very weak because of the small coefficients of thermal expansion, the effective heat capacity of the water column is proportional to local water depth. Thus the nearshore zone warms to temperatures above 4°C more quickly than the offshore water, and the convergence and sinking of water near the temperature of maximum density ensures that the horizontal boundary between warm, nearshore water, and cool offshore water remains sharp. This phenomenon, called the "thermal bar" lasts for several weeks in Lake Ontario (Zilitinkevich and Terzhevik, 1987; Rodgers, 1987; Schertzer and Sawchuk, 1989; Ivey and Hamblin, 1989) and during this time, the large flux of nutrients from spring runoff remains "trapped" in the warm water on the nearshore side of the thermal bar. High nutrient levels and warm temperatures result in increased biological productivity. As the nearshore water continues to warm differentially with respect to the open lake, the onshore/offshore density differences become dynamically significant, and the warm water tends to move offshore and spread over the cool open lake water. The time scale of this process being long, the offshore-moving warm water is deflected by Coriolis force to the right of its direction of motion forming a counterclockwise circulating band of warm water at the edge of the lake. This thermally driven circulation may persist well into summer (Bennett, 1971). The pathways and fates of contaminants introduced into the nearshore zone during the thermal bar period in the presence of elevated concentrations of biota, nutrients, and suspended material must be different from those occurring at other times, a topic worthy of study in view of its connections to management issues (Taylor et al. 1987).

In small lakes that exhibit seasonal stratification, water lying beneath the upper mixed layer (metalimnion and hypolimnion) is "sealed off" from exchanges with the atmosphere by virtue of the stability of the water column and the limited amount of mechanical energy that can be extracted from the wind. It can be demonstrated (Spigel and Imberger, 1980; Imberger and Hamblin, 1982; Gorham and Boyce, 1989) that for a given wind impulse, the mechanical energy available to displace the thermocline is an increasing function of the horizontal dimensions of the basin up to the point where Coriolis force dominates the transient response of water motions in response to changing winds. The Great Lakes, Lake Ontario in particular, fall into the latter category, behaving more like the coastal oceans. Thus a combination of wind stress and Coriolis force may be sufficient to move warm nearshore water away from the shore and to allow cooler subsurface water to upwell. The northwest shore of Lake Ontario is prone to episodic wind-driven upwellings of cool metalimnic water while the southeast shore experiences the concomitant downwelling (Simons and Schertzer, 1987). Again, these motions have consequences for biological productivity.

## Wind-driven water movements

Wind contributes mechanical energy to the water in three ways, through the creation of disorganized turbulence, through the creation of a surface gravity wave field, and through the creation of organized, horizontal currents. There are interactions among all three types of motion, particularly between turbulence and mean motion since it is the turbulence which transfers the stress exerted by the wind on the water surface to the subsurface layers. In a homogeneous water column, surface-generated turbulence can penetrate to the bottom although energy is continually dissipated to heat throughout the turbulent field. When the lake is stratified, vertical turbulent motion must overcome the gravitational stability of the stratified regions (lift cool water up, push warm water down) and may consequently be attenuated where the vertical density gradients are large. Away from the shore, organized, large-scale currents are thus initially confined to the upper mixed layer or epilimnion. However, the strong shearing motion that develops between the actively driven upper layer and the quiescent lower layer is also a potential source of mixing energy at the level of maximum shear through the mechanism of dynamic instability (Spigel and Imberger, 1980). Thus large scale motion or mean currents may contribute to turbulent mixing under the appropriate conditions (see earlier paragraphs on thermodynamic modelling). The surface wave field may also contribute to the turbulence and mixing in the upper layers through random wave-breaking and/or bottom shear, creating a connection between the characteristics of the wave field and the local wind stress. This connection together with its implications for the transfer of heat and mass (gasses, contaminants) across the water surface is an important and active field of research worldwide with many pioneering results coming from work on Lake Ontario (Donelan, 1989). Models of vertical mixing, such as the thermocline models mentioned earlier must take into account in explicit or implicit fashion, the interactions among all the types of motion listed above.

Large scale horizontal turbulence and currents are of particular interest because of their potential for distributing dissolved and suspended materials. It must be emphasized that horizontal motions occupy a continuous spectrum of spatial scales, the largest of which represents the cross-lake dimensions of the basin. The initial response of a closed basin to a suddenly imposed wind has some parallels with the thermal bar situation discussed earlier in that the total inertia of the water column responding to the wind stress is proportional to either the water depth or to the depth of the actively stirred layer. Thus currents at the shoreline parallel to the direction of the suddenly imposed wind accelerate downwind near the shore, with a compensating upwind transport in the deep water of mid-lake (Bennett, 1974). In both stratified and unstratified conditions, this initial circulation results in an extended transient response in the form of wave-like disturbances that propagate counterclockwise around the basin. The reader is referred to the review documents and monographs mentioned earlier for an explanation of the wave mechanisms. The signature of such basin-scale waves at a point near the shore is first a component of current alongshore in the direction of the alongshore component of the wind, followed by a reversal of current some days later. The zone of current reversal propagates couterclockwise around the shore of the basin (Csanady, 1982) at speeds of the order of 20 km/day. This response is confined to within 10 km of the shore, a region sometimes called the coastal boundary layer. During the stratified season the currents are associated with vertical displacements of the thermocline (upwellings and downwellings) but vertical motions of water occur near the shore even more vigorously during the homogeneous period. Current reversals are also associated with large onshore/offshore exchanges of water. These coastal currents move parallel to the shore for several days (excursions of 10's of km) and then reverse and flow the other for comparable, if unequal periods. During the intervals of unidirectional, shore-parallel flow, onshore/offshore mixing may be weak, and effluent from an outfall, for example, may be carried many kilometres along the shore (Ontario Ministry of the Environment, Ontario Hydro, National Water Research Institute, 1981). The water exchanges associated with the flow reversals tend, in crude terms, to "wipe the coast clean".

While flow reversals have beneficial aspects from the point of view of the dispersal of pollutants in the coastal region, there are other events such as periods of very low currents (less than 5 cm/s) or stagnation producing detrimental effects because of weak dispersal. The siting of effluent discharges along the coastline is undoubtedly dictated, among other things, by the climatology of coastal currents (Csanady, 1970, 1971; Murthy, 1972). Considerable progress has been made over the years to develop effluent transport and diffusion models for the coastal zone, based on knowledge of the complex physical processes acquired through theoretical and experimental investigations. For further information, the reader is referred to a recent monograph by Lam _et al._ (1984).

The open lake transient response is very much like the response to be expected in the open ocean; when the basin is stratified, the surface currents tend to move in circles with a frequency of one cycle roughly every 16 hours. The circular motion is a direct consequence of the earth's rotation (Simons, 1980).

Although the transient response of large-scale lake currents to wind can be simulated reasonably well by simple linearized numerical hydrodynamic models over short time scales (a few days), the accuracy of longer-term predictions remains poor, mainly because, as it turns out, the linearized model neglects subtle but important feedback processes. In a particularly well-planned field experiment, Simons (Simons _et al._, 1985) was able to demonstrate the existence of a substantial residual circulation comprising a fast belt of current moving east near the south shore of the basin balanced by a more diffuse and slower return flow to the west in mid-lake. The flux of this current in one direction is roughly equal to 10 times the flow of the Niagara River entering Lake Ontario. Simons was able to simulate the structure of this residual flow when he introduced non-linear acceleration terms into his dynamic model. The residual gyre is in effect the rectification of large amplitude wave-like flows. One direct implication of Simons' discovery is that the Niagara River, which often flows into this eastward moving residual boundary flow, is rapidly recirculated within the lake with a mixing time scale that is only a few weeks. The combined effect of the continuum of scales of motion is graphically demonstrated by satellite-tracked drifter experiments (Simons et al., 1985). The accurate fixes on drifter positions obtained several times a day reveal not only the residual current described above but also more irregular motion associated by the response of the currents to the individual pulses of wind. The distribution of mercury and Mirex emanating from known sources on the south shore of Lake Ontario and now located in the sediments is consistent with alongshore displacement by the residual current plus lateral mixing accomplished by the transient and small scale motions.

## Interaction Among Water Movements and the Pathways and Fates of Dissolved and Suspended Contaminants

The severity of the contaminant problem is ultimately judged by the distribution of the contaminants in living creatures and the damage they do there. Although this is fundamentally a biological problem, the pathway of a contaminant from its source to the biota, together with the mechanisms for removal or alteration may involve physical as well as chemical and biological processes. Experience has shown that attempts to measure contaminant budgets and fluxes in the field without accounting for physical processes of transport lead to ambiguous results (Royer et al. 1987), particularly in large, horizontally non-homogeneous lakes such as Lake Ontario. Not only do we require a basic understanding of the various physical processes acting to distribute contaminants but also we need to maintain the ability to measure these processes in support of chemical and biological field experiments.

Ignoring for the moment the processes that would remove contaminants from the water column (sedimentation, chemical or biological alteration), the distribution of contaminants introduced at the shores from rivers, outfalls, or distributed runoff, depends on the water motions discussed above. Existing information is sufficient to describe the gross properties of large scale redistribution using the circulation models developed by Simons and his colleagues (Simons and Lam, 1978). Detailed work along these lines has been carried out by Murthy and his associates in support of the Niagara River Study (Murthy et al. 1986).

The Niagara river, with a discharge ranging from 5500 to 7000 $m^3/s$, furnishes 83 percent of the total annual input of water to Lake Ontario. This same river also supplies approximately 4.7 million tons of sediment annually, 52 percent of the total sediment load to the lake. Industries and municipalities along the Niagara River discharge liquid wastes into it, while at the same time both the river and the lake immediately downstream are sources of drinking water and sites for recreation and tourism. Degradation of the Niagara River and Lake Ontario has been a focus of public anxiety for a long time.

In recent years, in both the US and Canada, there has been much concern about the transport, distribution, and pathways of toxic contaminants entering the lake from the Niagara River. An integrated, multidisciplinary study was undertaken to examine the toxics problem in the Niagara River/Lake Ontario system. In the years 1982-86, simultaneous experiments were undertaken to (i) delineate the transport and mixing of the river plume in the lake and (ii) the distribution, in both water and sediments, of selected contaminants associated uniquely with the Niagara inflow. This information aided the development of hydrodynamic models of the river-plume behaviour in the lake, and these models in turn formed the basis of a transport model that simulated the distribution and pathways of selected contaminants (Murthy et al. 1986; Stepien et al. 1987. A typical result from this study is shown in Figure 2.

Contaminants such as PCB's enter the lake through several pathways. For Lake Ontario, total inputs of PCB's are estimated to be 2540 kg per year, of which 178 kg, or 7 percent of the total are attributed to atmospheric loading. In comparison, some 90 percent of the total load of PCB's (606 kg per year, total) to Lake Superior comes from the atmosphere (Strachan and Eisenreich, 1986). Since the time scales of vertical mixing within the wind-stirred layer are relatively short compared with those of horizontal redistribution (hours compared to days or weeks), relatively simple layered models of horizontal transport may still be applicable. The models of thermal structure discussed earlier can be adapted to simulate the mixing of contaminants from the surface down through the water column.

The tendency for many organic contaminants to bind preferentially to suspended particles (Allan, 1986) means that in addition to transport and dilution by water movements, the distribution and fate of contaminants are influenced by the physical processes of erosion, resuspension, flocculation, and settling.

Zooplankton and phytoplankton produced in the lake itself are major sources of particulate material, dusts and pollens are carried by the wind, beach erosion and runoff from the land contribute still more. For example, Rukavina and Zeman (1987) estimate that silt-clay glacial sediments exposed to littoral currents and to wave orbital motions may contribute as much as 15% of the total sediments eroded from shore bluffs along the north-central shore of Lake Erie. Considering that each sediment type can differ in its affinity for a particular contaminant, an important area for research is the physics and chemistry of the partitioning of contaminants between the water and the suspended material. Successful modelling of the transport and fate of contaminants in the presence of suspended materials depends on this knowledge.

A key parameter in describing the behaviour of suspended material is the settling velocity of the particles. This rate determines the average residence time of the particle in the water column under calm conditions and this residence time can be usefully compared with time scales of vertical and horizontal mixing, average time between major storms, etc. in order to assess the relative importance of each process in determining particle distributions. A single "average" settling velocity is a very crude parameterization of what must in nature be a wide spectrum of settling speeds, and moreover, it is known that the process of flocculation, itself dependent on the energy levels of small-scale turbulence, greatly affects actual settling speeds (Tsai et al. 1987).

The preparation of samples for the laboratory determinations of settling speeds is known to affect the results. Sample treatment includes mechanical and chemical dispersion (Duncan and LaHaie 1979) which reduces sediment to individual particles, and in the process, breaks up the original aggregates from suspension as well as those formed by contact of the particles as they accumulated on the bottom or in settling traps. The resultant settling velocity distribution is distorted but reproducible; that is the rationale for this form of analysis. True settling velocity data will require in situ tracking of settling particles, and work is underway at NWRI to develop an optical technique (B. Krishnappan, National Water Research Institute, Burlington, Ontario; personal communication). In the absence of more refined techniques that yield realistic weighted spectra of in situ settling speeds, modelling of the settling process must remain at a primitive, order-of-magnitude level.

The actual progress of a particle from point of introduction to either final burial or to the outlet of the basin may be discontinuous. While very fine particles with low settling speeds may never settle appreciably from the water column, and are carried instead to the outflow or modified by processes occurring within the water column, coarser particles may settle to the bottom near to their source, only to be resuspended and transported during the next storm, tending eventually to accumulate in regions of the basin where the energy of the water movements is insufficient to resuspend them again (sediment focussing). Each time the particle is resuspended into the water column it may exchange contaminants with the water, depending on the relative concentrations and the partitioning coefficients. This effect can be expected to increase the effective residence time of the contaminant in the system. Thus the physical process of sediment resuspension is likely to influence the pathways and fate of sediment-bound contaminants in lakes.

The source of energy for the resuspension of sediment is the movement of water near the bottom. In a recent review Bedford and Abdelrhman (1987) discuss the nature of the bottom boundary layer in relation to sediment resuspension. The nature of the boundary layer depends on the time-variability of the forcing currents as well as on the nature (roughness) of the bottom material. In Lake Ontario, the oscillating motion and pressures induced by surface waves with periods of several seconds will govern sediment resuspension in shallow waters, in contrast to the steadier Ekman-like boundary layer obtained in deep water (Saylor and Miller, 1988). The structure of the boundary layer in steady flow conditions is reasonably well-understood, but the experimental difficulties associated with the small temporal and spatial scales of the wave-dominated boundary layer (cm and seconds) have delayed the verification of existing theories. Relating the boundary layer structure to sediment resuspension via an appropriate average of the bottom stress, for example, remains at the level of very crude parameterization (Simons and Schertzer, 1986) for lack of simultaneous and detailed measurements of suspended sediment concentrations and water movements near the bottom. This problem has received much attention in the oceanographic community and only now are the measurement techniques evolving to the point where theories can be tested and improved. The situation is further complicated by the variability of the mechanical properties of the sediments themselves ( Lick and Kang, 1987; Tsai and Lick, 1986; White et al., 1987), including the effects of benthic organisms. Within the Great Lakes work by Chambers and Eadie (1981), Rosa (1985), Lesht and Hawley (1987), Hamblin et al. (1989), Bedford et al. 1983 has addressed various aspects of this problem.

It is known that much of the contaminant flux to the Great Lakes is from the atmosphere, and it is suspected that the more volatile forms may return to the air from the lake. Mass transfer of contaminants across the water surface is again a problem occupying both oceanographers and limnologists and requires on the physical side, an understanding how surface waves may affect such transfers.

## Anticipating Lake Ontario's Response to Global Warming

Increases in global air temperature have been predicted in response to increases in atmospheric 'greenhouse gases' (CCC 1986; Hansen et al 1981). Within the Great Lakes basin, atmospheric general circulation models (GCM) generally predict a warming of 3.2 to 4.8°C (Maarouf 1985) under CO2 forced climate scenarios (Hansen et al 1984). Such responses are expected to occur within 40 to 50 years.

Considerable uncertainty in the various GCM predictions at regional scales have been indicated (Cohen 1986). Uncertainties stem from the dissimilar predictions among models for each month for important hydrometeorological parameters, the coarse resolution of spatial predictions, and the forecast of changes in only a limited number of the hydrometeorological parameters required for lake modelling. For Lake Ontario, only one GCM grid point is located near the lake and little lake information is used in the model prediction for that grid location. Although the magnitude of predicted climate changes are different among the GCM's (Schertzer and Sawchuk 1989), there is general agreement that the Great Lakes region will experience an increase in mean air temperature.

Climate warming is expected to change the Great Lakes basin hydrological and meteorological conditions and will therefore change inputs to the lake such as the surface heat flux and wind stress. These changes, in turn, will modify the lake thermal structure. Lake thermal structure, as indicated previously, influences many physical, biological, and chemical processes and ultimately impacts on lake water quality. The assessment of probable effects of climate change on the Great Lakes requires a thorough understanding of the physical exchange processes at the lake surface (Sawchuk and Schertzer, 1988), as well as those processes associated with the formation, maintenance, and decay of the seasonal thermocline together with an ability to estimate the potential impact of changes in these processes on a wide variety of important dependent factors.

Sanderson (1987) has summarized some preliminary predictions of hydrological changes to be expected if the present concentrations of CO2 were doubled (2x CO2). It is anticipated that flows in connecting channels of the Great Lakes would decrease approximately 20 percent. Reductions in flows result from changes in precipitation and evaporation; Lake Erie water levels could decrease by 60 cm or more. Lake Ontario water levels are also expected to decrease (5.8m), although downstream hydraulic controls could prevent such extreme changes. Schertzer and Sawchuk (1988) examined some of the implications of climate warming on the thermal regime of the lower Great Lakes based on (i) current GCM predictions for selected key hydrometeorological parameters, (ii) observations under 1 x CO2 conditions, and (iii) on an analysis of anomalously warm conditions occurring over the period 1966 to 1983.

Hansen and Lebedeff (1988) have indicated that the four warmest years for global air temperatures in the period for which useful instrument data has been recorded occurred in the 1980's. The warmest years were 1981, 1987, 1980 and 1983. Figure 3a depicts water surface temperatures for Lake Ontario for one of these years (1983) derived from satellite digital data (AES 1988) in comparison to the long term range of values determined from NWRI surveillance, ART overflights and satellite data over the period 1966 to 1983. Figure 3a illustrates that the water temperatures observed in 1983 were anomalously warm compared to other years. Similarly, Figure 3b shows computed lakewide heat storage based on temperature profile data collected at a grid of stations during routine surveillance by NWRI. In comparison to the long term range of values, the conditions of 1983 were at the extreme maximum of observations with heat storage over the winter months showing the largest change from the long term mean.

Considering the uncertainties in the current GCM model predictions, Schertzer and Sawchuk (1989) used the anomalous conditions of 1983 as an analogue of climate warming in order to provide an indication of potential changes in the lower Great Lakes. A detailed examination of the meteorological conditions was conducted for Lake Erie in particular but this also has implications for Lake Ontario. 1983 wintertime conditions coincided with one of the most intense and longest lasting El Nino events on record (Ramage 1987). Briefly, 1983 wintertime (November 1982 to April 1983) showed air (and dew point) temperatures from 2 to 10 degrees above average, several intense cyclonic events which were largely responsible for warm air advection into Great Lakes basin, lower than normal wind speeds and a substantially reduced surface heat loss which resulted in the higher heat storage as shown in Figure 3b. During the summertime, air (and dewpoint) temperatures were 2 to 4°C above average with conditions of high atmospheric pressures, reduced wind speeds and reduced cloudiness. The extended anticyclonic conditions resulted in above average surface heat flux (gains) which contributed to higher water temperatures and heat storage. Analysis of selected key hydrometeorological variables (air temperature, wind speed, cloud amount, solar radiation and surface heat flux) generally showed responses in the direction predicted by the GCM (GISS) model.

Schertzer and Sawchuk (1989) then examined the 1983 thermal structure for the lower Great Lakes. Figure 3 c shows observed ice cover for Lake Ontario for the winter of 1983 compared to the long term range. Under normal conditions, Lake Ontario experiences a maximum ice cover of approximately 30 percent. Under 2x CO2 scenarios, Sanderson (1987) has estimated ice extent to decrease from 33% to 0%. As indicated in Figure 3 c the ice extent during 1983 reached a maximum of only 10 percent and significant ice cover occurred only in February, a significantly shorter period than the long term mean.

The warm conditions indicated in Figures 3 a to 3 c affected the thermal bar. Comparing the conditions of 1983 with those of 1984 (for which there are good satellite surface water temperature observations (AES 1988)) revealed that under conditions of climate warming, the thermal bar ($4^{o}$C isotherm) would be expected to disappear sooner than in normal years. In the example shown in Figure 1d, the 4 degree isotherm has nearly disappeared on May 17, nearly 16 days prior to the disappearance in 1984. Rodgers (1987) examined the onset of full stratification or disappearance of the 4 degree isotherm as a function of the April 1 water temperature (top 100m) in the deepest basin of Lake Ontario, confirming that the anomalous conditions of 1983 in Lake Ontario are among the warmest 5% of winters on record.

Assessment of the potential changes in thermal structure during the stratified season is more difficult; the anticipated thermal structure is simulated using predicted hydrometeorological parameters derived from uncertain GCM model outputs. Preliminary simulations of the thermal structure for Lake Michigan under climate change scenarios (McCormick, 1989) for the period 1981-1984 suggest that the mixed layer depth under climate change may be shallower than under current conditions. Using an empirical diffusion model developed by Simons (1980b) and verified on Lake Ontario using IFYGL data, Schertzer (pers. comm., 1989) conducted preliminary simulations of the daily lakewide vertical temperature profile for Lake Ontario. Figure 3e illustrates a time series of the simulations for the upper 60m for the anomalously warm year 1983 in comparison to observations. Both the simulations and observations indicate that under the warmer conditions of 1983, the upper mixed layer was relatively shallow and persisted as a shallow mixed layer throughout the stratified season. Lower than normal wind conditions during this warm year as well as increased surface heat flux contributed to this result.

One of the largest uncertainties in the GCM model predictions for the Great Lakes is in the magnitude of changes for wind speed. As discussed previously, the wind speed is an important variable affecting surface heat exchange, lake mixing processes, and other dynamical processes including upwelling, downwelling and lake circulation. GCM model outputs are vector-averaged winds and may not be indicative of the magnitude of change expected in the required scalar-averaged values, especially for overlake conditions. In general, GCM models show disagreement in the projected monthly mean wind speeds under 2 x CO2 conditions

(Schertzer and Sawchuk 1989). The GISS model, in particular, indicates a decrease for most months in the range of 1 m/s for monthly vector-averaged wind speeds. A qualitative assessment of the effects of a decreased wind speed was attempted by studying intensive measurements of the thermal structure of Lake Erie during 1979 and 1980 (Schertzer et al 1987) for which there are detailed measurement of overlake winds. The results suggest that the length of the stratification season and the depth of the thermal stratification under changed climate conditions is an important area for continued research. Reduced wind speeds would also be expected to influence dynamical processes such as upwelling, downwelling, and circulation; potential changes in the prevailing wind directions may also be an important consideration (Simons and Schertzer 1987).

The thermal structure of the lake integrates the combined effects of climate changes. Long term monitoring of the lake thermal structure is an effective means of detecting climate changes in the Great Lakes. Other areas of potentially useful research include the continued development of models incorporating more physical insight that are capable of incorporating the effects of potential changes in atmospheric composition and that are more effective in transforming of land-based hydrometeorological observations to representative over-lake values. This last is essential given the uncertainties in GCM model outputs. Increased confidence and accuracy in projecting climate change impacts on the Great Lakes depends on the continued improvement of GCM models for regional scales.

## Conclusions

The presence of many overlapping and interacting scales of motion in large lakes is also reflected in a patchiness of the distribution of non-physical variables. This must be allowed for in both the collection and interpretation of field data. The multiplicity of scales has important consequences for our ability to "predict" lake behaviour via numerical models as information about previous states is progressively lost in model-generated noise. In the past two decades, the general features of the circulation and mixing of Lake Ontario have been successfully delineated, although detailed, site-specific studies of a climatological nature will still be required from time to time in areas of concern. Increasingly sophisticated models of lake thermal structure have been developed and they will be useful in assessing the potential impact of climate change, particularly in the matter of convective overturning. Despite the increasing sophistication based on better physical understanding, these models, like their predecessors, require empirical inputs. Improved measurement techniques make us hopeful that this empirical information may eventually be determined in the lake itself instead of artificial laboratory situations. The process of "sediment focussing", so strongly linked to the fate of many organic contaminants, is only recently amenable to in situ study with instruments that respect the natural time and space scales of resuspension and settling. The rates of gas and vapour transfer across the air-water interface are known to depend on the physical behaviour of this interface, and in particular on the surface wave field; these dependencies are being actively explored. Experience over many years has consistently shown that large-lake studies of chemical and biological processses are difficult, if not impossible, to interpret in the absence of an adequate base of concurrent physical measurements, one that respects both the scales of the site and those of the intrinsic variability.

To a casual reader it may seem that our understanding of the physical workings of large lakes such as Lake Ontario has improved so substantially over the past two decades, that little research remains to be done. The attentive reader will have noted however, that while the general framework of our understanding has been strengthened, the structure requires cladding in many important places. A list of some of these research areas is included as Appendix A to this paper. Because of the very large effort and expense required to obtain appropriate physical information, a multidisciplinary and multi-institute "field year" approach has much to recommend it.

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## APPENDIX A: Areas for further physical research.

1. The relatively weak mixing processes in the hypolimnion are poorly quantified.

2. Understanding of the general process of sediment focussing in large lakes would be improved by studies in:
   - the critical conditions for resuspension of cohesive or fine-grained sediments;
   - the conditions required for the deposition of fine-grained sediments;
   - the possibility that the concentrations of suspended sediments may at times be large enough to initiate turbidity currents;

3. The development, verification, and application of more physically-based radiative transfer models suitable for climate studies.

4. A program for monitoring thermal structure of large lakes in order to detect the effects of climate change.

5. Systematic investigation of the potential impacts of climate change on ecosystem components and water quality using a combination of long time series data and updated atmospheric general circulation models.

6. Improvements in algorithms for the extrapolation of land-based meteorological measurements to the adjacent lake surfaces.

7. Better observational base leading to improved simulations of small to medium scale processes in the nearshore zone. The processes to be studied include lateral mixing, dynamics of the bottom boundary layer as related to sediment resuspension, upwellings and downwellings.

8. Observational base and model development for the transfer of heat, momentum, and materials across the air-water interface, taking into account the effects of breaking surface waves.

9. Investigation of the spatial variability or "patchiness" of biochemical parameters as a result of physical and biochemical processes. This information would help define more rational sampling strategies for long term monitoring.

## Figure Captions

Figure 1. Temperature profile resulting from the gravitational collapse of two initially homogeneous water columns at two temperatures at or below the temperature of maximum density (McCrimmon and Hamblin, 1988).

Figure 2. a) Vertically integrated current field for 1400 GMT, 10 August, 1983 as derived from the hydrodynamic model (top panel), and horizontal current velocities deduced from drogue trajectories for the same time (lower panel). b) Computed (contours) and observed (circles) concentrations of 1,2,4-TCB (ng/L) [total (upper panel), dissolved (middle panel) and particulate (lower panel)] for 10 August, 1983. Figures originally published by Stepien et al., 1987, and reproduced with the authors' permission.

Figure 3. Thermal characteristics of Lake Ontario for the anomalously warm year, 1983: a) surface water temperature, b) heat storage, c) ice cover, d) depth of 4°C isotherm and, f) time series of vertical temperature structure.

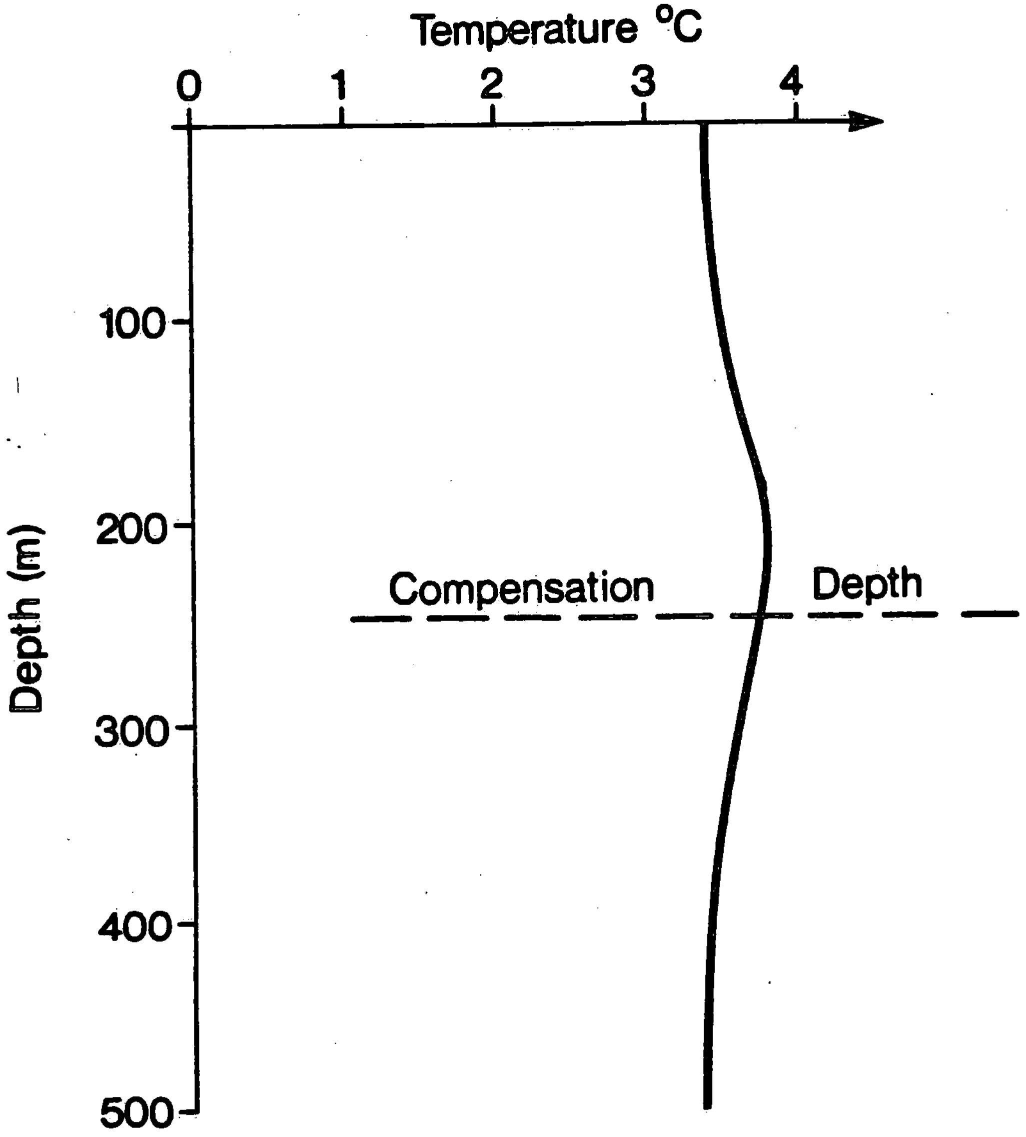
Temperature °C
0
1
2
3
4
Depth (m)
100
200
300
400
500
Compensation
Depth

FIGURE 1

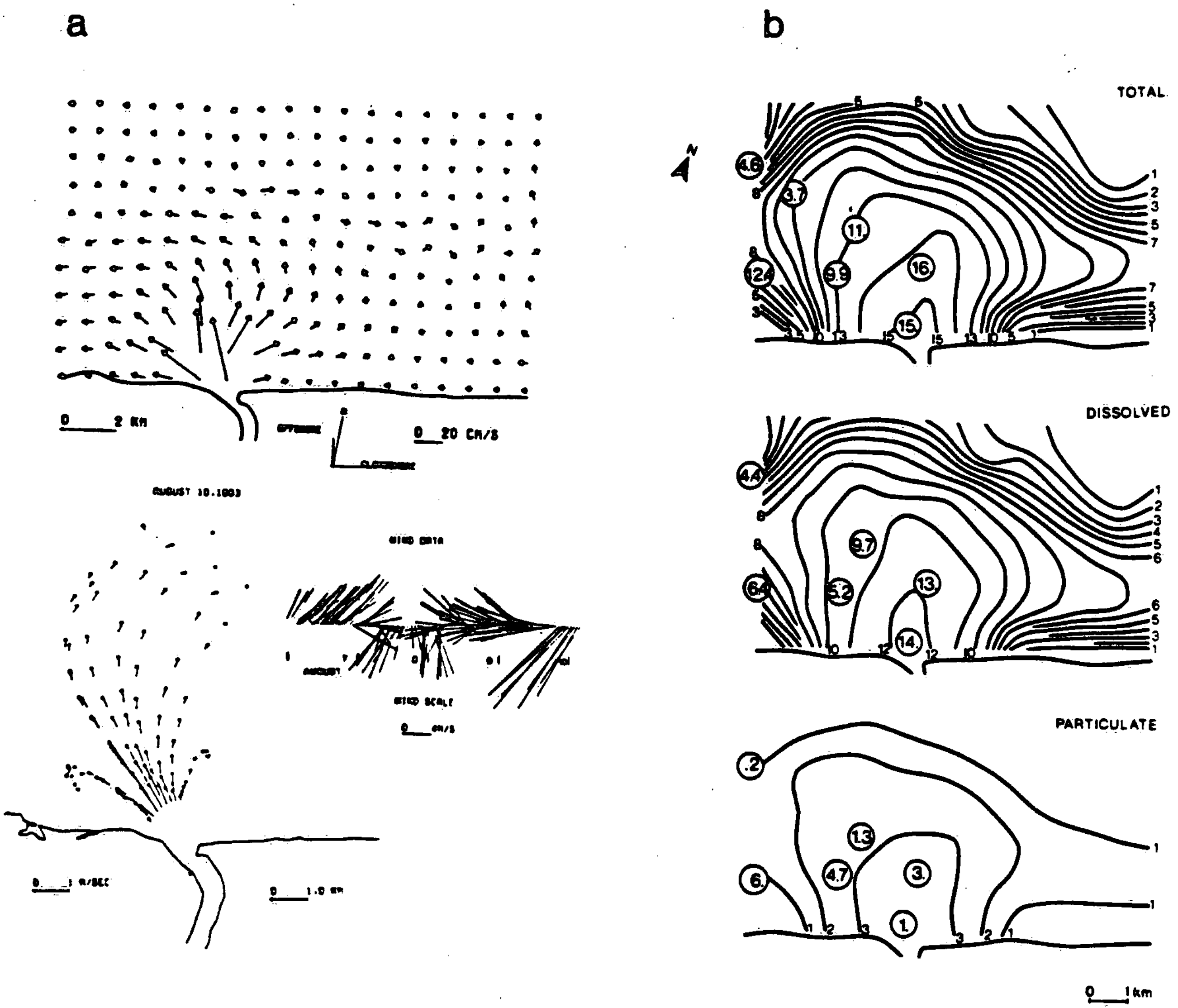
a
0 2 KM
0 20 CM/S
AUGUST 10,1983
WIND DATA
AUGUST
WIND SCALE
0 CM/S
0 1 M/SEC
0 1.0 KM
b
N
TOTAL
4.6
3.7
11
9.9
16
12.4
15
DISSOLVED
4.4
9.7
5.2
13
6.4
14
PARTICULATE
.2
1.3
4.7
3
6
1
0 1km

FIGURE 2

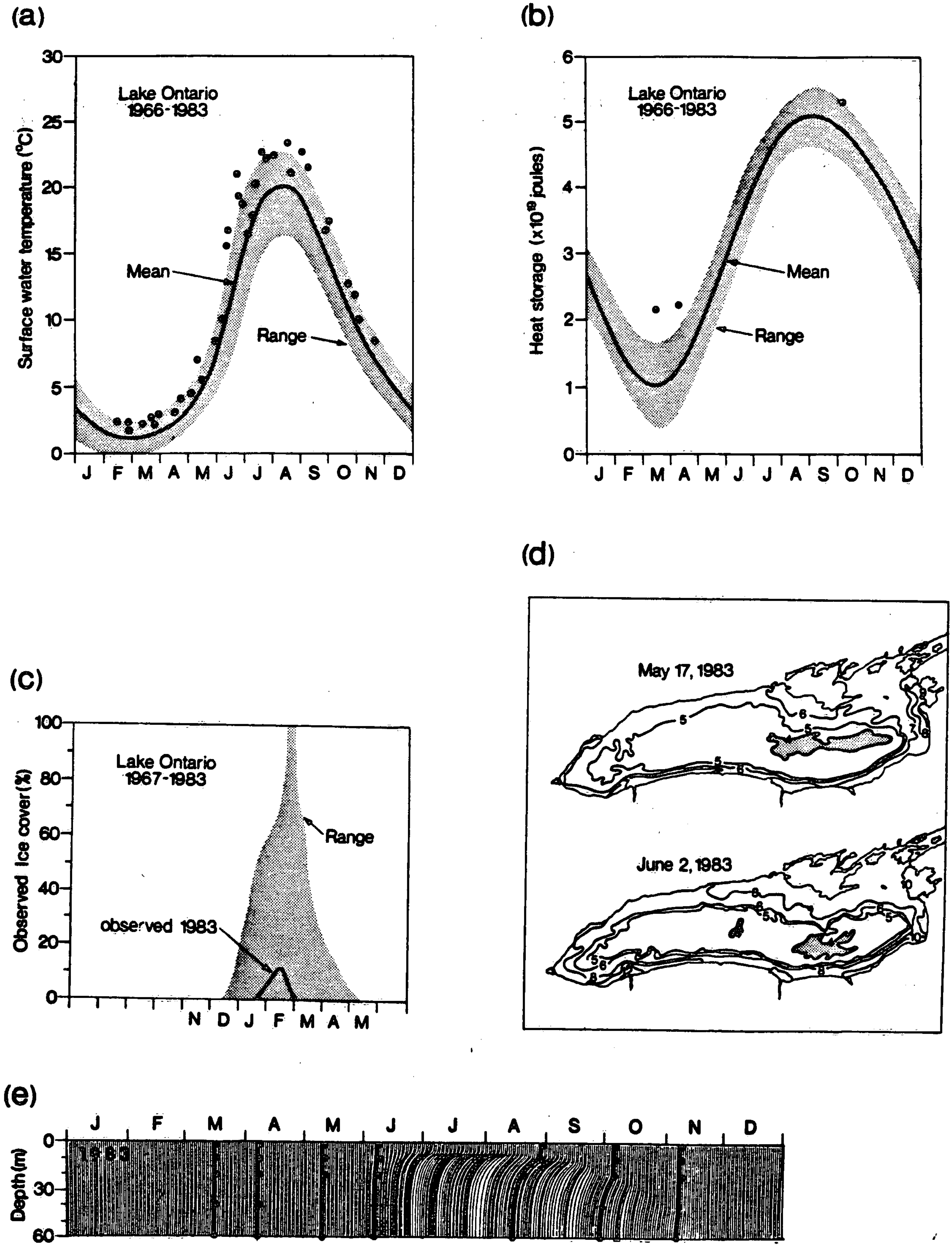
(a)
Lake Ontario 1966-1983
Surface water temperature (°C)
Mean
Range
0
5
10
15
20
25
30
J F M A M J J A S O N D
(b)
Lake Ontario 1966-1983
Heat storage (x10$^{18}$ joules)
Mean
Range
0
1
2
3
4
5
6
J F M A M J J A S O N D
(c)
Lake Ontario 1967-1983
Observed Ice cover (%)
Range
observed 1983
0
20
40
60
80
100
N D J F M A M
(d)
May 17, 1983
June 2, 1983
5
6
8
10
(e)
J F M A M J J A S O N D
Depth (m)
0
30
60
1983

FIGURE 3