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Lake Erie Hydrodynamics: Regime Variability and Potential Changes

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Lake Erie Hydrodynamics : Regime, Variability and Potential Changes

by

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Abstract : A review of key hydrodynamical processes conducted on Lake Erie is presented along with trends, variability and possible changes. Primary focus is on knowledge gained from past physical limnological observations, modelling and current state of knowledge on possible changes in currents and circulation which may result from climate warming. The circulation of Lake Erie is shown to be complex largely because of physiography. Specialized observation programs during stratified and unstratified periods have been successful in identifying large-scale circulation patterns including the occurrence of clockwise and anti-clockwise gyres. Research has also documented inter-basin exchange of water and materials, current oscillations, flushing and diffusion time scales, upwelling, surface waves and turbulence. Modelling has been particularly useful in helping to simulate the 2- and 3-dimensional flow fields and there have been improvements leading to first generation forecast capability for this lake. Knowledge of the complexities of water movements is found to be important for understanding ecological problems (e.g. fish-kills, hypolimnetic anoxia, etc.). Further improvements in instrumentation such as the acoustic doppler current profiler have shown promise in measurement of flows in the upper reaches of the water column. Recommendations for increased spatial and temporal observation of key meteorological components are presented. More research is required to allow projection of possible changes in Lake Erie hydrodynamical processes which may result from changes in climatic forcing. It is suggested that radical changes in thermal structure (e.g. dimictic to monomictic states) will exert a profound influence on winter circulation and mixing. Further, weaker wind forcing expected from climate change in combination with increased bottom friction due to the presence of mussels may lead to a reduction in the strength of lake circulation and mixing which could have consequences on the biology and chemistry of lake Erie.

1. Introduction

Lake circulation is important in mediating the biogeochemical processes of large lake systems (Vollenweider 1987). In Lake Erie, hydrodynamics has an important role influencing such phenomena as eutrophication, contaminant fluxes and complex interrelationships between ecosystem components (see Boyce et al. 1987a). Large-scale and small-scale water movements have been determined from a range of observational techniques and from modelling approaches. Significant advances have been made in understanding the complexities of circulation patterns in Lake Erie. However, it is also recognized that an increase in predictive capability is required for such applications as short-term forecasting and more research is necessary to project possible changes in currents and circulation which may result from climatic changes.

Considerable research has been conducted on the physics of Lake Erie under several large-scale investigations. Hamblin (1971) provided a detailed historical review of the state of knowledge on Lake Erie circulation over the period 1928-1970 with extended references to original research. Project Hypo (Burns and Ross 1972) represented one of the earliest systematic investigations of links between physical limnology and observed biological and chemical changes in the hypolimnion. The Lake Erie Binational Study (Boyce et al. 1987a) was a major international investigation conducted in 1979-1980 that examined the lake-wide physical, chemical and biological characteristics. In response to major ecological trends, stemming from the Canada-US Water Quality Agreement and the invasion of exotic species such as the zebra mussel, an integrated programme of study was undertaken in Lake Erie by Canadian investigators in 1994 which provides more recent understanding.

The object of this paper is to provide a review of key hydrodynamical characteristics of Lake Erie based on historical observational programs as well as critical advances in modelling of lake circulation. This paper is prepared, along with a companion paper (Schertzer and Hamblin 1999), to describe the physical limnological characteristics of Lake Erie and to provide background on the variability of water movements and considers the current state of knowledge related to potential changes which may result from changes in meteorological forcing (e.g. climate warming).

2. Priority Issues and Key Variables

Prediction of waves and storm surges and the study of transboundary movement of pollutants have been long-term priorities of physical limnologists studying Lake Erie. The more recent concern for such water quality issues as hypolimnetic anoxia have sparked the development of mathematical modelling of material transport and associated phenomena such as turbulent mixing. Invasion of exotic species appear to have aggravated the problem of fish-kills which often occur as a result of sudden upwelling of cool and poorly oxygenated water, in addition, alteration of the properties of bottom sediments and the benthic boundary layer have been attributed in part to exotics. Finally, climate change may present a different meteorological and hydrological regime in which could alter physical processes in a fundamental manner.

3. Lake Erie Physical Characteristics

Lake Erie is the southernmost and shallowest of the five Laurentian Great Lakes (Fig. 1). At low water datum it has a maximum depth of 64 m, a surface area of 25,320 km^2 and a volume of 473 km^3. Three distinct basins are formed on the basis of the bathymetry. The western basin (surface area 2,912 km^2; volume 20 km^3; depth 10 m) is separated from the relatively flat-bottomed central basin (surface area 16,746 km^2; volume 20 km^3; depth 25 m) by a rocky island chain extending from Point Pelee, Ontario to Marblehead, OH. A low, wide submerged sand and gravel ridge, called the Pennsylvania Ridge extends from Long Point, Ontario to Erie, PA, separating the central and eastern basins. The maximum depth of the Ridge at a point near the southern shoreline is 21 m. The eastern basin has a surface area of 5,672 km^2, a volume of 150 km^3 and a maximum depth of 64 m. The physical characteristics of the lake and its basins have a major influence on such factors as the spatial variability in over-lake meteorological components, net basin supplies, heat storage, water temperature distribution, circulation and water level changes etc. A major contribution of past hydrodynamical studies in Lake Erie has been to specify inter-basin fluxes of materials as needed for input to water quality and ecosystemic models.

4. Observational Data Sources

Hydrodynamical research conducted on the Great Lakes have included both large-scale and small-scale investigation of water movements and modelling. Such research often requires a combination of in situ lake observations and supporting meteorological and hydrological observations. One of the complicating factors include observations at differing spatial and temporal scales. Fortunately, on Lake Erie, there is a wealth of routine long-term meteorological observations from stations at the lake periphery and at buoys during the navigation season (Fig. 1), although spatial representation is biased to the south shore locations. The utility of shore-based stations is that they can also provide reliable data on such hydrological components as major inflows and outflows and water levels. Water movement observations have been conducted on Lake Erie through use of both Lagrangian (e.g. drogues and dyes) and Eulerian (e.g. current meter) techniques. Recent advances have included the development of the acoustic doppler current profiler (ADCP) which has shown significant promise in evaluation of currents especially in the upper "near-surface" depths. Simultaneous meteorological measurements from moored buoys or from ship surveys are particularly useful for determining over-lake fields which impact on water movements. Lake-wide ship surveillance cruises on Lake Erie have ranged up to about 10 surveys per year (Schertzer and Hamblin 1999) which have yielded information on the thermal stratification characteristics but not on circulation. Remote sensing has been shown to have utility in tracking circulation phenomena such as fronts and upwelling. Remotely-sensed water temperatures from airborne radiometer over-flights (ART) and more recently from satellite digital imagery have been particularly useful. An example of an extensive array of physically based instrumentation deployed in Lake Erie including current meter moorings and supporting in situ meteorological observations is provided in Figure 2. The unusual density of stations portrayed in Fig. 2 was possible largely through collaborative investigation involving Canada at the National Water Research Institute (NWRI) and the USA at the Great Lakes Environmental Research Laboratory (GLERL).

5. Meteorological Forcing : Wind and Water Level Fluctuations

Among the primary lake responses to meteorological forcing are short-term fluctuations in water level, wind set-up, seiches, storm surges and waves. Meteorologically-forced events have the potential of causing considerable damage in shallow lakes such as Lake Erie. For example, shoreline erosion and flooding have been notable problems particularly in the western and central basins of Lake Erie and extreme meteorological events can pose considerable hazards to large and small shipping. Mortimer (1987) provides detailed references related to these physical processes. In the following, we provide brief examples of the current state of knowledge for determination of over-lake meteorological fields (e.g. wind speed, heat fluxes), hydrological influences (e.g. water level and storm surge) and an example of the potential of remotely sensed techniques for augmenting direct measurements of water movements.

5.1 Over-lake Meteorological Fields : Although most meteorological variables are observed routinely during the navigational season on the lake surface, the number of buoys is insufficient for hydrodynamical and thermodynamical modelling and must be augmented by data from shore-based stations. For example, the over-lake wind field is one of the primary forcings of lake circulation and a combination of lake and land observations are often used to evaluate the over-lake wind field. Historical observations of wind spectra have shown that the most energetic periods appear to occur at the average time between storm occurrences from 7 to 10 days (Irish and Platzman 1962; Hamblin 1987). In Lake Erie, there is a persistent tendency for clockwise rotation of the wind over the lake consistent with cyclonic disturbances passing from west to east on the north side of the lake or anticyclones travelling on the south side in the same direction

(Hamblin 1987). High spatial variability in wind speed is also observed especially for winds 2 m s^{-1} or less. Comparison of shore-based and lake wind observations (Hamblin 1987) revealed that differences could be significant and in some cases could lead to wind stress differences as large as a factor of 2 between stations. On longer temporal scales (e.g. daily-averaged winds) the over-lake wind field is seen to be more uniform.

A significant complication in hydrodynamical modelling is the necessity to modify land-based observations to over-lake values. Adjustments are important for such variables as wind speed and air temperature but less important for such variables as relative humidity (Schertzer 1987). Considerable research has been directed to development of methods to scale land-based observations to representative over-lake values. For wind speed, methods have ranged from simple ratios to regression techniques involving measurement height, stability, fetch and time over the lake (e.g. Phillips and Irbe 1978; Resio and Vincent 1977). Unfortunately, quite different over-lake wind speed estimates are possible depending on whether simple lake-land wind ratios (e.g. Lemire 1961; Richards et al. 1966) or more complex regression techniques (Phillips and Irbe 1978) are used (Fig. 3). Figure 4 shows an example of an interpolated over-lake wind field (Hamblin 1987). In addition to statistical approaches, the problem of predicting over-lake wind fields should be studied as a problem in mesoscale meteorological modelling.

As well as, the standard meteorological fields, the surface energy exchange is required as a source term in circulation models. In many respects, the specification of the heat flux is a more serious problem than for winds since most of the radiative and turbulent exchange components are not routinely observed at buoys. Long-term estimates of heat balance components for Lake Erie have been conducted by Derecki (1975) and Schertzer (1987) which provide the expected mean and range for monthly mean values, however, hourly estimates of flux components are generally required for driving hydrodynamical models. Most of the components must be estimates from shore-based stations and reliance on lake-land adjustments for key meteorological variables. Chu (1998) and Chu and Bedford (1998) have developed an operational method of specifying one of the heat flux components, (i.e. the over-lake incoming shortwave radiation), from GEOS-8 satellite cloudiness data.

5.2 Water Level Fluctuations : The dominant factors influencing water level fluctuations (see Fig. 5) in Lake Erie include net basin supplies, major inflow and outflows, storm surges and tides. In general, water level fluctuations on Lake Erie are well understood relative to internal motions (Mortimer 1987). Hamblin (1987) showed that due to the shallow bathymetry of Lake Erie, the lake experiences the largest astronomical tides of any of the Great Lakes and that under thick ice cover, they are a dominant oscillation throughout the lake. Large water level fluctuations associated with storm surges have the potential to cause significant damage especially for set-up from wind along the longitudinal axis of the lake. Analysis of a storm surge occurring on April 6, 1979 (Hamblin 1979) showed that a wind stress along the longitudinal axis of the lake peaking at 1.5 pa resulted in an observed set-up of 4.5 m which is the largest recorded set-up between Buffalo and Toledo. Prediction of storm surges depends on knowledge of the spatial and temporal distribution of wind stress and barometric pressure. On a synoptic scale, the barometric pressure forcing of Lake Erie is much less important than that of the wind (Hamblin 1987).

5.3 Remotely-sensed Water Movements : Much of the Lake Erie shoreline is subject to intermittent erosion and wave-induced resuspension of temporary bottom sediments especially in the shallow nearshore zones (Mortimer 1987). These processes as well as others (e.g. algal blooms and high spring-melt runoff) increase turbidity and the attenuation of light through the water column and impact on the vertical distribution of heat, particularly in the upper portion of the water column, and thus influence flow and turbulent mixing (e.g. Schertzer and Hamblin 1999). From a hydrodynamical perspective, remote sensing of higher turbidity areas (as well as other surface changes) can provide valuable information on water movements which augment direct measurements. For example, satellite images often show sediment plumes entering Lake Erie from the Detroit River and Maumee River, in addition, complex structures of plumes and eddies can indicate areas of interbasin sediment transport. Entrapment of debris between the shoreline and the offshore advancing 4°C isotherm during the April-May period often makes it possible to track the progression of the thermal bar (spring thermal front) and the beginning of the lake-wide thermal stratification. Areas of higher turbidity include the western basin, Point Pelee, the southern shore of the lake as well as erodible bluffs along the north shore between Rondeau and Long Point. Long-term (1967-1982) light attenuation coefficient for lake-wide and basin-wide cases (Fig. 6), dramatically indicates that light attenuation is greatest in the western basin throughout the ice-free period (Schertzer and Lam 1991).

6. Hydrodynamics : Thermal Structure and Water Movements

Determining the fate and transport of substances in large lake systems requires accurate prediction of circulation patterns. Specification of the current structure in a large lake system is often quite difficult since water movements can be complex. In Lake Erie, complexity is compounded by exchange between three distinct physiographic basins (Fig. 1) and the effect of thermal stratification. The following provides a brief description of the current state of knowledge of the key features of water movements in Lake Erie. We concentrate here on results from large-scale observational research.

6.1 Thermal Stratification : Water temperature exerts a fundamental influence in large lakes through its control of density stratification and the formation of ice cover which shelters the lake from the direct force of the wind. Circulation features associated with the temperature of maximum density (4°C), the present state of thermodynamical modelling and other characteristics of Lake Erie's thermal regime are reviewed in a companion paper, Schertzer and Hamblin (1999). In general, the thermal characteristics vary both temporally and spatially between the western, central and eastern basins. The shallow western basin (10m) has the smallest heat content range and has a more uniform summer vertical temperature distribution compared to the other basins. During the spring heating phase, the lake warms progressively from the western basin to the eastern basin. Unlike the deeper eastern basin (64 m), the central basin (25 m) can develop thermal stratification characteristics which have been shown to be associated with the development of hypolimnion anoxia. Long-term thermal simulations (e.g. Lam and Schertzer 1987) demonstrated that a shallow hypolimnion (i.e. thickness < 4 m and vertical diffusivity < 1 cm^2 s^{-1}) is associated with low hypolimnetic dissolved oxygen concentrations often anoxic conditions (Lam et al 1987). Hydrodynamical processes such as vertical entrainment of higher oxygenated water from the mesolimnion or intrusion of the hypolimnion of the eastern basin are seen to ameliorate such conditions.

6.2 Observed Circulation : Unlike surface temperature, circulation cannot be remotely sensed from aircraft or satellites. Further, routine flow measurements have not been taken on surveillance cruises to date. Rather, circulation has been observed in a few specialized studies, for example, those conducted by Hamblin (1971) or in large-scale intensive studies (Saylor and Miller 1987). Beletsky et al. (1999a) summarized the annual, winter and summer mean circulation of Lake Erie from historical current meter data over depths ranging from 6 to 37m. Generally, Lagrangian (i.e. drifters or dyes) and/or Eulerian (fixed current meter) measurements have been used to describe currents largely below 10 m of the surface. However, the recent development of the acoustic doppler current profiler (ADCP) has provided a method to assess currents in the upper 10 m of the water column (e.g Hamblin et al. 1996; Edwards and Culver 1999).

6.1.1 Summer or Stratified Circulation : The intensive 1979/80 summer field investigation of Lake Erie (Saylor and Miller 1987) demonstrated complex monthly-averaged currents, however, strong flow patterns generally did not persist for lengthy intervals. Several frequently observed circulation modes were documented. For example, July to September had a consistent pattern of near-bottom flow in the central basin in which a west-southwest flow of bottom water flowed parallel to the south coast. A clockwise flow pattern dominated the eastern portion of the central basin in August and September while a counter-clockwise gyre occurred in the western end of the central basin (see also Blanton and Winklhofer 1972). Saylor and Miller (1987) delineated westward flow along the south shore, eastward flow along the north shore of the central basin with bottom waters transported northward in the western part of the central basin and southward flow in the east part of the central basin. Earlier drifter studies summarized by Hamblin (1971) also suggested counter-clockwise monthly averaged currents in the eastern basin from May through August. Seasonal integration of the currents from July to mid-September revealed a general clockwise flow encircling the central basin in the mid-depth epilimnion as well as near bottom flow with near-bottom velocities of approximately 2 cm s^{-1}. In Lake Erie, thermal stratification does not play a major role in shaping the current responses although thermocline configuration clearly responds to the wind stress.

6.1.2 Winter or Unstratified Circulation : In the isothermal months of October to December 1979/80 currents were similar with near bottom current flows in directions comparable to and magnitudes slightly greater than in the summer season. Larger wind stresses in fall months only slightly increased bottom currents. In general, persistent circulation patterns were observed based on resultant current vectors, a clockwise gyre in the northern half and anticlockwise gyres in the southern portion of the central and eastern basins (Fig. 7). Saylor and Miller (1987) describe the correspondence between the observed circulation patterns and the surface wind stress field and persistence of the flow patterns. It is noted that the double counter-rotating circulation pattern is what would be expected for a prevailing wind from the west. Because of the stronger winter flow and longer period of unstratified conditions, the annual flow is indistinguishable from that of the winter (Beletsky et al. 1999a).

6.2 Basin Exchanges : Hamblin (1998) has reviewed exchange processes in lakes and found that while understanding is rudimentary, exchange flows are better understood than the associated transport of materials in these flows. The major exchange mechanisms in Lake Erie include hydraulic or riverine flow from the mouth of the Detroit River to the entrance of the Niagara River, longer-term pressure gradient driven subsurface flows that are the cumulative result of wind-driven surface flows, and to a lesser degree, flushing due to oscillating seiche motions and turbulent horizontal diffusion (Bartish 1987). The exchange between basins is complex occurring in either west or east directions and can occur across the epilimnion, mesolimnion or hypolimnion layers.

Wind and surface pressure gradients essentially control epilimnion transport between the central and eastern basins (Bartish 1987), whereas, hydraulic gradients largely influence exchange between the west and central basins. Westward transport of central basin hypolimnetic water occasionally occurs at times of east winds or in the presence of seiche oscillations (Bartish 1987; Loewen et al. 1999) through inter-island passages (Saylor and Miller 1987) and can result in rapid stratification of the western basin (Fig. 8) with deleterious impact on the benthic fauna if the central basin hypolimnion water is anoxic or near anoxic.

Horizontal exchange of colder oxygenated water from the eastern basin to the central basin hypolimnion was one mechanism of oxygen renewal in the bottom waters of the central basin considered by Burns and Ross (1972) and Burns et al. (1976). Boyce et al. (1980) and Chiocchio (1981) determined that deep layer flows occur across the Pennsylvania Ridge with 80 percent of the flow occurring through the deep channel at the southern end of the ridge, flowing through the channel turning north-west affecting the north-eastern part of the central basin. The hypolimnetic exchange had frequent reversals of 2 - 6 days and the particle excursion typically extends ~ 9 km which is just sufficient to clear the Pennsylvania Ridge and enter the other basin. Eid (1981) determined that the principal driving force for this exchange was surface wind drift and bottom return flow based on the surface pressure gradients. Slightly less intense westward currents through the channel could also contribute to bottom water renewal in the central basin hypolimnion (Saylor and Miller 1987) and westward flow of bottom water across the Pennsylvania Ridge from the east to the central basin was inferred during unstratified conditions as well (Boyce et al. 1980).

6.3 Current Oscillations : Current oscillations are an important mechanism for transport of pollutants in the mid-lake and also from the nearshore to offshore area. Characteristics of the time and space scales of horizontal motion in the mid-lake were examined by Boyce and

Chiocchio (1987). They found that motions at frequencies larger than 0.125 cph were horizontally coherent over a few kilometres only, whereas, lower frequency motions tended to cohere significantly over tens of kilometres in the stratified season. Circularly polarized clockwise rotating motion at the inertial period (about 18hr) at 15 m depth were responsible for the highest observed current speeds. Hamblin (1971) also found inertial motions in drogue trajectories. It is suggested that unexplained variance in the current is related to measurement errors, small (horizontal) scale internal pressure gradients, unidentified non-linear mechanisms, bottom topography effects and large-scale turbulence. The role of stratification in producing internal pressure gradients appears to be primarily a small-scale phenomenon, however, the role of stratification in controlling the vertical distribution of turbulence was suggested as being very important. In the central basin, the largest inertial motions tended to occur above the seasonal thermocline.

6.4 Lagrangian Current Movements and Horizontal Turbulent Motions : The dispersion characteristics of effluents and other substances in the nearshore and mid-lake areas is of particular importance especially for design of outfalls. An effective means of determining water movements is through the use of Lagrangian measurement techniques (e.g. dyes, various drogues). Extended period tracking of drogues in Lake Erie was conducted by Hamblin (1971). Recently, Sanderson (1987) examined the motion of clusters of drogues to find the mean flow as well as Lagrangian deformations and eddy-diffusivities to provide insight into which dynamical processes cause two-dimensional dispersion in the central basin of Lake Erie. It is recognized that horizontal dispersion is caused by advective processes (i.e. divergence) and eddy diffusion. Sanderson (1987) observed that during periods of weak wind, inertial motions were strongly evident in movement of (3 m depth) drogue clusters while strong winds caused acceleration in a direction related to the wind and the initial state of the water motion (Fig. 9). Water motion tended to lag the wind by about 4 to 8 hours and was about 2.8 % of the wind speed. Spectral analysis of centroid and individual drogue positions suggested that the motion at various frequencies is spatially invariant with no dispersion at the 3 m depth and that most of the variability of the cluster area occurs at frequencies lower than the inertial frequency. At greater depths, it is suggested that inertial-internal waves (i.e. Blanton and Winklhofer 1972) may be contributors to dispersion. Non-linear Lagrangian deformations are suggested to be responsible for progressive changes in cluster area. The general trend is for eddy diffusion to increase the cluster area in proportion to the elapsed time squared. Large-scale diffusion characteristics in the central basin hypolimnion, investigated using dye patch diffusion experiments (Murthy 1972), showed eddy diffusivities in the range 10^3 cm^2 s^{-1}, and drift of a dye patch over a 3 km distance in 60 hours.

6.5 Flushing and Diffusion Time-Scales : Flushing and mixing time-scales are important for chemical and biological processes. These time-scales were estimated at a control volume of 10 km diameter in the central basin at 10m, 19m and 21m below the surface (Royer et al. 1987a and 1987b). Horizontally averaged currents were used to define the flushing time-scale while local deviations from these average flows were used to compute effective diffusion coefficients, and in turn, mixing time-scales for the control volume. The presence of horizontal variability in the distribution of temperature and transport processes produced significant changes at time-scales less than a day. Flushing time-scales were 5.6, 9.1 and 9.6 days at the 10 m, 19 m and 21m depths respectively. Mixing time-scales were 27, 11.1 and 34 days at the 10 m, 19 m and 21 m depths respectively. Vigorous mixing at the 19 m depth was influenced by increased inertial frequency motion at mid-depth.

6.6 Upwelling : Upwelling refers to vertical flow along the upwind shoreline that transports cooler hypolimnetic water into the nearshore zone in response to wind forcing. In the stratified period this generally occurs along the north shore but occasionally is evident along the southern shore, depending on the wind strength and direction. This phenomenon is not as pronounced as it is for Lake Ontario because of Lake Erie's shallower depth and its orientation relative to the prevailing winds (Webb 1974). Examples of upwelling and the antecedent wind strength and directions are given by Richards et al. (1969) and by Irbe (1974) based on surface thermal mapping by an airborne radiation thermometer (ART). Satellite images also show upwelling with more spatial resolution than the ART surveys. Frequently, upwelling is localised to Long

Point Bay in the eastern basin and close to Erieau in the central basin. The western basin is too shallow and unstratified to exhibit upwelling.

The implications of upwelling on lake biota have become noticeable with the recent invasion of an exotic bottom dwelling species, the round gobie. A massive fish-kill to the west of Erieau was reported by residents beginning at 7am on September 3, 1998 (T. Johnson, Ontario Ministry of Natural Resources, pers. comm.). Dissolved oxygen near the shore ranged from 0.8 to 2.3mg/l and water temperatures were 15.3 °C in the morning. Satellite imagery on the day of occurrence does not exist due to cloud cover but the average offshore surface water temperatures were approximately 24°C that day (Schwab et al. 1999). Figure 10 shows 3-hourly observed wind speed and wind direction from shoreline stations (Detroit, Toledo, Cleveland, Erie and Buffalo) over the period August 29 to September 3, 1998. The record clearly shows that over the period of Sept. 1-3 the mean wind direction was from the SW at 225° N (generally ranging from 150° to 320° N) at an average wind speed of 3.69 m s^{-1} (2.34 - 5.54 m s^{-1}). The mean wind directions were nearly parallel to the orientation of the shore axis from Wheatley to Erieau (axis from 240° to 63° N) which would be conducive to the occurrence of upwelling along the north shore. Although this example of the transport of poorly oxygenated water into the nearshore zone is detrimental to the ecosystem health, upwelling can be beneficial by replenishing nutrient deficient epilimnetic waters.

6.7 Small-scale motions and turbulence : Small-scale motions and turbulence are particularly important processes for a range of aquatic ecosystem concerns. These processes include wind waves, turbulence, reverse entrainment between the mesolimnion and hypolimnion layer and fronts as well as others. We provide here a synopsis of current knowledge related to these processes.

6.7.1 Wind waves : The current state of knowledge of wind waves on the Great Lakes has been reviewed by Liu (1999). Lake Erie has significant wave heights that are somewhat lower than Lakes Superior, Huron and Michigan. Accurate wave forecasts are routine due to a good coverage of wind stations around and on the lake and an advanced stage of mathematical modelling.

6.7.2 Turbulence : Direct measurements of profiles of temperature microstructure are feasible with recent advances in thermistor technology. McCune (1998) has inferred the dissipation rates of turbulent kinetic energy from profiles of thermal microstructure in the offshore zone of the central basin in the western basin and related them to vertical turbulent conductivity. An example from a stormy period is shown in Figure 11. In 1994, over a zebra mussel encrusted shoal in the western basin, Loewen et al. (1999) have determined two turbulent properties, one, known as the bed friction velocity, from current profiles from self-recording current meters and the other, the effective bed roughness height under various conditions of stratification and flow. The friction velocity is related to the turbulent kinetic energy which, in turn, along with turbulent kinetic energy dissipation is employed in some circulation models to provide estimates of vertical eddy conductivity and viscosity. Various formulations for mixing need to be verified by field measurement of these quantities. Similarly, Edwards and Culver (1999) at a different site in the western basin deduced friction velocity and bed roughness height of approximately 5cm from best fits to current profiles measured acoustically within 3m of the bottom. The implications of vertical mixing and mussel filtration over the reef studied by Loewen et al. (1999) on the distribution of phytoplankton surrounding the reef are discussed by Ackerman et al. (1999).

In a survey of the the zooplankton biomass of Lake Erie, Stockwell and Sprules (1995) related plankton distributions to physical factors. Temperature appeared to be correlated with abundance as seen in Figure 12. As well, since the peak distribution is located at the intersection of the mesolimnion with the bottom augmented turbulent mixing due to the close proximity of the bed may play a role. Further measurements are needed to confirm this possibility. It is interesting that this transect demonstrates the cross basin tilt of the thermocline noted by Blanton and Winklhofer (1972) due to the deflection of wind-driven epilimnetic currents to the right of the prevailing wind direction.

6.7.3 Reverse entrainment : A remarkable aspect of the hydrodynamics of the hypolimnion of the central basin of Lake Erie is that the level of turbulent motion is thought to be more vigorous at times than in the wind and convectively stirred epilimnion. This mixing of epilimnetic water into the hypolimnion is uncommon in lakes in general and has been termed reverse entrainment. Due to the unusual situation when the hypolimnion is less thick than the epilimnion currents associated with internal seiches can exceed those in the epilimnion. This leads to strong turbulent shear stress at the bottom and consequent high levels of turbulence (Ivey and Boyce, 1982). Ivey and Patterson (1984) formulated a bottom mixed layer model based on the physics of reverse entrainment and observation of flow in the hypolimnion which was incorporated into their vertical thermal simulation model. Based on the successful application of this approach to hypolimnetic mixing in the central basin, Patterson et al. (1985) added dissolved oxygen to their water quality model. McCune (1998) observed temperature microstructure during a storm in the central basin and likely reverse entrainment (Fig. 11).

6.7.4 Fronts : Schertzer and Hamblin (1999) state that the well known thermal front associated with the temperature of maximum density, the thermal bar, is not pronounced in Lake Erie due to its shallow bathymetry. Schertzer et al. (1987), however, showed that there is pronounced warming progressing from the shallow west basin to the central and east basin during the early spring period. Satellite photos indicate that the disappearance of the 4°C isotherm takes ~ 5 weeks which is similar to the other Laurentian Great Lakes. Ullman et al. (1998) provide examples of fronts defined by surface temperature as determined by analysis of satellite thermal imagery.

7. Circulation Modelling

Determination of lake circulation is important for understanding the distribution of substances in a lake. In one of the earliest modelling studies, numerical simulation of lake-wide advective and diffusive transports were conducted using chloride as a conservative tracer (Hamblin 1975).

Model simulations, showed high chloride concentrations on the south shore of the central basin due to local river discharges. High and low concentration patches were also observed to occur in the central basin. Chloride transport in the western basin closely resembled simulations in which loadings from the Detroit River are carried by the eastern half of the River. The gradient of chloride in the eastern basin was always small indicating that it is a well mixed region.

Simons (1976) applied a numerical model to Lake Erie to compute water transports. Under quasi-homogenous conditions a vertically integrated model was used and under summer stratification a two-layer model was applied. Many of the features suggested by Saylor and Miller (1987), including clockwise circulating gyres in the epilimnion are simulated by the numerical models.

Schwab and Bennett (1987) examined low-frequency (sub-diurnal and inertial) fluctuations in currents in Lake Erie with numerical model predictions. Comparison of the numerical model output with Lagrangian tracers, suggested that it has the advantage of integrating the circulation pattern as opposed to previous single point vector time-series comparisons. Comparison of simulated particle trajectories with Lagrangian drifter observations indicated that modeled trajectories over the course of a storm event in the central basin differed from the observed by 8.5 km or more after 5 days compared to a mean distance travelled of 14.9 km.

Ideally, circulation models should be available for real-time forecasting for hazard warning and avoidance, enhancement of commercial and recreational activity and natural resource preservation. Recently, Schwab and Bedford (1994) developed a Great Lakes Forecasting System in which 3-d baroclinic models can be applied for short-duration runs on a routine basis on either a supercomputer for high resolution (2 km) grids or a workstation for lower resolution (5 km) grid. Validation of the 3-d circulation and heat transport models is described in Kuan (1995) and Kuan et al. (1995). Except for water level, comparisons of modelled currents and temperatures with point observations show less favourable correspondence. Kuan et al. (1995) found that these variables had to be averaged across the central basin in order to demonstrate agreement with corresponding observations. Recently, a breadth averaged two-dimensional model has been compared to field temperature profiles in the central basin at the location shown in Figure 1 by Schertzer and Hamblin (1999) and for currents in Figure 13. This model was driven by meteorological forcing at two stations shown in Figure 1.

8. Longer-term Potential Changes and Projections

Hydrodynamical and well as thermodynamical processes in large lakes are influenced by atmospheric forcing. Lake measurement programs and modelling have been instrumental in defining the means as well as ranges in key components of the water movements and thermal characteristics of the lake. Understanding of the potential changes to lake circulation patterns and related hydrodynamical components under changed surface forcing such as might occur through climatic change is not well understood. Lam and Schertzer (1999) have prepared a state-of-the-art review of potential climate change effects on Great Lakes hydrodynamics and water quality. An important finding is that modeling techniques for the simulation of climate change effects on lake hydrodynamics are available, however, the data input to these models, particularly for long-term climate scenarios, do not always exist. It is recognized that use of available data combined with existing hydrodynamical modelling with appropriate climatic scenarios is an important initial step in understanding possible consequences of meteorological change on lake hydrodynamical components. Much work needs to be done in all aspects of the lake hydrodynamical and thermodynamical simulation capability in this regard. We provide here a brief synopsis of some of the findings related to lake hydrodynamics. In addition, we provide an example of possible influence of zebra mussels on affecting currents through re-engineering of the lake bed.

8.1 Changes in Surface Forcing and Major Flows : Climate (weather) has a significant role in the physical processes occurring in aquatic systems. As demonstrated in the previous discussion, major forcing occurs through the action of surface heat exchanges, precipitation and wind. Recently, there has been growing consensus by climate modelers, (e.g. Zwiers and Kharin 1998), that global air temperatures will rise 2 to 4 °C with increasing concentrations of atmospheric greenhouse gases depending on location but that winds will decrease. Lower wind speeds could partially compensate increased air temperatures through lower turbulent energy fluxes. Croley et al. (1996) projected significant reductions in the net basin inflows to the Great Lakes ranging from -23 % to -51% compared to current climate conditions. It is anticipated that temperature changes in the magnitude 2 to 4 °C could have significant effects on the circulation of the Great Lakes. A review of regional climate change impacts on the Great Lakes basin (Schertzer and Croley 1997; Schertzer and Croley 1999) is based on a range of climate scenarios which include those derived from Global Circulation Models (GCM's) (e.g. the Canada Climate Centre GCM, CCC-II) and also from climate transposition scenarios.

8.2 Lake Currents and Circulation Patterns : Beletsky et al. (1999b) examined the large-scale circulation patterns of the Great Lakes. An extension to their analysis was consideration of possible changes to the circulation of the Great Lakes under climate warming. Setting aside complications related to numerical modelling and known deficiencies in GCM derived climate scenarios, it is hypothesized that milder winters leading to longer stratification periods (McCormick 1999) and less ice cover (Assel 1999) combined with lower wind speeds and water levels (Croley 1996; Schertzer and Croley 1999; Schertzer and Hamblin 1999) could have an impact on currents. Since the amplitude of the currents is proportional to wind speed and density gradients, and inversely proportional to depth, Beletsky et al. (1999b) suggest that an increase in the duration of thermal stratification period will increase the duration and amplitude of the density driven currents. In addition, it is suggested that a decrease in ice cover during warm winters may also increase the transfer of momentum from wind to currents. A decrease in water level may also increase current amplitude in shallow regions. Alternatively, a decrease in wind speed may result in a compensating decrease in current amplitude. There is even less confidence in specifying possible changes to lake circulation patterns compared to currents.

8.3 Re-Engineering of the Lake Bed by Mussels : With the continued colonization of the bottom of Lake Erie by two species of freshwater mussels the characteristics of the bed and the near-bed boundary layer are likely to change. For example, laboratory experiments have demonstrated that the jets emanating from marine bi-valve exhalant siphons have significant impacts on the properties of the boundary layer (Monismith et al. 1990 and O'Riordan et al. 1995). Presently, mussels are considered to occupy most of the hard substrate and to expand into softer material at an estimated rate of 1000.5 ± 6.3 km^2 yr^{-1} (Haltuch and Berkman, 1999). The bed roughness is particularly important for circulation in the western basin, nearshore regions and in the hypolimnion during stratified periods. For the purposes of illustration consider a change in the bed roughness from an appropriate value for sand and mud of 0.1mm to 10 cm for a highly developed mussel colony (Loewen et al. 1999). In this case the bottom drag coefficient would increase by an order of magnitude. Surface seiches and storm surges would be more highly damped than they are at present and currents generally weaker especially near the bottom. On the other hand, in cases where bedforms form the main bed roughness elements, mussels preference for occupying the troughs between the bedforms may decrease the effective roughness.

As well as biotic induced roughness changes the new organisms are likely to alter the cohesive strength of cohesive sediments. Without further field investigation it is impossible to say whether these changes will augment or decrease sediment resuspension due to bottom currents and wind wave orbital motions.

9. Summary and Recommendations

An understanding of hydrodynamical processes in large lake systems such as Lake Erie is critical to understanding of many ecosystem processes including the water quality of lakes. The primary focus of this review has been to describe key areas of hydrodynamical research in which elements of water movements, its variability and potential changes are considered. The key processes which have been discussed include a brief review of the observational data sources, important aspects of meteorological forcing on water movements and fluctuations, primary hydrodynamical elements describing the main features of the stratified and unstratified circulation, basin exchanges, current oscillations and diffusion including discussions on small-scale motions and turbulence. Finally, advances in circulation modelling and longer-term potential changes and projections were considered. Case study examples were used to highlight some of the major features of the water movements in Lake Erie. While a number of studies have advanced understanding of lake hydrodynamics, large-scale investigations such as Project Hypo and the Lake Erie Bi-national Study are the most notable.

A consistent finding from the preceding is that the circulation of Lake Erie is complex and less well known than the thermal regime for several reasons. Foremost, is lack of routine monitoring both spatially and temporally except for very specialized collaborative programs between NWRI, GLERL and others. Another difficulty has been in measurement. A new generation of instrumentation such as the ADCP shows promise in helping to understand the current regime in the upper reaches of the water column. As for modelling of circulation, uncertainties occur in over-lake meteorological forcing due to paucity of meteorological buoys and the bias of meteorological observations to south-shore locations. The existing land-based meteorological networks are utilized to derive over-lake values using empirical corrections in conjunction with buoy data, however, further advances may be possible by integrating results from operational mesoscale meteorological modelling. To date, there have been some initial work along these lines and more research should be encouraged to integrate results into large-scale circulation models. Accurate estimation of the surface heat flux is critical for hydrodynamical modelling. A valuable consideration from a hydrodynamical perspective would be to measure incoming radiation components (e.g. solar and longwave radiation fluxes) on meteorological buoys as well as at shore-based meteorological stations.

Lake Erie is relatively shallow with a long east-west fetch. This renders it susceptible to extreme water level fluctuations from storm surges. In addition, Lake Erie has experienced large extremes in water levels partly due to its down stream location in the Great Lakes system. These factors, in addition to wave activity, contribute to sediment resuspension and erosion with different intensities in the three basins. Little is known of the possible effects of climatic change on extreme water level fluctuations such as storm surges or consequences on wave activity although a reduction in wind speed over the Great Lakes may have an influence on the intensity of these processes.

Water movements in Lake Erie are complex and a combination of measurements and models have been successful in describing many of the main features which have an impact on the fate and distribution of substances in the system. Current measurements have identified frequently observed large-scale circulation patterns in the Lake Erie basins including the occurrence of clockwise and anticlockwise gyres in the central and eastern basins. New instrumentation such as acoustic doppler profilers is showing promise in measuring currents while microstructure profilers are capable of measuring turbulent characteristics. Work on turbulent mixing (e.g. D. Culver, and associates) is particularly promising and should be further related to more easily measured variables such as current and temperature. Application of two and three dimensional continuously stratified models to Lake Erie is showing some potential. Circulation modelling is still unreliable on a point by point basis. The same recommendations made by Schertzer and Hamblin (1999) with regard to thermal modelling would apply to hydrodynamic modelling.

It was noted that potential changes to lake circulation patterns and related hydrodynamical components under changed surface forcing such as might occur through climatic change is not well understood. It is apparent that modelling techniques for the simulation of climate change effects on lake hydrodynamics are available, however, the data input to these models, particularly for long-term climate scenarios, do not always exist. More research is required to apply appropriate climatic change scenarios to existing or modified hydrodynamical modelling as an important initial step in understanding possible consequences of meteorological change on lake hydrodynamical components. There have been hypothetical investigations which have provided some insight to possible future changes in currents and circulation from climatic warming. For example, it is known that changes in circulation and mixing are closely related to changes in the thermal regime. Thermal modelling using GCM derived and climate transposition scenarios have indicted that it is possible that Lake Erie could change from a dimictic to a monomictic lake. Such a change in the thermal characteristics would exert a profound influence on the winter circulation and mixing. In addition, weaker wind forcing expected from climate change in combination with increased bottom friction due to the presence of mussels may lead to a reduction of the strength of lake circulation and mixing which could have consequences on the biology and chemistry of Lake Erie.

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Figure Captions

Figure 1. Lake Erie bathymetry, basin boundaries, locations of primary shore-based meteorological stations and the two buoys and FTP mooring described in this paper.

Figure 2. Station locations from Lake Erie Binational Study (from Saylor and Miller, 1987).

Figure 3. Comparison between Lake Erie long-term monthly mean wind speeds derived from land station data with over-lake estimates based on two different lake-land transformation techniques.

Figure 4. Example of over-lake interpolated wind field (from Hamblin, 1987).

Figure 5. Lake Erie mean monthly water level and years with extreme maximum and minimum levels. (based on Canadian Hydrographic Service, DFO, 1999).

Figure 6. Seasonal variation of mean vertical light extinction coefficient for lake-wide and basin-wide cases in Lake Erie based on 1967-1982 lake surveys (from Schertzer and Lam 1991).

Figure 7. Generalization of a dominant circulation pattern observed in Lake Erie. (from Saylor and Miller 1987)

Figure 8. Extreme upwelling of the hypolimnion in the western end of the central basin, in a normalized longitudinal section of the western and central basins. The inset above indicates the station locations from which the section was drawn. (from Bartish 1987)

Figure 9. Centroid trajectory for 3 m depth drogues in Lake Erie showing strong inertial motions. Points are at 20-minute intervals. Four-hour averages of the wind velocity vectors are

superimposed for periods when wind speed exceeded 5 m s^{-1}. The tail of the wind vector starts at the centroid position at the start of the 4-hour interval. (from Sanderson 1987)

Figure 10. Three-hour records of (a) wind speed, and (b) wind direction for Detroit, Toledo, Cleveland, Erie and Buffalo for the period August 29 to September 3, 1998 corresponding to the occurrence of upwelling along the north shore of Lake Erie between Wheatley and Erieau.

Figure 11. Examples of profiles of turbulent kinetic energy(ε, bars), vertical eddy diffusivity (K_z, solid circles) and temperature (continuous curve) in the central basin of Lake Erie (adapted from McCune 1998)

Figure 12. Offshore to onshore transect 50km east of Cleveland in June 1993; (a) zooplankton biomass (wet mg/l), and (b) temperature. (from Stockwell and Sprules 1995).

Figure 13. A preliminary result of an application of a 2-d modelling in the circulation modelling of Lake Erie undertaken using the breadth-averaged version of the equations of motion and heat transport equations. Longitudinal components of flow simulations at four depths are compared to measurements at the mid-axis in the central basin taken in 1994. Dots represent model simulation and the thin line represents observations. (from Boegman et al. 1999)

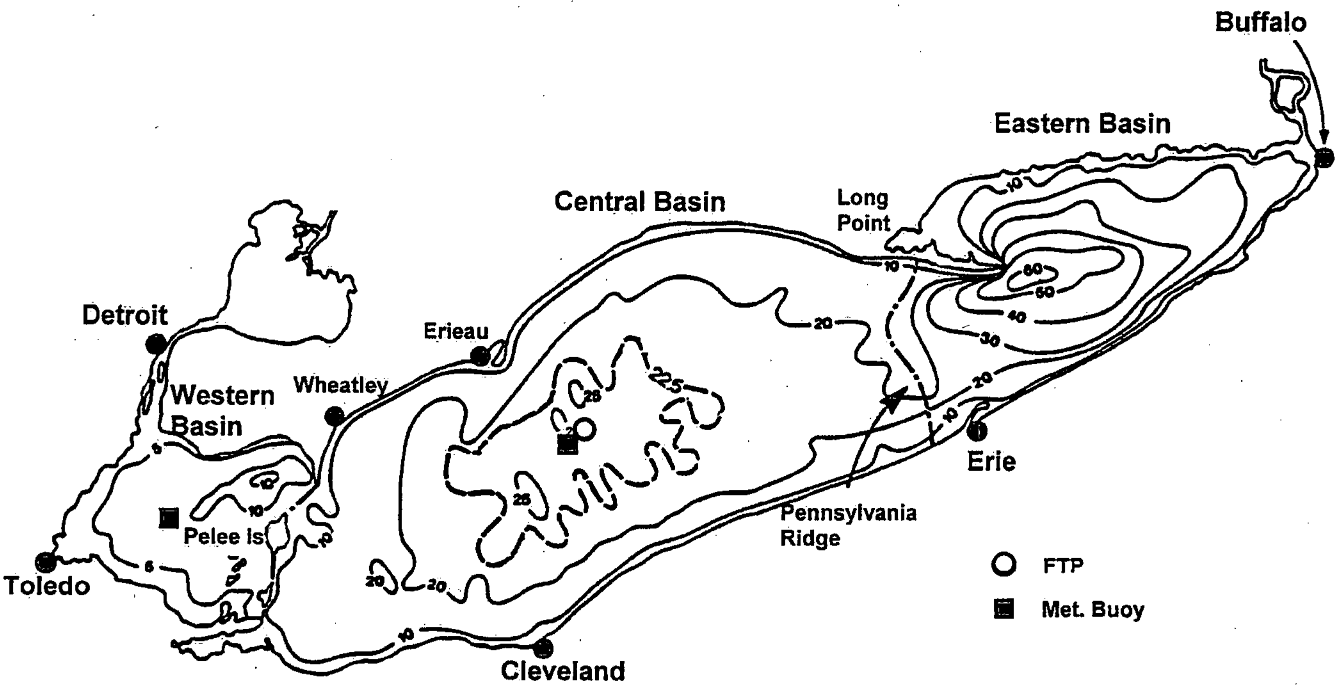
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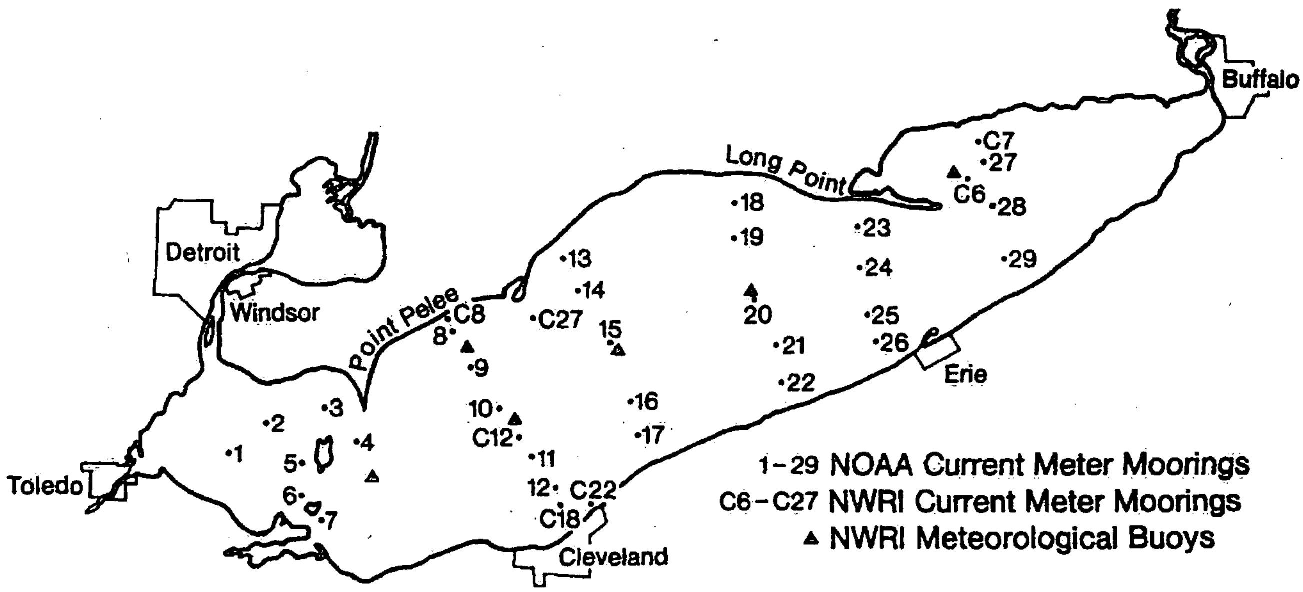
Figure 1



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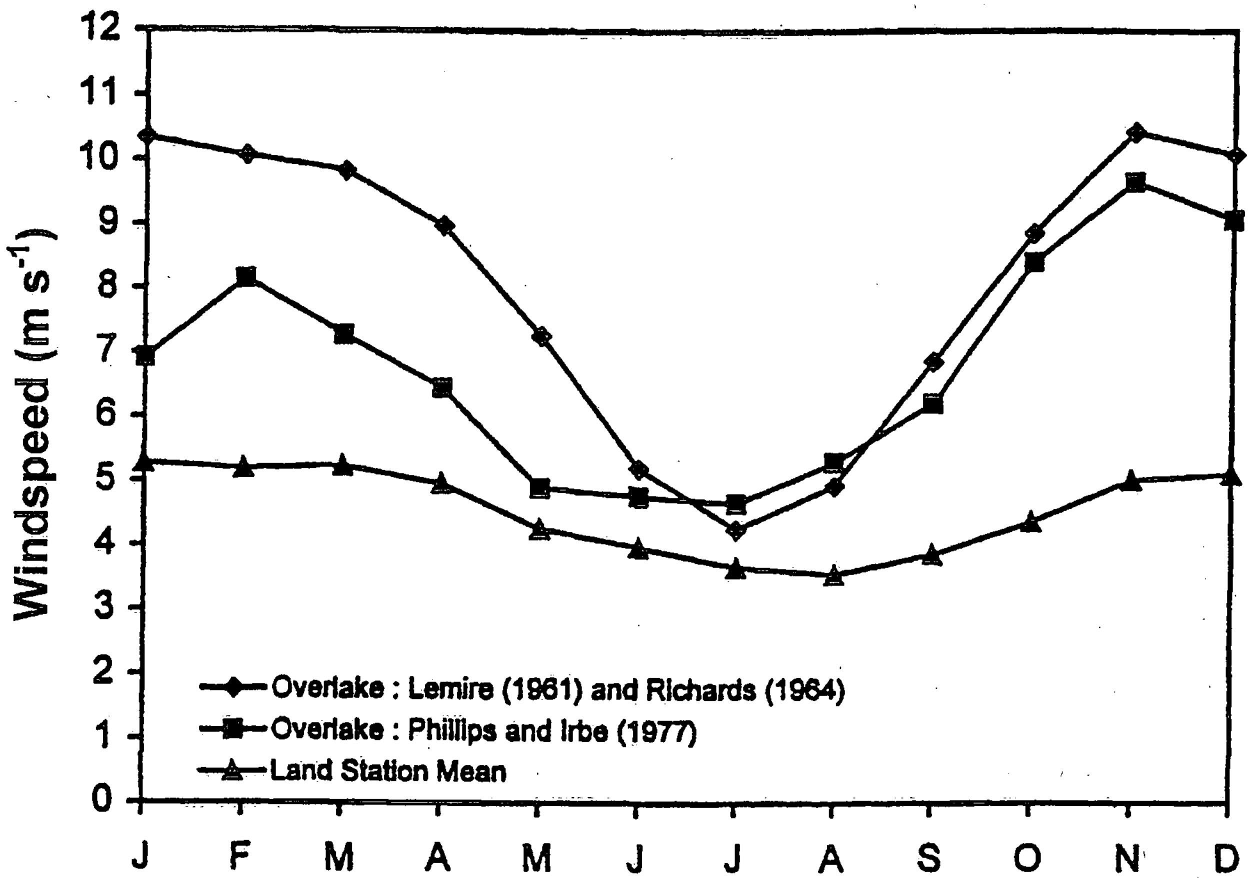
▲ NWRI Meteorological Buoys

Figure 2



Windspeed (m s-1)
12
11
10
9
8
7
6
5
4
3
2
1
0
J F M A M J J A S O N D
Overlake : Lemire (1961) and Richards (1964)
Overlake : Phillips and Irbe (1977)
Land Station Mean

Figure 3

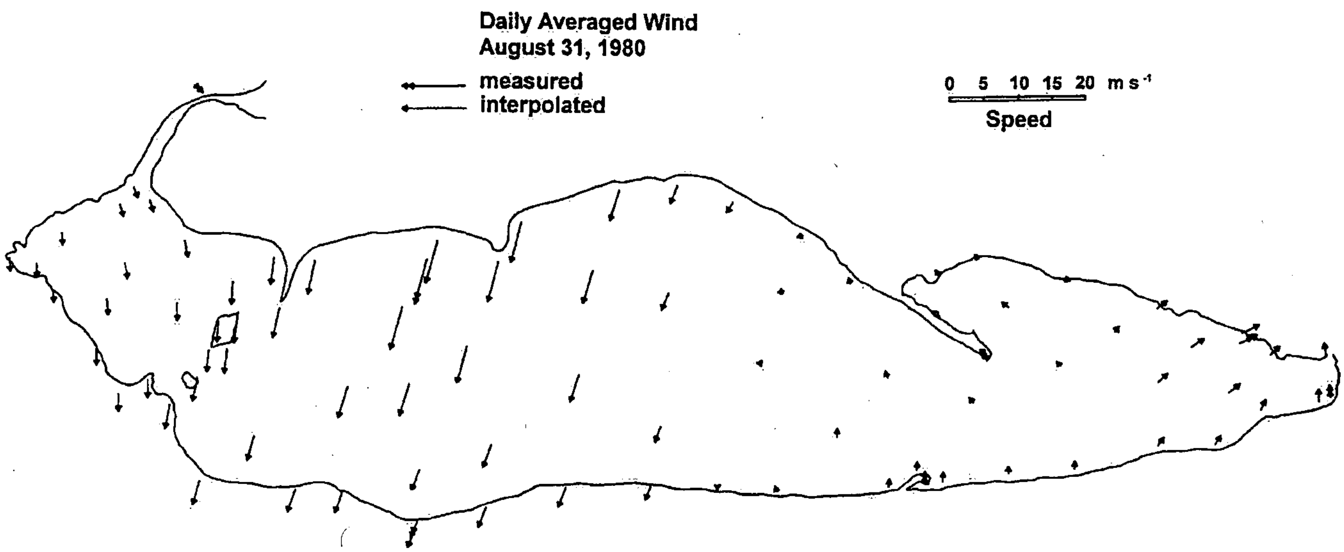
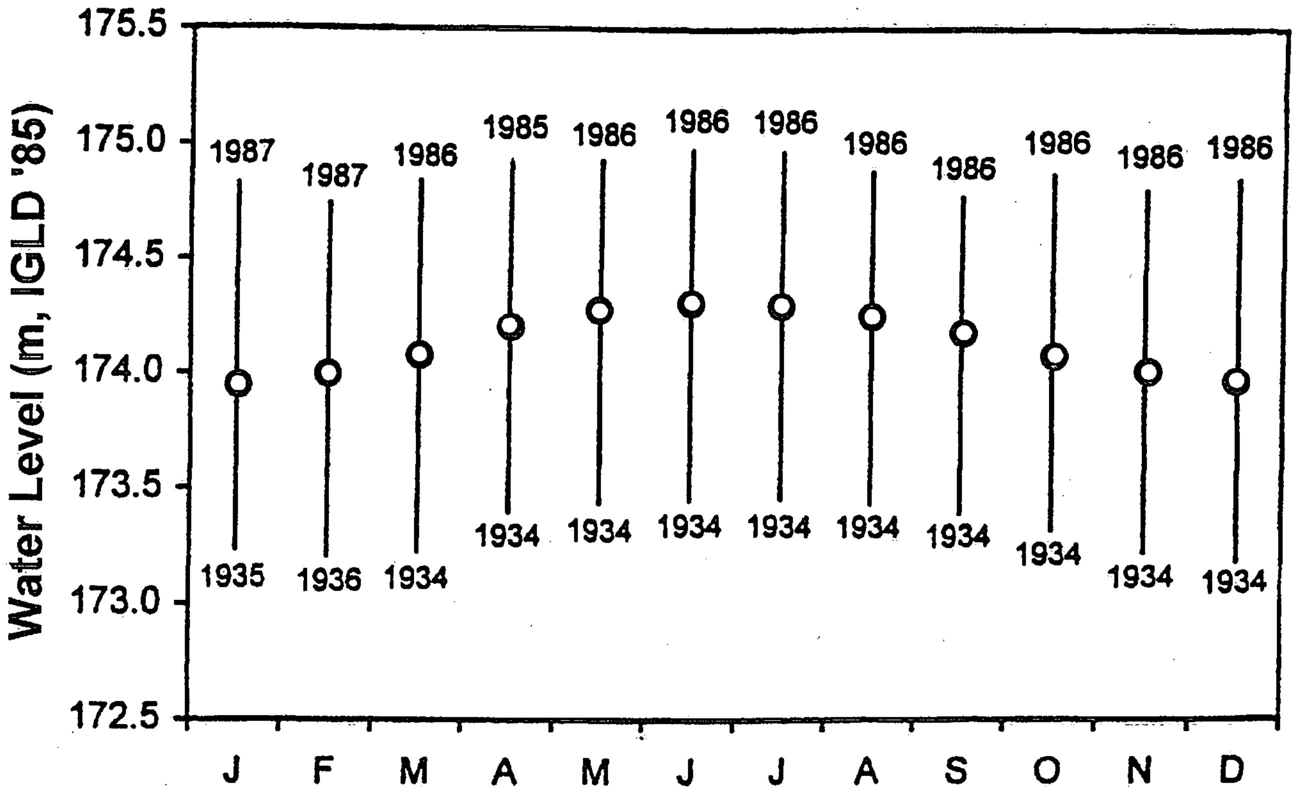
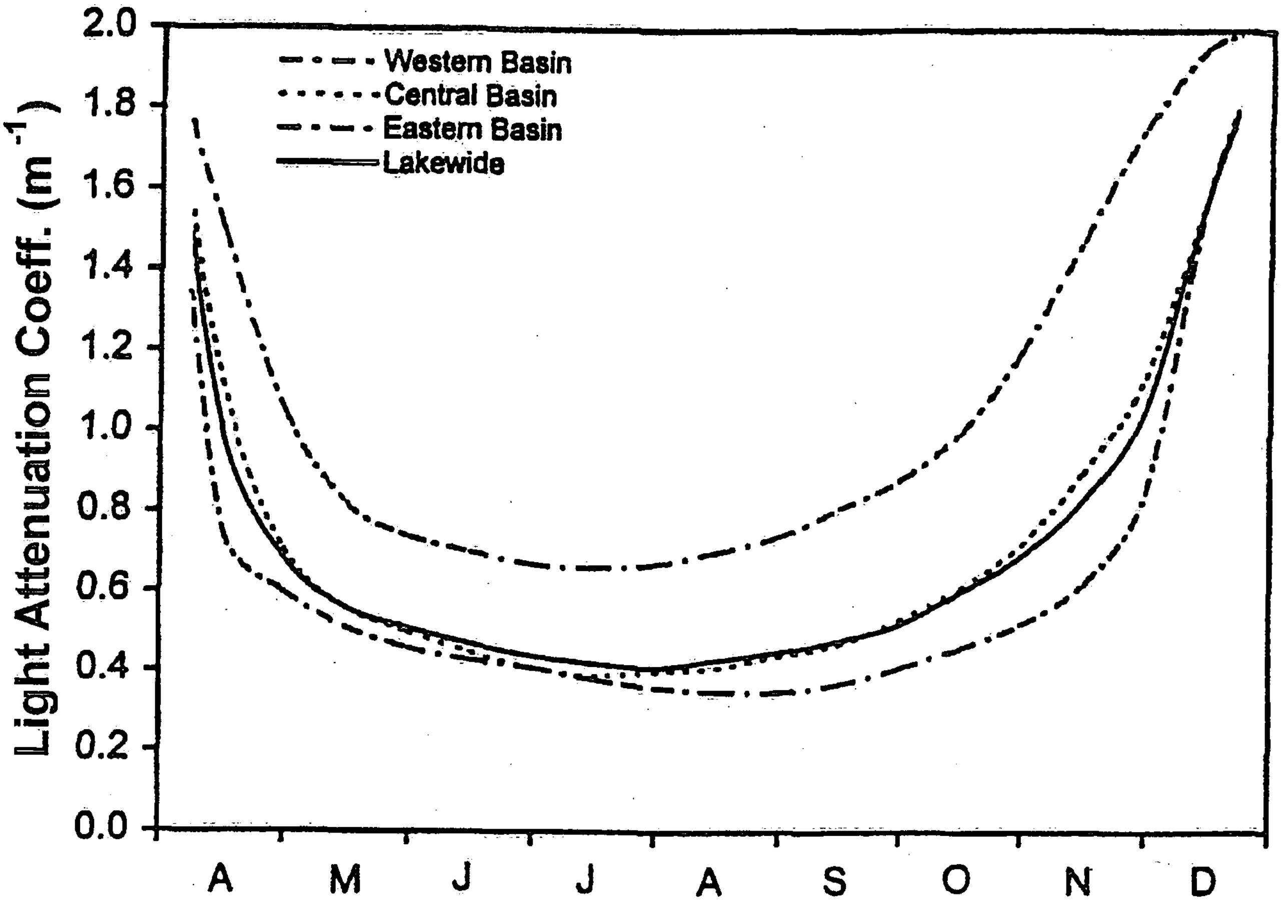

Daily Averaged Wind
August 31, 1980
measured
interpolated
0 5 10 15 20 m s-1
Speed

Figure 4



Water Level (m, IGLD '85)
175.5
175.0
174.5
174.0
173.5
173.0
172.5
1987
1987
1986
1985
1986
1986
1986
1986
1986
1986
1986
1986
1935
1936
1934
1934
1934
1934
1934
1934
1934
1934
1934
1934
J
F
M
A
M
J
J
A
S
O
N
D

Figure 5



Western Basin
Central Basin
Eastern Basin
Lakewide
Light Attenuation Coeff. (m⁻¹)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
A
M
J
J
A
S
O
N
D

Figure 6

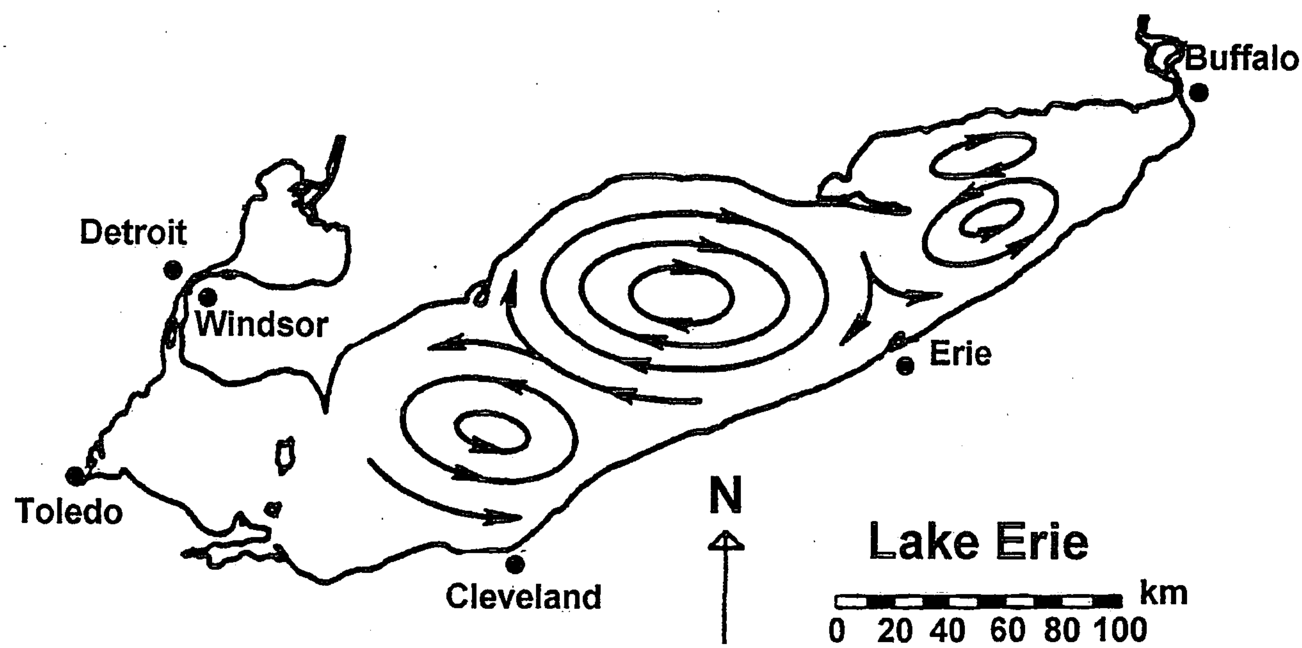

Buffalo
Detroit
Windsor
Erie
Toledo
Cleveland
N
Lake Erie
km
0 20 40 60 80 100

Figure 7

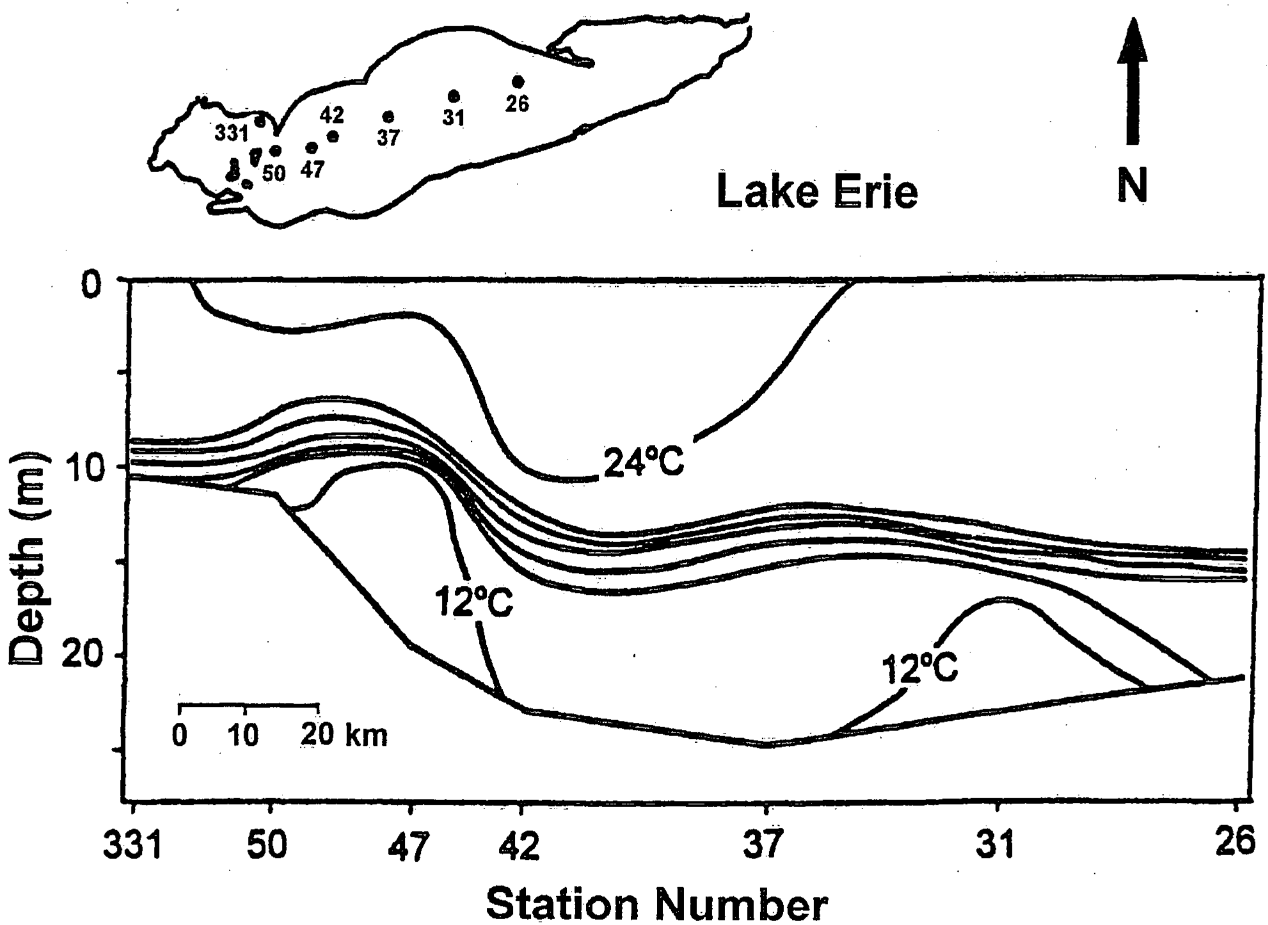

Lake Erie
N
331
50
47
42
37
31
26
24°C
12°C
12°C
0 10 20 km
Depth (m)
0
10
20
331
50
47
42
37
31
26
Station Number

Figure 8

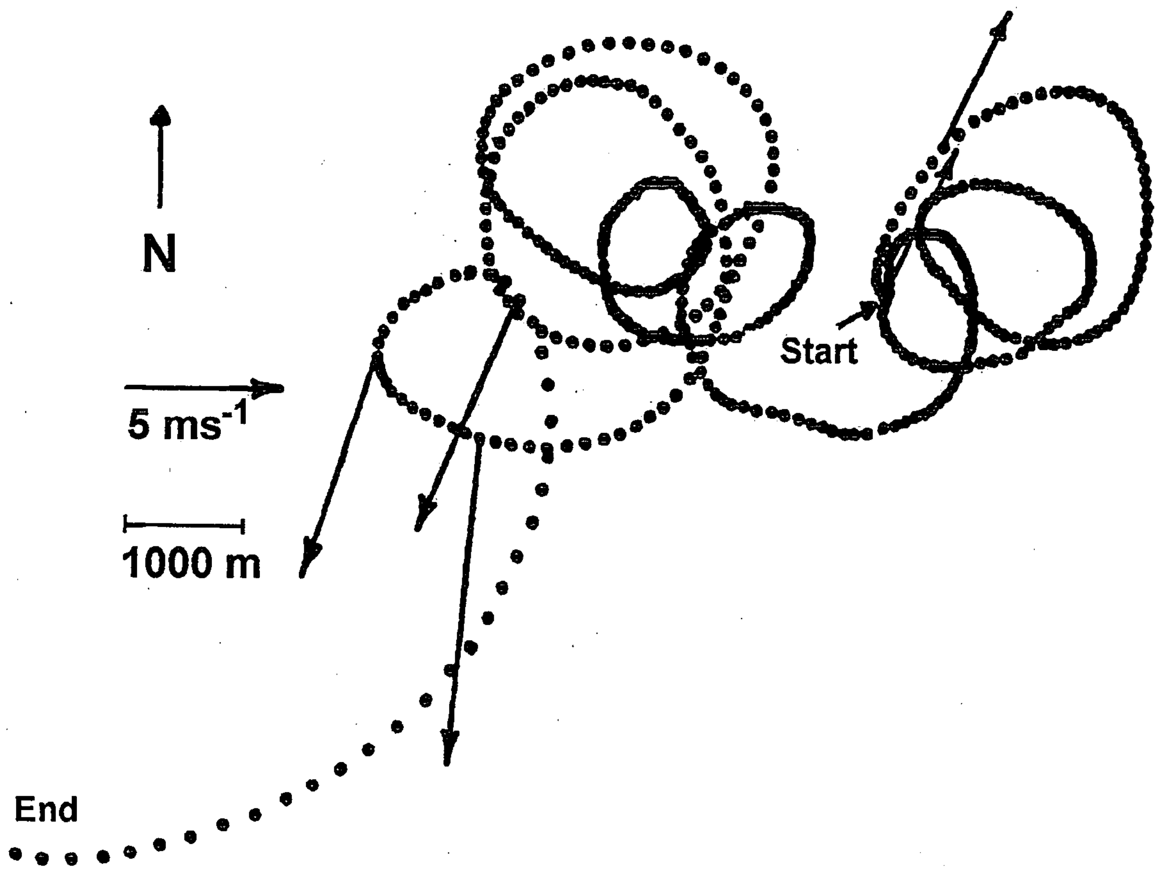
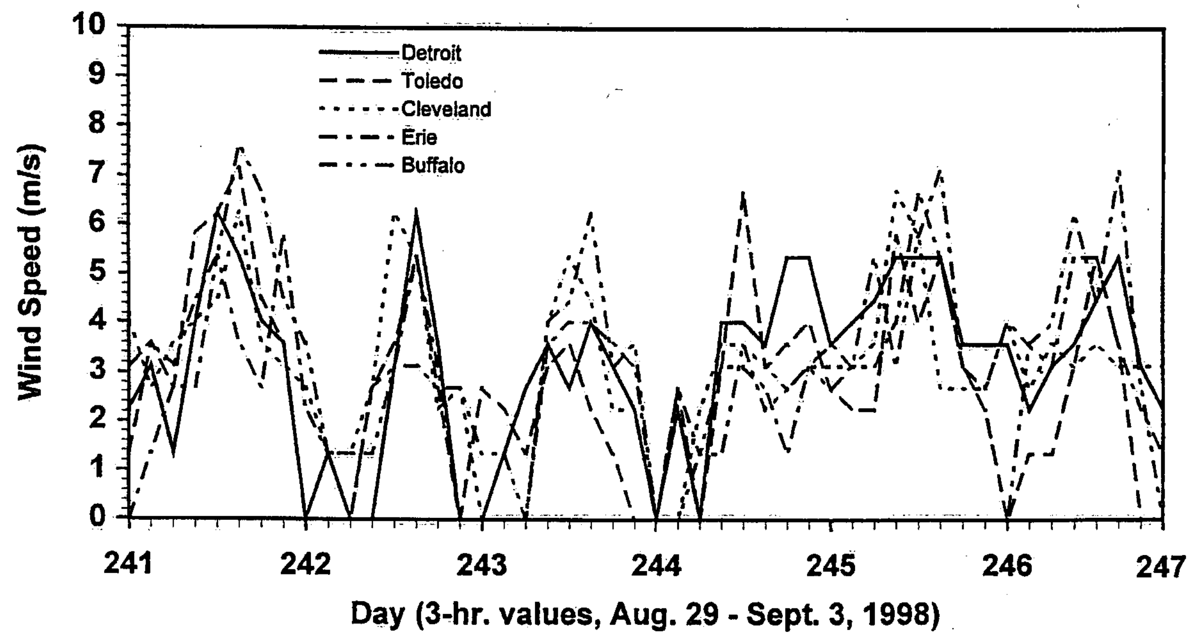


Figure 9


Wind Speed (m/s)
10
9
8
7
6
5
4
3
2
1
0
Detroit
Toledo
Cleveland
Erie
Buffalo
241
242
243
244
245
246
247
Day (3-hr. values, Aug. 29 - Sept. 3, 1998)

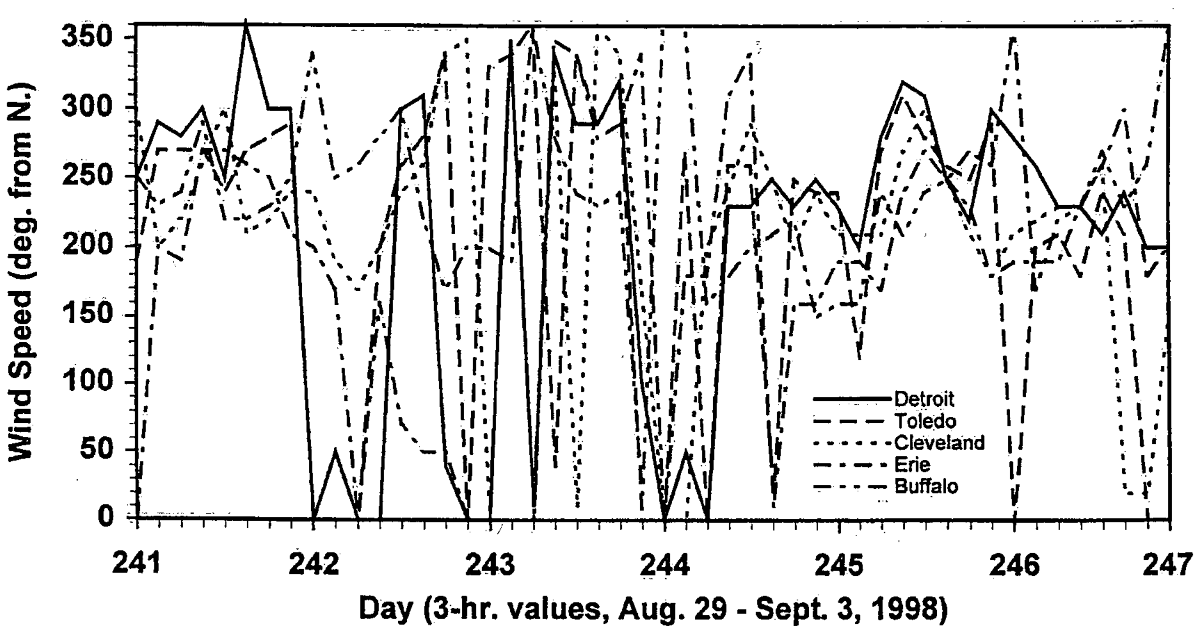
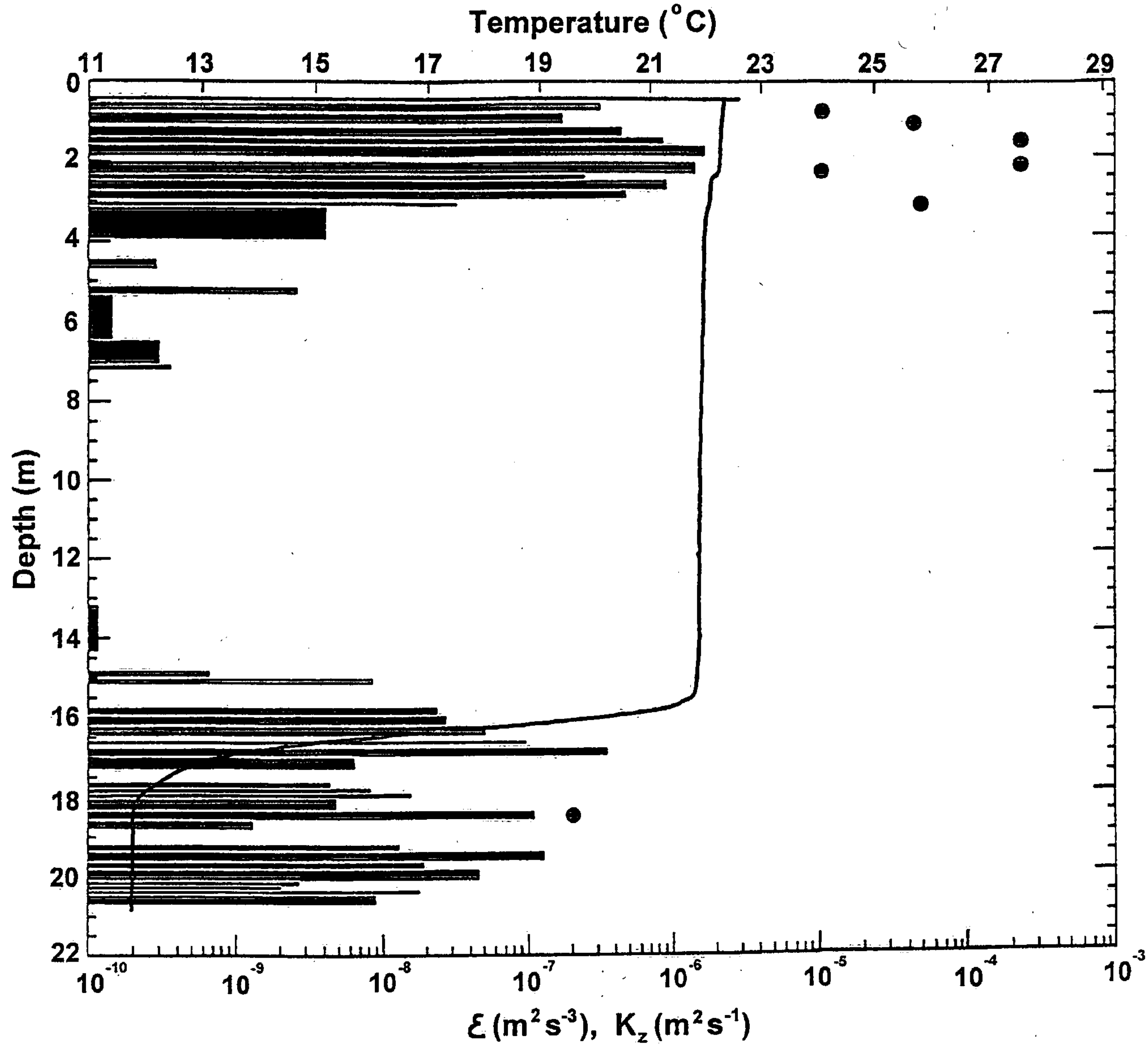

Wind Speed (deg. from N.)
350
300
250
200
150
100
50
0
Detroit
Toledo
Cleveland
Erie
Buffalo
241
242
243
244
245
246
247
Day (3-hr. values, Aug. 29 - Sept. 3, 1998)

Figure 10



Temperature (°C)
11
13
15
17
19
21
23
25
27
29
Depth (m)
0
2
4
6
8
10
12
14
16
18
20
22
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
ε ($m^2 s^{-3}$), K_z ($m^2 s^{-1}$)

Figure 11

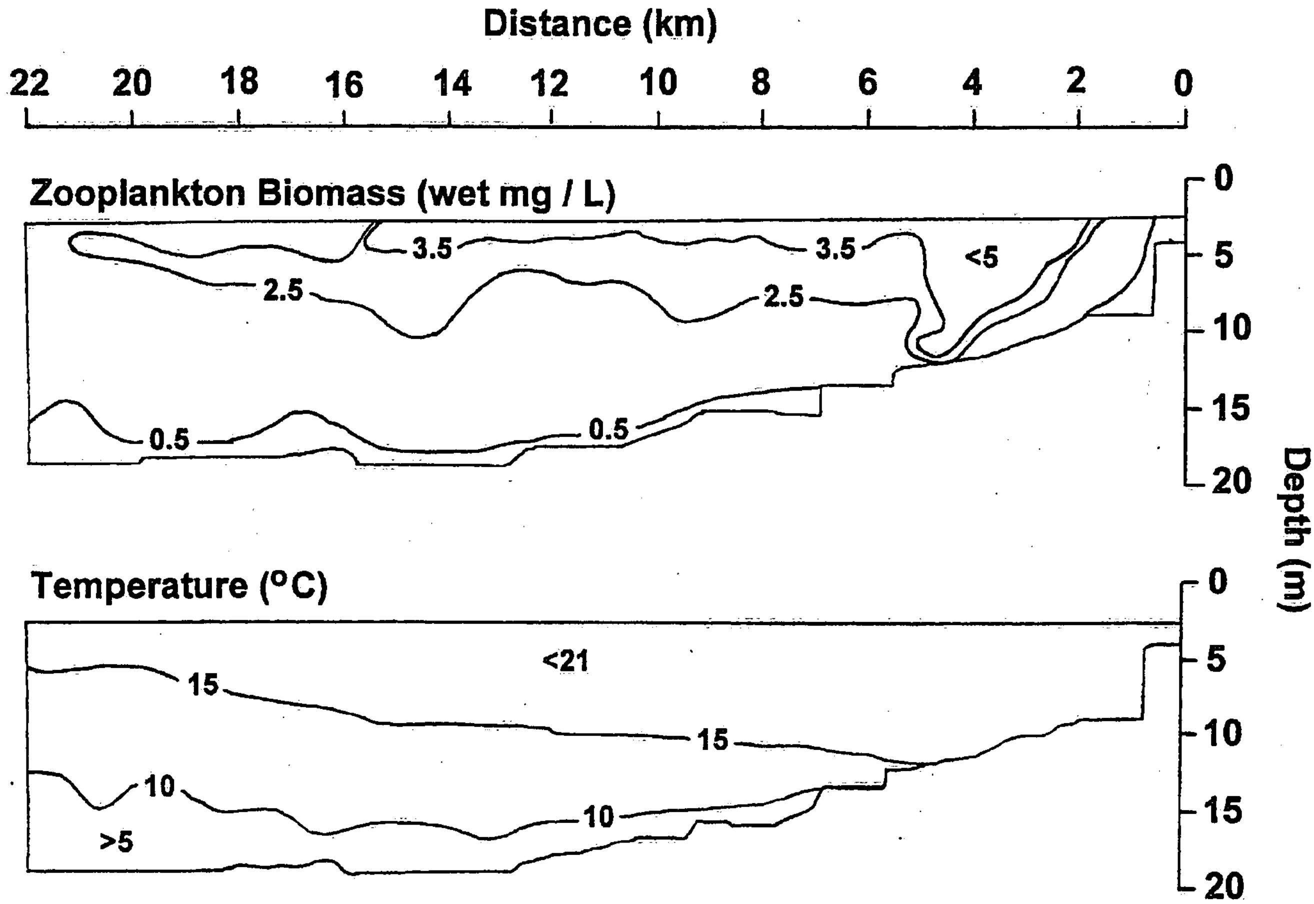
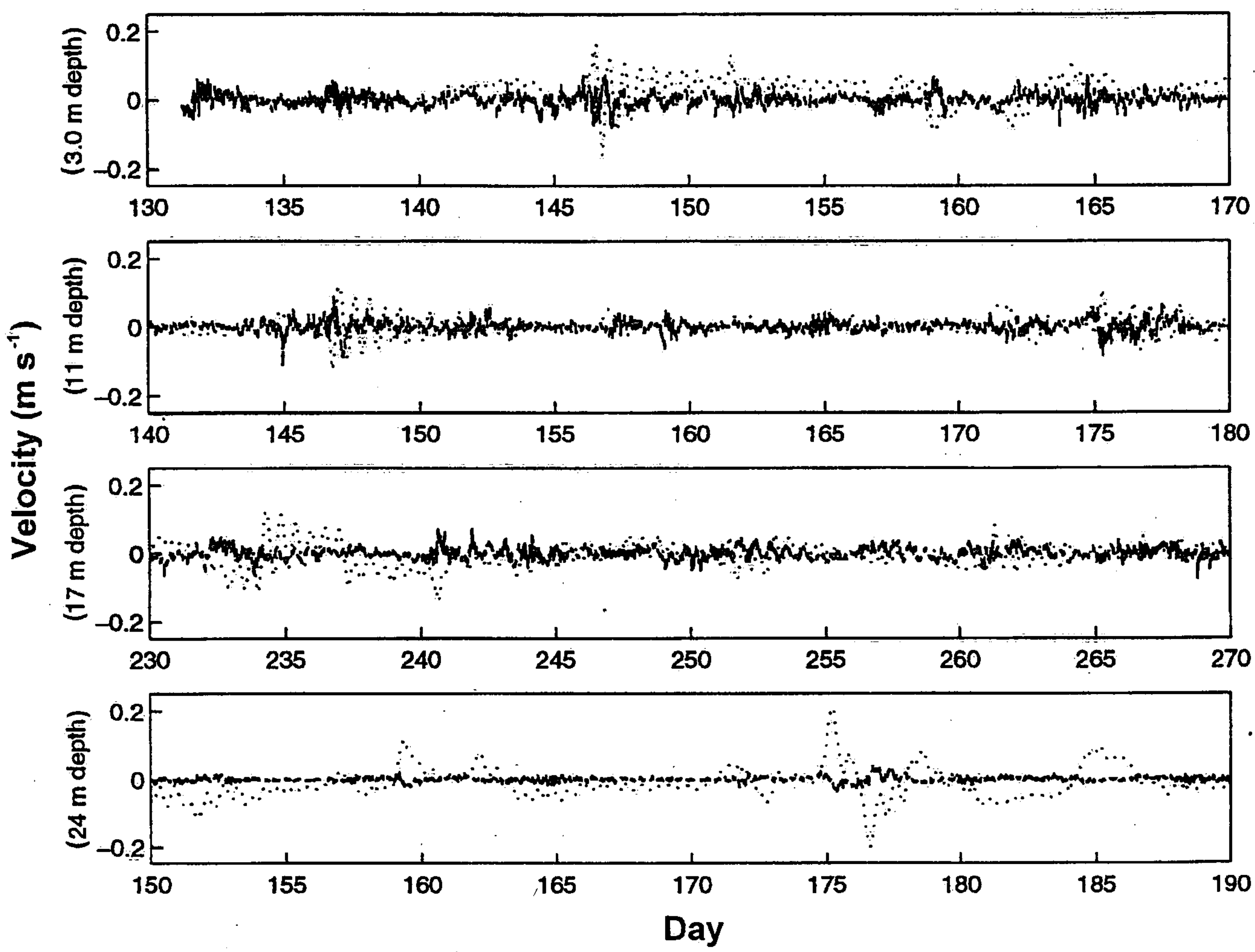

Distance (km)
22 20 18 16 14 12 10 8 6 4 2 0
Zooplankton Biomass (wet mg / L)
3.5
3.5
<5
2.5
2.5
0.5
0.5
Temperature (°C)
<21
15
15
10
10
>5
0 5 10 15 20
0 5 10 15 20
Depth (m)

Figure 12



Velocity (m s^{-1})
(3.0 m depth)
(11 m depth)
(17 m depth)
(24 m depth)
0.2
0
−0.2
130 135 140 145 150 155 160 165 170
140 145 150 155 160 165 170 175 180
230 235 240 245 250 255 260 265 270
150 155 160 165 170 175 180 185 190
Day

Figure 13

Environment Canada Environnement Canada

Canada

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