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Canada and the USA Cooperating

Nearshore Waters of the Great Lakes

1.0 Introduction

In October 1994, the governments of the United States and Canada convened the first State of the Lakes Ecosystem Conference (SOLEC '94). The conference was designed to further the purpose of the Great Lakes Water Quality Agreement between the United States and Canada, which aims to restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes basin ecosystem. Background papers prepared for the conference and discussions that occurred at SOLEC '94 are summarized in a document prepared by the U.S. and Canadian governments titled "State of the Great Lakes 1995" (EC and EPA 1995). A second, follow-up conference (SOLEC '96) scheduled for fall 1996 is designed to focus more intensively on the status of the Great Lakes coastal ecosystem, which includes the coastal shorelands, coastal wetlands, and coastal or nearshore waters. A major objective of SOLEC '96 is to examine the effects of human activity-and particularly land-use practices-on the coastal ecosystem. The present paper is designed to provide background information that will facilitate discussion of the status of the nearshore waters element of Great Lakes coastal ecosystems.

2.0 The Nearshore Waters as a Significant Natural Element of the Great Lakes Basin Ecosystem

The Great Lakes basin ecosystem covers about 760,000 km^2 (USEPA and GC 1995), spans 9^{o} of latitude and 19^{o} of longitude, and lies halfway between the equator and the North Pole in a lowland corridor that extends from the Gulf of Mexico to the Arctic Ocean (Figure 1). The Great Lakes, which are the most prominent feature of this system, have a combined surface area of about 244,000 km^2, a volume of 22,700 km^3, and are the largest single collection of fresh water on the surface of the earth, excluding the polar ice caps (TNC 1994). The Great Lakes basin ecosystem has been divided into major elements by TNC (1994), Dodge and Kavetsky (1995), and Edsall (1996). These elements basically include open lake (including nearshore and offshore waters); connecting channel; wetland (including coastal and inland wetland); tributary; coastal shore; lakeplain; and terrestrial inland. This paper focuses on the Nearshore Waters as a significant element of the Great Lakes basin ecosystem.

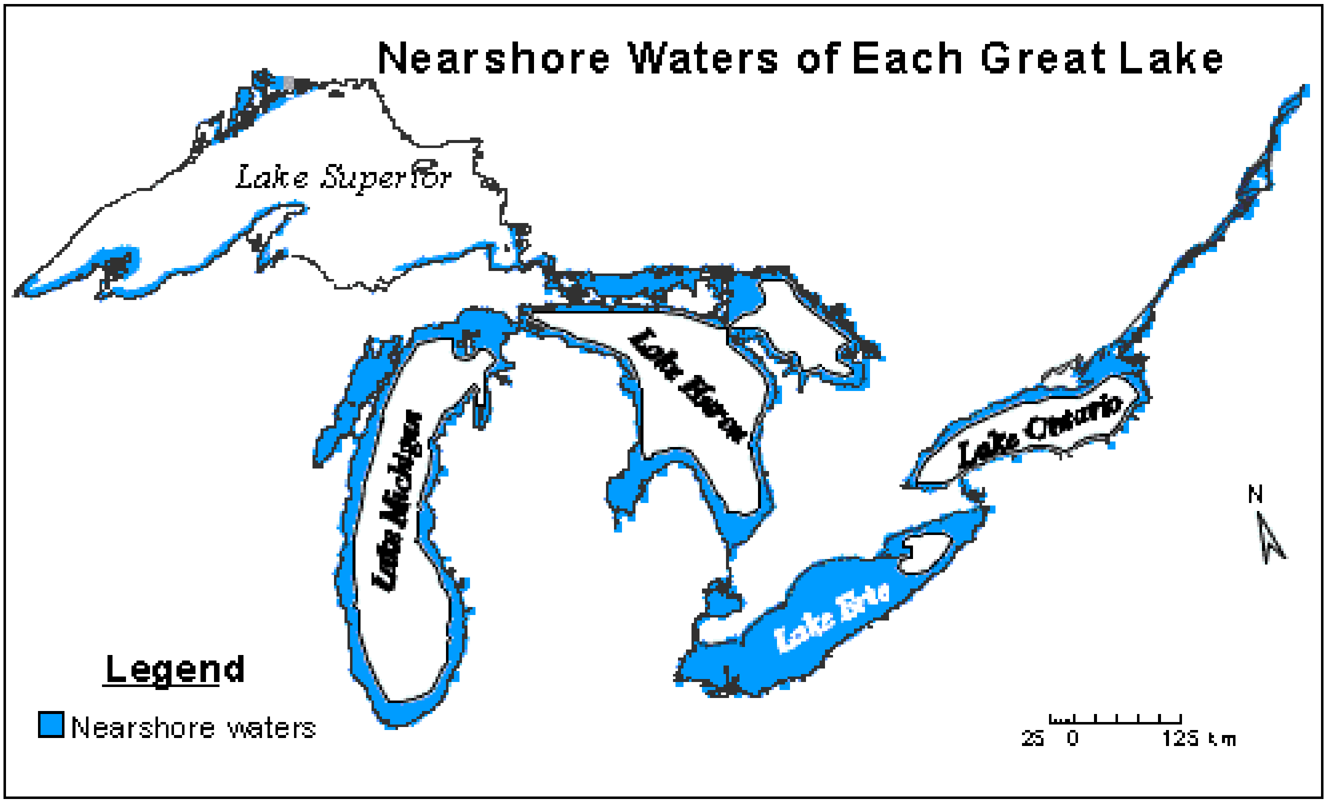
Figure 1. The Great Lakes Basin Ecosystem

2.1 A Definition of Nearshore Waters

The nearshore waters largely occupy a band of varying width around the perimeter of each lake between the land and the deeper offshore waters of the lake (Figure 2). The band is narrowest where the slope of the lake bed is steep and continuous. More specifically, as we define them for this paper, the nearshore waters begin at the shoreline or the lakeward edge of the coastal wetlands and extend offshore to the deepest lake-bed depth contour, where the thermocline typically intersects with the lake bed in late summer or early fall. In Lake Superior, the boundary between the nearshore and offshore waters typically occurs at about the 10-m depth contour (Bennett 1978). In the other four Great Lakes, which are farther south and display a wider range of temperatures seasonally, the boundary between the nearshore and offshore waters may occur as deep as the 30-m depth contour (Schertzer et al. 1987). In the central basin of Lake Erie, the lower limit of the thermocline is highly variable and responds to meteorological events. A detailed set of records collected in 1979 (Schertzer et al. 1987) shows that the thermocline depth in central Lake Erie increased in the May-to-September period and that the bottom of the thermocline extended to 24 m in mid-September immediately before thermal stratification ended. Thus, virtually all of Lake Erie's central basin would have been considered to be nearshore waters in 1979. The temperature of the nearshore waters at the lake bed in summer in all five lakes exceeds 15^oC and may reach 25^oC in portions of Lake Erie. In winter, the nearshore waters are typically covered with ice, and the water temperature approaches 0^oC from surface to bottom (Assel 1986; Assel et al. 1983).

Physical processes such as the lake's thermal cycle and circulation can have a pronounced influence on water-quality conditions in the Great Lakes. The major features of the thermal cycle that affect water quality include stratification characteristics such as the timing of spring and fall overturn and the temperatures of the epilimnion and hypolimnion waters, the thermal bar, the thermocline depth, and upwelling and downwelling dynamics. These thermal characteristics govern the unique circulation patterns, especially within the nearshore zone. What follows is a brief synopsis of some of the relevant characteristics of the seasonal physical processes and how they affect water-quality concerns for large lake systems.

Figure 2. Nearshore Waters



The interaction of meteorological and hydrological factors is responsible for the seasonal thermal response of the lakes. The basic processes include radiative and turbulent heat exchanges at the air-water interface, energy storage within the lake, and net energy flowing into or out of the lake (Schertzer and Sawchuk 1990). Meteorological factors such as radiation, air temperature, precipitation, and evaporation affect the surface temperature, while winds provide the mechanical energy required to mix the heat downwards. Hydrological factors such as inflow and outflow cause local temperature changes by inducing horizontal movement and mixing of the lake waters. Solar radiation penetrates into the water column, affecting the heating of the uppermost layers.

At the temperate latitudes, the Great Lakes are subject to major seasonal changes in net heat input resulting in their going through an annual thermal cycle. The Great Lakes are dimictic-that is, they mix from top to bottom (a process called *overturn*) twice yearly, in the spring and in the fall. The timing of the overturn is closely related to the time when the surface water temperatures fluctuate through the temperature of maximum density of fresh water (i.e., 4^{o}C).

As a result of increased surface heating in the early spring, the nearshore littoral regions begin warming more rapidly than do the lake's deeper regions. Progressive warming results in nearshore water temperatures above 4^{o}C while deeper regions remain below the temperature of maximum density. The region of convergence between the two horizontal thermal regimes is referred to as the thermal bar. The thermal bar has been studied extensively in large lakes (Rodgers 1965; Tikhomirov 1963) to determine the physical dynamics and also to investigate its impact on water-quality conditions during the spring. Measurements of the thermal bar have included satellite images and detailed observation of temperature, current velocity, and optical characteristics, as well as biological and chemical characteristics. Satellite images have clearly indicated that the thermal bar is a zone of convergence not only for water masses of different temperature but also for floating debris. Of practical significance for water-quality concerns is that the sharp density front across the thermal bar effectively limits nearshore/offshore exchange of pollutants and thus affects the nearshore water quality. Meteorological conditions such as heating and wind mixing affect the rate at which the thermal bar progresses offshore to the midlake. In the Great Lakes, this process can take as long as six weeks (Schertzer and Murthy 1994).

Figure 3. Thermal Stratification Cycle in Lake Ontario

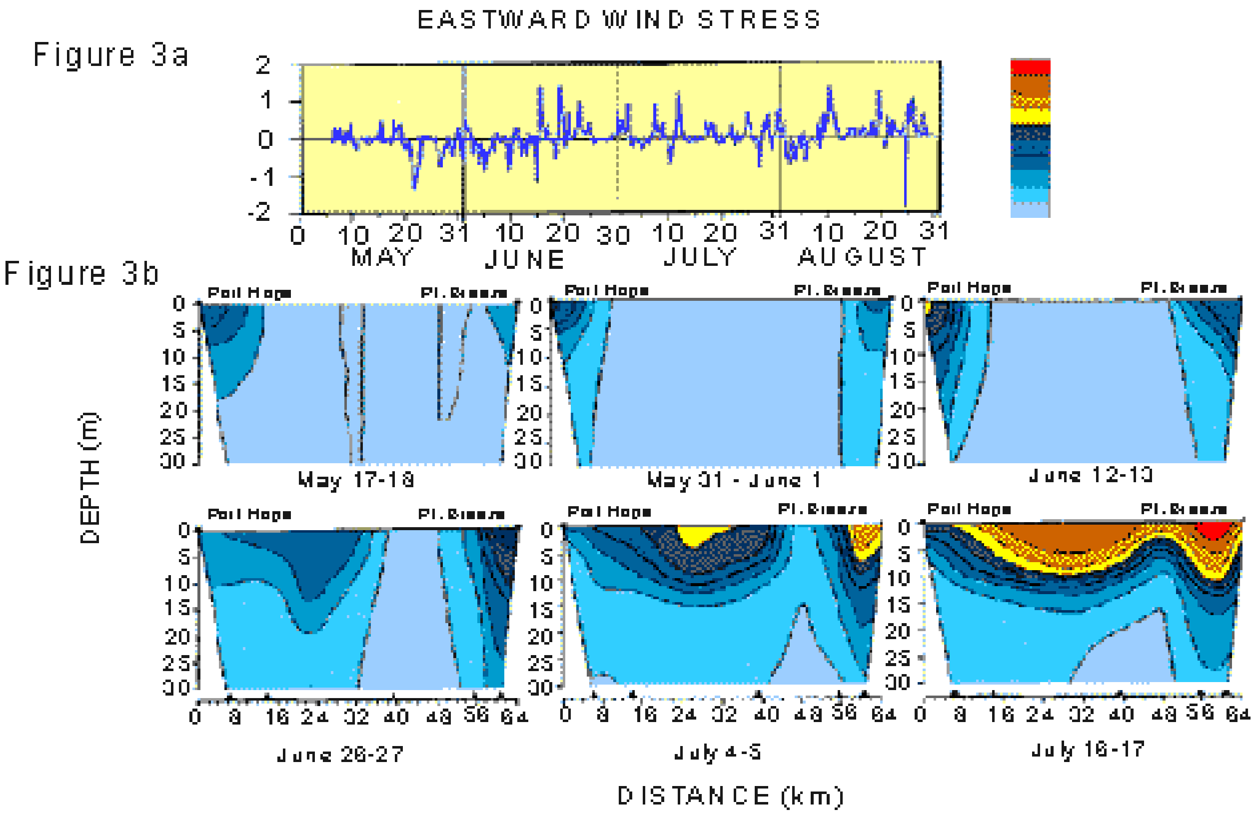
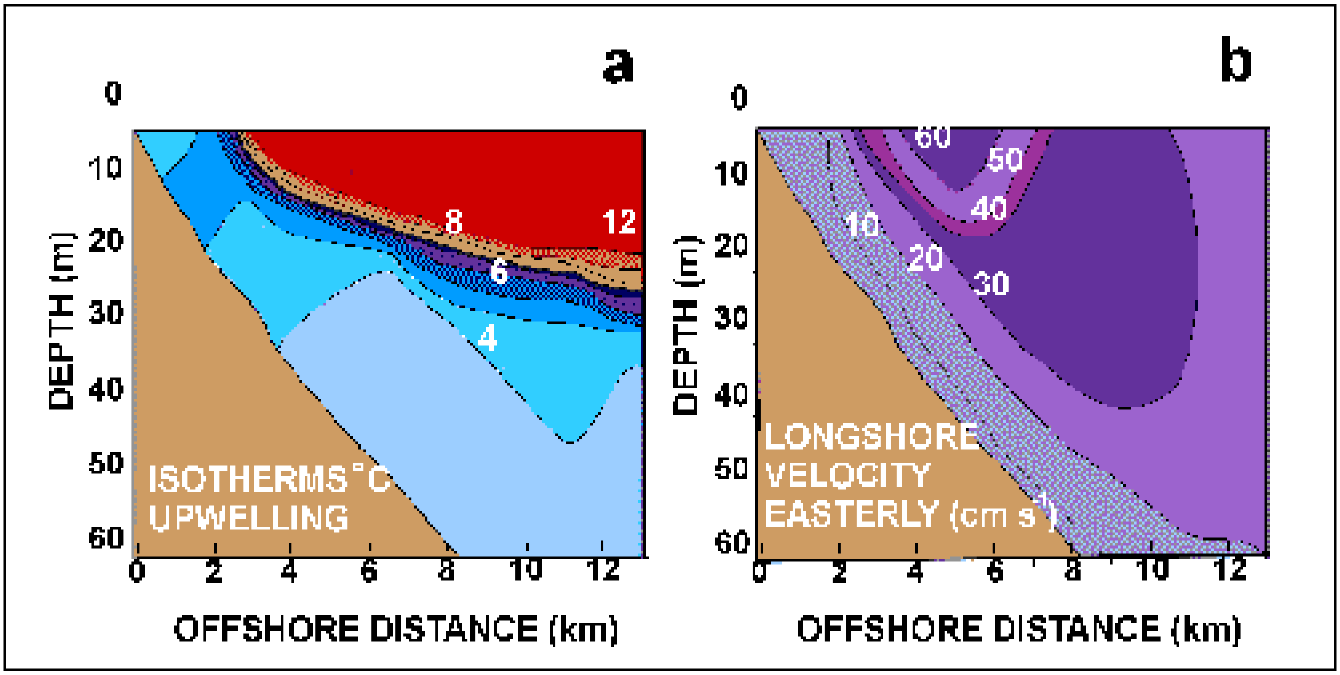


Figure 3 illustrates the thermal stratification cycle in Lake Ontario based on measurements made on a midlake cross-section (Simons and Schertzer 1987a). Figure 3a is a time-series of eastward wind stress. The wind stress plays a dominant role in the stratification process. Figure 3b shows isotherms along the cross-lake transect. The isotherms for May 17-18 clearly show isothermal conditions in the midlake (T less than 4ºC) and the development of the thermal bar on both shores. Due to topographic effects (i.e., the depth of the water and the configuration of the bottom and shoreline influence both the temperature and the circulation), the thermal bar is more developed along the shallower north shore compared to the deeper south shore. It is of interest to note the progression of the thermal bar towards the centre of the lake as the heating intensifies towards the midsummer period. Typical summer stratification occurs when the surface water temperature reaches 4ºC over the entire lake and the thermal bar disappears.

Figure 4. Upwelling in Lake Ontario with Longshore Velocity Distribution (a) Temperature isotherms. (B) Longshore velocity contours along the coastal zone of Oshawa, Lake Ontario, following a major storm (October 1972), indicating episodes of upwelling and downwelling and the location of a coastal jet.



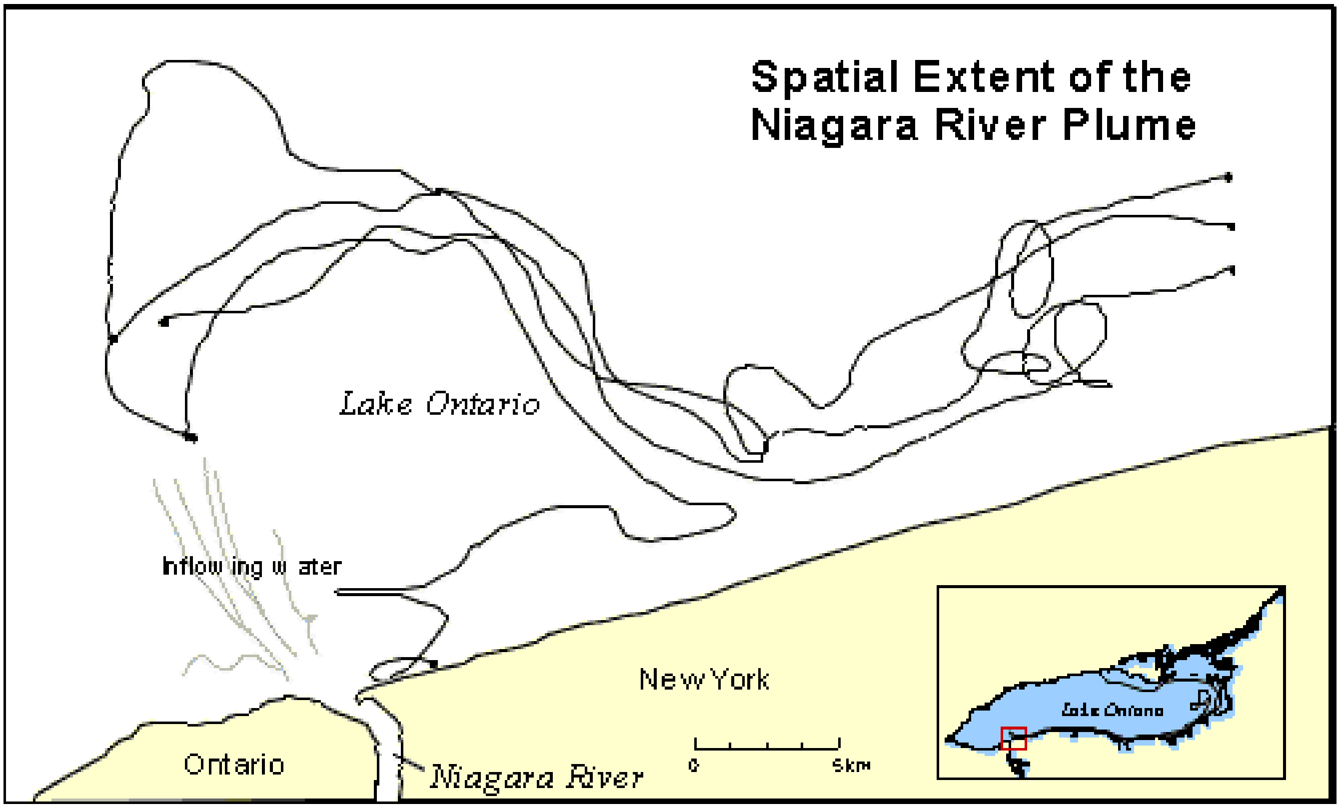
Summer stratification is characterized by warmer, less dense water at the surface layers and cooler, denser water in the lower layer. Progressive heating results in the development of a stable stratification and a well-defined epilimnion (warm water), mesolimnion (transition temperatures), and hypolimnion (cool water) layer. It is also interesting to note (from Figure 3b, July 16-17) that the thermocline depth is not uniform over the whole lake. The 10ºC isotherm is highlighted to mark the approximate depth of the thermocline in Lake Ontario.

Dynamic processes that have an impact on the temperature distribution in large lakes include upwelling and downwelling, internal waves (along the thermocline), and Kelvin waves (coastally trapped waves that propagate along the shoreline, particularly after large storms) (Simons and Schertzer 1987b). With respect to upwelling and downwelling processes, strong easterly winds along the axis of Lake Ontario will cause a surface drift to the right, which can result in tilting the thermocline. Satellite digital temperature data, along with surveillance data, has demonstrated large-scale upwelling along the north shore and downwelling along the south shore of the Lake Ontario. Figure 4 illustrates an upwelling event in Lake Ontario along the north shore, with corresponding longshore (easterly) velocity distribution. In this case, the thermocline tilting along the nearshore zone is so intense that a major "outbreak" of cold hypolimnion water has upwelled to the surface; 4ºC water extends 2 km from the shore. Between 2 km and 3 km offshore, there is a very intense temperature gradient, from 6ºC to 12ºC. The velocity distribution clearly shows that the upwelling event has resulted in weaker longshore currents in the upwelled region closer to shore and in the formation of a "coastal jet," with velocities ranging from 35 cm s^{-1} to 60 cm s^{-1} (Csanady and Scott 1974). The higher current speeds within the region of the coastal jet are highly effective in transporting and dispersing pollutants along the nearshore zone. The persistence of upwelling events depends on the duration of the strong wind event. During an upwelling episode, the nearshore waters are replenished with nutrient-rich hypolimnetic waters; thus, upwelling affects the nearshore water quality.

Hydrological factors also have a significant effect on a lake's dynamic processes and water quality. Whereas pollutants can be introduced to lakes through loading from precipitation, tributaries, and land runoff, inputs from connecting channels can play a significant role in introducing and redistributing substances in a large lake. Connecting channels among the Great Lakes include the St. Marys River, the Straits of Mackinac, the Detroit River, the Niagara River, and the St. Lawrence River. Lake Ontario, being at the downstream end of the Great Lakes, receives large inflows from the Niagara River. Water-quality analyses of the Niagara River have shown high concentrations of toxic chemicals that are introduced into Lake Ontario. Much research has been conducted to investigate the dynamics of the Niagara River inflow into Lake Ontario (Murthy and Miners 1989). The nearshore thermal structure is altered significantly by the inflow: the warmer Niagara River plume extends beyond the river mouth in excess of 10 km, after which it eventually mixes with the ambient lake water. The vertical extent of the Niagara River plume can be 8 m to 10 m, with the warmer inflowing water developing a frontal structure as it enters the lake (Murthy et al. 1986). The gradient across the thermal front depends on the time of year and therefore on the difference between the temperature of the inflowing water and the ambient lake temperatures.

Prevailing wind conditions and lake circulation patterns determine the spread of the Niagara River plume in Lake Ontario (Murthy and Schertzer 1994). In most circumstances, a plume develops from the Niagara River mouth and tends to extend eastward along the south shore of the lake. Figure 5 illustrates an example of the spatial extent of the Niagara River plume, as determined by progressively tracking the position of drifters within the current. In this example, inflowing water (bearing its load of pollutants) generally flows out of the mouth to a distance of approximately 10 km. In the initial phase, horizontal velocities from the Niagara River mouth are reduced significantly, and the river water is vertically well mixed over the shallow bar area. Beyond this initial phase, the river plume is bent over in response to lakewide circulation and the prevailing winds. In most cases, the river plume is diverted to the east, and the weakly buoyant plume responds to the prevailing winds and lakewide circulation forces. Figure 5 shows that in the transition phase, a large clockwise eddy of between 10 km and 12 km in diameter is formed to the east of the Niagara River mouth. The eddy appears often and last for a few days. From a water-quality standpoint, river outflow that is entrained into this zone of low net transport is effectively isolated from the mixing effects of the main shore-parallel currents. Consequently, this nearshore area can be a zone in which fine particulate material is deposited. As shown in the inset of Figure 5, the Niagara River plume continues eastward along the south shore and around to the north shore of the lake. Considering the dynamics and characteristics of large inflows from connecting channels such as the Niagara River is significant from a water-quality standpoint, since such inflows are responsible for transporting and distributing contaminants and other pollutants over the lake.

Figure 5. Niagara River Plume

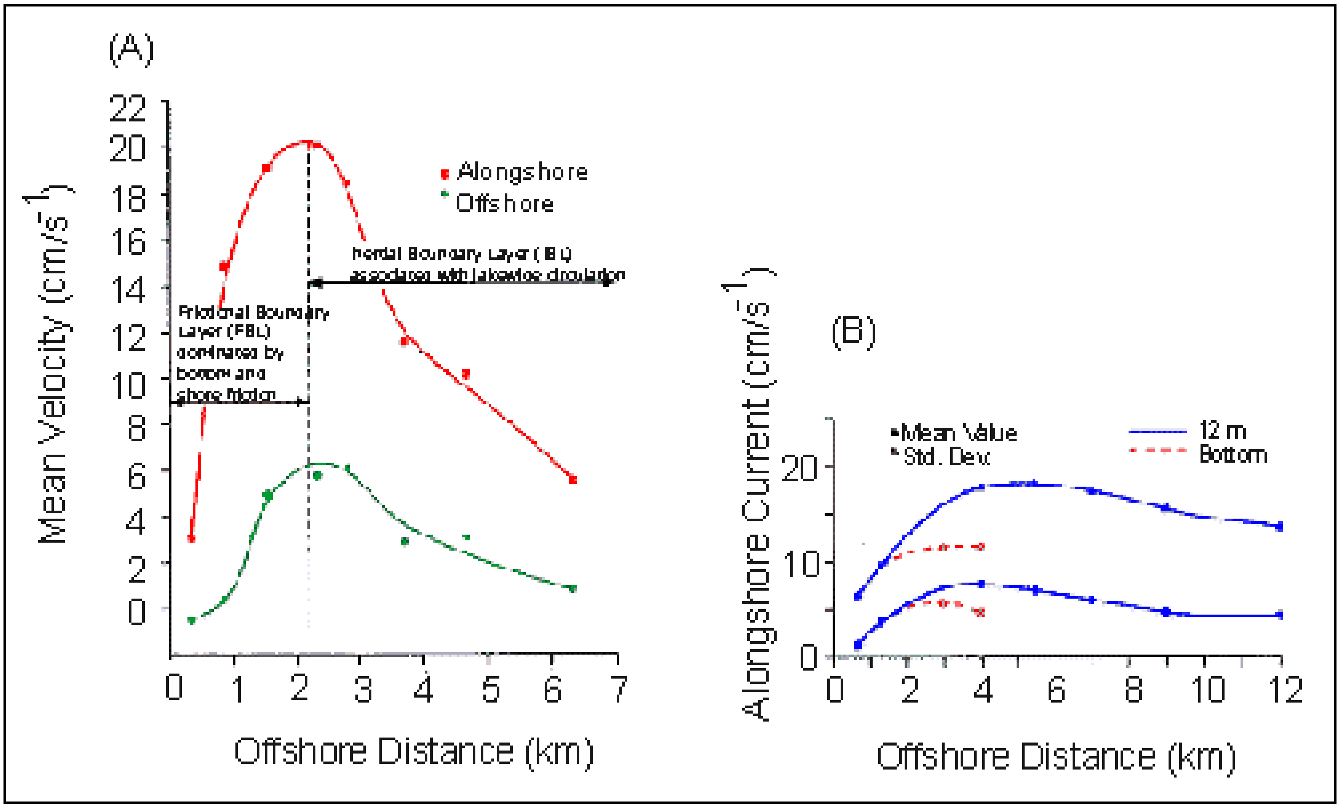


Coastal boundary layer characteristics during the lake's thermally stratified period are shown in Figure 6 (from Murthy and Schertzer 1994). The alongshore component dominates the flow field, peaking at a distance of between 2 km and 3 km from the shore. This peak divides the flow field into two distinct zones. Closer to the shore, an inner boundary layer flow develops, with bottom friction gradually bringing the flow to a halt at the shoreline (frictional boundary layer). Beyond this, an outer boundary layer develops as a consequence of the adjustment of inertial oscillations to the shore-parallel flow (inertial boundary layer). Water movements within this coastal boundary layer are complex, as indicated in some of the discussion above. Knowing the extent of the coastal boundary layer is critical for understanding the impact of such activities as waste disposal through sewage outfalls, large-scale dumping operations, shore erosion, sediment transport, installation of coastal structures, land reclamation, and recreation (Murthy and Schertzer 1994). Since the dilution capability of the nearshore current regime increases in the first few kilometres of the coastal boundary layer, effective dispersal of effluents depends on the distance of the discharge from shore.

During the summer stratified period, the thermocline largely prevents the transfer of heat and particles from the epilimnion to the lower layers and thus has water-quality implications. A strong thermocline acts as a "diffusion floor," suppressing vertical mixing and inhibiting the transport of mass, momentum, and heat into the hypolimnion. For a shallow lake, such as the central basin of Lake Erie, a deep thermocline with a high temperature gradient has been observed to severely limit the transfer of oxygen and materials between the upper and lower layers, often leading to anoxia (Schertzer et al. 1987). Vertical entrainment across thermal interfaces has also been observed after high-wind events (Boyce et al. 1989).

Figure 6. Coastal boundary layer for (a) summer stratified conditions at Douglas Point, Lake Huron, and

(b) winter homogenous conditions at Pickering, Lake Ontario. (Murthy and Dunbar 1981)



Towards the late summer, large lakes such as Lake Ontario attain their highest temperatures and heat storage. After the period of maximum heat storage, surface heat losses to the atmosphere occur through radiative and turbulent exchange processes (Schertzer and Sawchuk 1990). Since the heat losses are not uniform over the entire lake volume, there can be significant lags in the seasonal vertical temperature distribution. Surface heat losses and mixing processes in the fall result in decreasing the lake's mean heat content. With strong storm episodes, the depth of the mixed layer increases until the entire water column is mixed around 4ºC to 5ºC. The breakdown of thermal stratification is commonly referred to as the annual fall overturn. The period of thermal stratification varies for each Great Lake according to its latitudinal location and bathymetry. For Lake Ontario, thermal stratification generally extends from late June to October.

As a consequence of cooling coupled with wind mixing, the temperature of the main water mass continues to become more uniform, eventually attaining the temperature of maximum density. Because the rate of cooling is higher in the shallower nearshore regions, horizontal surface temperature gradients can occur and persist in winter months. During the late fall and early winter, mixing of cold inshore water with warmer offshore water may set up a thermal bar phenomenon similar to the one described earlier.

Towards the end of winter, the entire water mass cools down to below 4ºC, with the coldest water remaining close to the shore. During winter, ice begins to form in the nearshore waters of the Great Lakes in December and January and in the deeper offshore waters in February and March, reaching its greatest extent in late February or early March. Expected maximum ice covers are as follows: for Lake Erie, 90 percent; for Lake Superior, 75 percent; for Lake Huron, 68 percent; for Lake Michigan, 45 percent; and for Lake Ontario, 24 percent (Assel et al. 1983). During a severe winter, maximum ice cover can exceed 90 percent on all the Great Lakes (Assel et al. 1996); during a mild winter, maximum ice cover is usually limited to the nearshore waters (Assel 1985). The type of ice that forms in the nearshore waters includes flat shorefast ice (which forms under calm conditions); brash ice, which consists of a matrix of ice of various sizes and shapes (and which forms over several days or weeks as episodes of ice formation and breakup occur in the more exposed nearshore areas in response to high winds followed by calm); and icefoot complex (which forms as waves of freezing spray build up mounds of ice and ice ridges along lee lake shores-usually adjacent to deep waters that do not freeze until later in the winter) (Evenson and Cohn 1979; Marsh et al. 1973; O'Hara and Ayers 1972). Ice cover is an important climatic variable that affects the winter ecosystem (Vanderploeg et al. 1992), the fishery (Taylor et al. 1987), the economy (Niimi 1982), and the weather of the Great Lakes (Peace and Sykes 1966; Petterssen and Calabrese 1959). An extensive ice cover can also affect lake temperature and the length of the stratification period, since ice cover can decrease heat losses from the surface and can also affect the initial period of heating of the lake in early spring months.

Recently, there has been growing consensus among climate modelers that global air temperatures will rise with increasing concentrations of atmospheric greenhouse gases, particularly carbon dioxide, methane, nitrous oxide, and freons. There is less agreement about the magnitude of estimated temperature change, although most estimates range from $2^{o}C$ to $4^{o}C$. Observation of thermal stratification characteristics for warm years has implied that warmer conditions may result in higher lake temperatures, lengthened stratification periods and significantly reduced ice cover (Rodgers 1987; Schertzer and Sawchuk 1990). Preliminary modelling investigations incorporating GCM model projections under steady-state, transient, and transposition scenarios have indicated that climatic warming may alter basin hydrological conditions and lake surface heat exchanges. Such changes can be expected to have an impact on the mainlake and nearshore thermal regimes of the Great Lakes. Further integrated research is required to quantify the potential physical, chemical, biological, and water-quality ramifications of climatic warming for the Great Lakes.

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