Variation in Lake Water Temperature in the Nanticoke Region of Long Point Bay, Lake Erie, during the Open-Water Season

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Lake water temperature on the north shore of Long Point Bay near Nanticoke (Lake Erie) over the years 1971–83 varied considerably during the lake warming cycle. Upwellings, resulting in temperature drops of 5–10°C over a 2–3 d period, were common from mid-May to mid-August. Warmer surface waters returned within 6 d (usually 3 d) following summer upwellings. In spring, the recovery times were variable but typically lasted longer, up to 25 d. Temperature fluctuations that exceeded 5°C but lasted less than 48 h were also frequent during the lake warming cycle. The progressive deepening of the epilimnion to the 12-m depth of Long Point Bay and the associated increase in the heat content of the Bay resulted in a stable temperature regime by mid-August. Diurnal heating and cooling of surface waters, by as much as 4°C, was apparent under calm conditions. Mean April–November temperatures varied by more than 2°C, reflecting annual variation in atmospheric warming.

De 1971 à 1983, la température de l'eau du lac sur la rive nord de la baie Longue Pointe près de Nanticoke (lac Erié), a varié énormément pendant le cycle de réchauffement du lac. Des remontées d'eau froide, attribuables à des chutes de température de 5 à 10°C pendant 2 ou 3 jours, étaient courantes de la mi-mai à la mi-août. Les eaux de surface redevenaient plus chaudes en 6 jours (habituellement 3) après des remontées d'eau froide estivales. Au printemps, le temps de rétablissement était variable mais il était en général plus long, pouvant atteindre 25 jours. Des variations de température supérieures à 5°C, mais de moins de 48 h, étaient également fréquentes pendant le cycle de réchauffement du lac. L'enfoncement progressif de l'épilimnion jusqu'à la profondeur de 12 m de la baie Longue Pointe et la hausse associée à la chaleur de la Baie ont produit un régime de température stable dès la mi-août. Le réchauffement et le refroidissement diurnes des eaux de surface, de 4°C, étaient évidents par temps calme. La variation des températures moyennes d'avril à novembre était supérieure à 2°C, ce qui traduit une variation annuelle du réchauffement atmosphérique.

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Although dynamic physical processes can be expected to influence components of the aquatic environment, many studies, particularly those concerned with the effects of anthropogenic activity, assume that a degree of environmental homogeneity exists in space and over short periods of time. This assumption often leads to an inability to distinguish anthropogenic effects from natural variability. One approach to this problem is to determine the normal, or non-stressed, condition and then examine deviations from this condition and the physical forces that contribute to these deviations. Natural events, which can have profound effects on the environment are considered to be unusual if they are perceived to be infrequent. However, whether or not an event is perceived to be unusual often depends on the duration of the particular study (Lewin 1986). Long-term studies are valuable in understanding the significance of the extent and causes of natural heterogeneity and should be an essential part of environmental impact assessment.

Meteorological conditions directly influence water movement in large lakes and associated temperature changes, including the abrupt temperature excursions that result from upwellings (Boyce 1974). In large lakes upwellings are common within 8–10 km of shore, in a region defined as the coastal boundary layer (Csanady 1984). In the nearshore region of Long Point Bay (Lake Erie) near Nanticoke, water movement is mainly responsive to wind stress and shore parallel currents predominate, with net water transport directed to the east (Kohli and Farooqui 1980). Ekman–type upwellings occur when these nearshore waters are displaced both alongshore and offshore, being replaced by cooler, hypolimnetic water (Csanady 1977; Simons 1978; Simons and Schertzer 1987). Warm surface water returns to the nearshore area (downwelling) when conditions

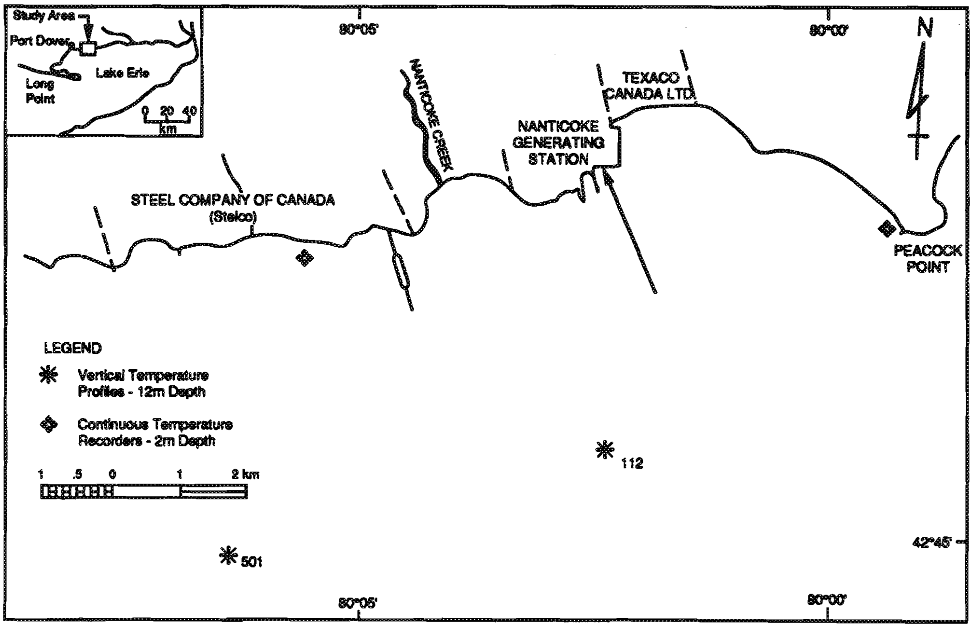

FIG. 1. Temperature measurement locations in the Nanticoke region of Long Point Bay, 1971–83.

change. Vertical mixing, induced by upwelling–downwelling events, affect nutrient levels and the distributions and productivity of biota within the nearshore euphotic zone (Schleske et al. 1971; Yaguchi 1977; Evans 1981; Heufelder et al. 1982).

In this paper we test the hypothesis that homogeneity within the nearshore environment is often transitory. The analyses are based on continuous measurements of nearshore water temperatures taken in the area of Nanticoke, over the years 1971–83. The extent and causes of annual, seasonal, and daily variations in natural lake water temperatures were examined for the open-water period.

The goal of our study was to determine the influence of industrial activity at Nanticoke on the aquatic environment (Haymes and Dunstall 1989). The long-term data that formed the basis for our analyses consisted of measurements of physical, chemical and biological variables[1]. In a companion paper (Dunstall et al. 1990) we test the hypothesis that physical forces contribute to short-term variability among biological and chemical components of the nearshore environment.

Materials and Methods

The study area was located on the north shore of Long Point Bay, Lake Erie, near the town of Nanticoke (Ontario, Canada) (Fig. 1). Long Point Bay, bordered to the south and to the west by Long Point, is relatively shallow with depth increasing gradually offshore. Industrial development along the shoreline includes a steel mill, a fossil-fired electric generating station and an oil refinery.

Water temperatures were recorded continuously at several nearshore locations from the Stelco site to Peacock Point during the open-water seasons from 1971 to 1983 (Fig. 1). The predominance of westerly winds results in lake currents being directed mainly to the east. The water to the west of the generating station is seldom affected by the generating station's thermal plume (Kohli and Farooqui 1980; Burchat 1984). Thus, continuous temperature readings taken at the 2-m depth near Stelco, 3.7 km west of the generating station outfall, were used to describe ambient near-shore conditions. The effect of Nanticoke generating station on lake water temperature has been described by Arden and Farooqui (1981).

Temperatures were recorded as an analog trace on pressure-sensitive paper using single channel Rustrak temperature recorders. Data were abstracted at hourly intervals from the analog strip charts using a Gradicon digitizing system and were transferred to a computer for storage in Standard Time Series format. Overall accuracy was considered to be ± 0.5°C. Occasional missing data for the Stelco site were supplemented with temperature records from other near-shore locations, primarily Peacock Point, which was affected to only a limited extent by the generating station (Lawler 1985).

Upwellings were considered to be persistent events, being defined as a sustained decrease in daily mean water temperatures of ⩾ 5°C over a 2 to 3-d period. Declines in daily mean temperatures of 6°C or more over 2 d were considered to represent major upwelling events. Temperature data were also examined to identify transient temperature fluctuations. These were defined as differences of 5°C or more between minimum and maximum hourly temperatures that occurred within a 2-d period, and included abrupt (i.e. 1 d) upwelling–downwelling events. Fluctuations exceeding 5°C were also a component of many of the upwellings that lasted longer than 2 d.

Thermal structure of Long Point Bay was determined from vertical temperature profiles taken at the two deepest sampling sites (bottom depth 12-m), located approximately 4 km from shore (Fig. 1). These profiles were taken at 2 wk intervals during the open-water seasons, from 1971–83, using a Yellow Springs Instrument (YSI) thermistor probe.

Hourly wind speed and direction data for the Long Point meteorological station and mean monthly air temperature data for the Port Dover meteorological station were obtained from the Atmospheric Environment Service, Toronto, Ontario.

[1]Complete set of tabular data is available, at a nominal charge, from the Depository of Unpublished Data, CISTI, National Research Council of Canada, Ottawa, Canada, K1A 0S2

TABLE 1. Nearshore water temperature conditions in the Nanticoke region of Long Point Bay, 1971–83.

Year	Upwelling events[a] Total	Upwelling events[a] Major	No. of times temperature changed ≥5°C in 48 h	Onset of Thermal[b] Stability	Mean temperatures (°C) Lake water (Apr.–Nov.)	Mean temperatures (°C) Air (Apr.–Nov.)	Mean temperatures (°C) Lake water[c] (Jan.–Feb.)
1971	8	3	41	Aug. 17	13.9	13.7	
72	1	1	34	Aug. 12	12.8	12.6	
73	2	1	27	Aug. 12	14.4	14.3	
74	1	0	22	Aug. 7	13.2	13.1	
75	2	0	34	Aug. 3	14.5	14.2	1.3
76	2	1	22	Aug. 1	13.0	12.8	1.1
77	1	0	28	July 4	13.9	13.9	1.3
78	3	3	32	Aug. 20	13.6	13.2	1.6
79	4	3	37	Aug. 18	13.8	13.2	1.5
80	0	0	27	July 11	13.9	13.5	1.3
81	2	0	15	July 14	14.0	13.6	1.6
82	2	0	42	Aug. 17	13.4	13.2	1.4
83	4	3	41	Aug. 9	15.1	13.6	2.0
Means	2.5	1.2	31	Aug. 4	13.8	13.5	1.5

[a]Upwelling defined as a temperature drop of ≥5°C in a 3-d period. A major event is a change ≥6°C in a 2-d period.
[b]Date of last upwelling or temperature fluctuation during warming cycle.
[c]Winter lake water temperature for GS intake cooling water; 1975–83.

Results

Thirty-two upwellings, including 15 major events, occurred during the 13-yr period (Table 1). Up to three major upwelling events occurred in a given year. The total number of upwellings per year varied from eight during 1971, to none during 1980. These 2 yr exemplify the differences among years in the relative stability of lake water temperature.

Upwelling occurred on 28 occasions during the lake warming cycle, from mid-May to mid-August (Fig. 2). All major upwelling events occurred during this period. On four occasions upwellings resulted in temperature decreases of more than 9°C over a 2-d period: May 30–June 1, 1972 and 1978, July 4–6, 1973, and July 16–18, 1971. Four upwellings occurred between late September and mid-October but these events were not followed by a return to warmer lake water temperatures.

The meteorological conditions that preceded an upwelling typically followed two patterns. In both cases winds from the south-west quadrant with speeds of 25–70 $km \cdot h^{-1}$ persisted for at least 1 d prior to upwelling. Thirteen upwellings occurred when winds continued to prevail from the southwest quadrant. These events occurred during spring warming (May–early July) or fall cooling (September–October). The remaining upwelling events occurred following a shift in the origin of the strong winds, from the southwest quadrant to the northwest quadrant (Fig. 3). This pattern accounted for all nine summer upwellings that were recorded after the first week of July. However, it should be noted that these wind patterns did not always generate an upwelling.

The time required for surface water to recover to within 10% of the pre-upwelling temperatures, varied from 3–25 d for the 15 upwellings which occurred during the spring. Summer recovery periods were shorter, averaging 3 d, with a range of 1–6 d (Fig. 4). Longer recovery periods, following both spring and summer upwellings, resulted from a persistence of moderate to strong winds with the same westerly component that initiated the upwelling. Seven upwelling events were followed by winds that remained strong, but the origin of the winds had shifted to the north-northeast. Winds from this sector also delayed the return of warm waters to the nearshore zone. The relatively long recovery period of 6 d for the summer upwelling shown in Fig. 3 appeared to result from the persistence of moderate winds from the south to southwest and subsequently from the northeast. In contrast, recovery periods of short duration occurred when wind velocity diminished and the source of the winds became variable, but with a tendency to rotate in a clockwise direction.

Short-term temperature fluctuations (i.e. < 48 h), like upwellings, were most frequent during the lake warming cycle (Fig. 2). Changes in lake water temperatures of 10–16°C were recorded within a 48 h period but these were relatively uncommon, comprising only 6% of the total number of fluctuations. The remainder of the fluctuations represented temperature changes of 5–10°C. The most pronounced 48-h fluctuations generally occurred at the onset of upwellings. Fluctuations were most frequent during 1971, 1982, and 1983 (Table 1). In all years, however, there was considerable temperature instability as identified by these short-term fluctuations.

Towards the peak of the lake warming cycle, surface temperatures (2-m depth) became relatively stable and upwellings or short-term temperature fluctuations rarely occurred (Fig. 2). The onset of thermal stability in Long Point Bay varied con-

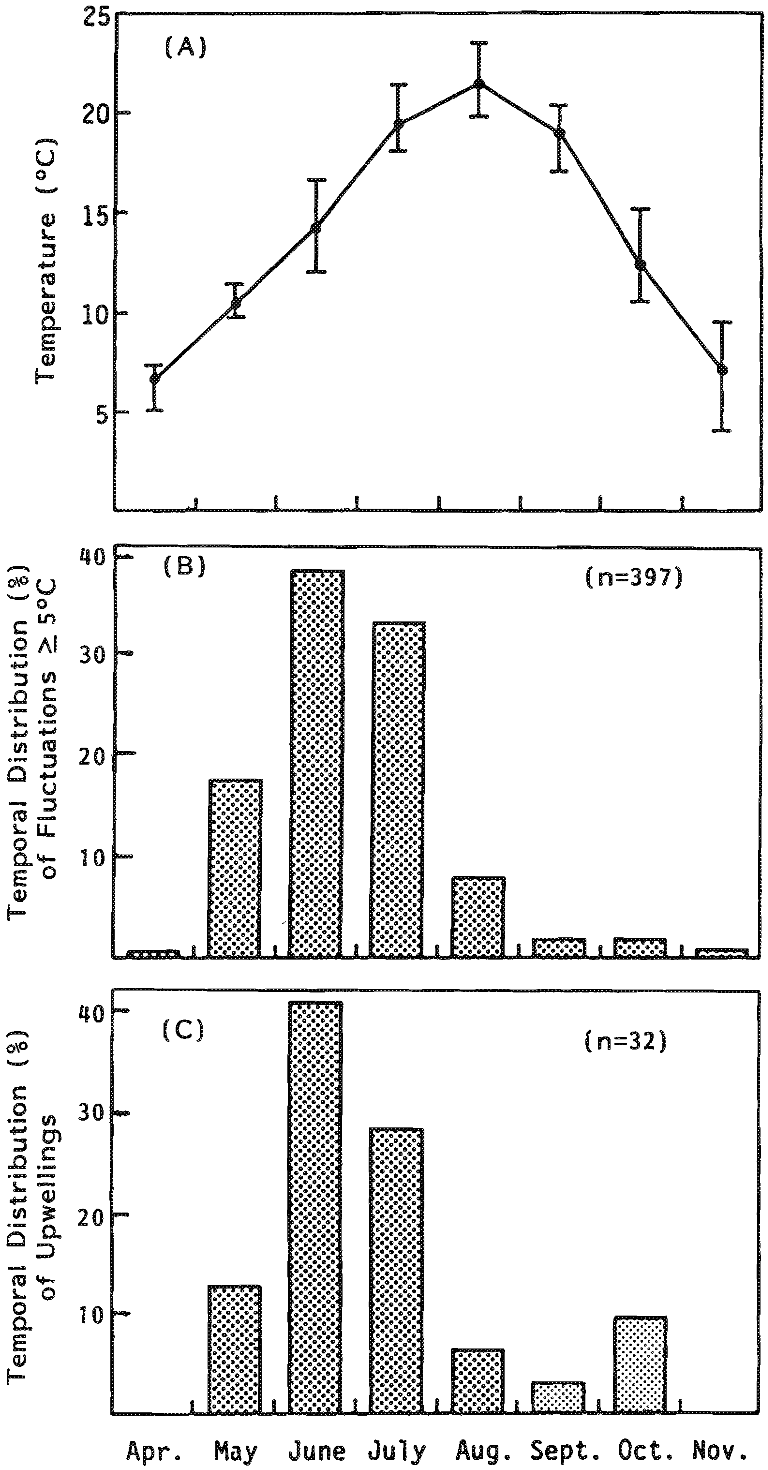

FIG. 2. Mean monthly temperatures (vertical bars = range) at the 2-m depth of Long Point Bay for the years 1971–83 (A), frequency of temperature fluctuations ≥ 5°C in a 48 h period (B) and frequency of upwellings (C) defined as a change in daily mean temperature ≥ 5°C within a 3-d period. (Light stipple indicates upwellings that were not followed by temperature recovery.)

siderably among years with the earliest and latest dates being July 4 (1977) and August 20 (1978) (Table 1).

The depth of the epilimnion (below which temperature decreased by more than $1°C \cdot m^{-1}$), as determined from offshore vertical temperature profiles to the 12-m depth, was variable from May through July (Fig. 5A). During this period steep temperature gradients at a depth of 1–2 m were not uncommon, indicating that unstable thermal conditions existed at this time of the year. By August the minimum depth of the epilimnion was 8 m. In nearly half the profiles taken during August, iso-

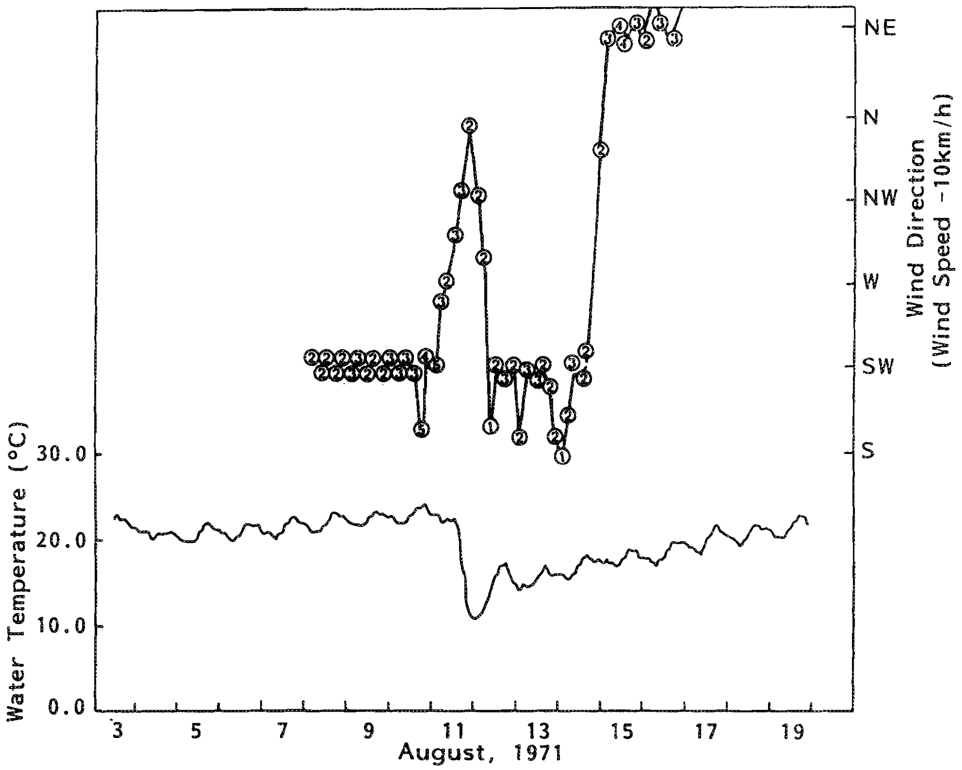

FIG. 3. Chronology of a lake upwelling event at Nanticoke displaying hourly lake water temperatures for 3–19 August, 1971 (lower graph), and wind speed (rounded to tens of km) and direction averaged over 4-h intervals (upper graph).

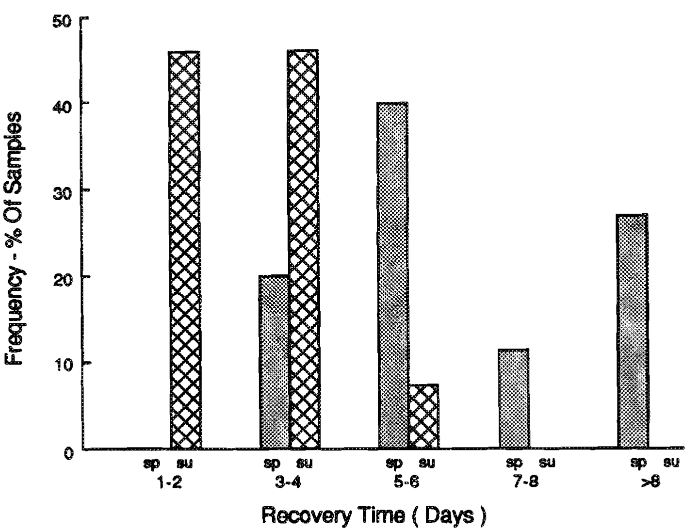

FIG. 4. Interval in days between peak upwelling and recovery of lake surface waters to within 10% of pre-upwelling temperatures for the spring (shaded) and the summer (cross-hatched).

thermal conditions existed in Long Point Bay (Fig. 5B). The heat content ($MJ \cdot m^{-2}$) of Long Point Bay (to the 12-m depth) was also greatest in August, and followed the same pattern as the mean monthly temperatures derived from the 2-m continuous recorders (Fig. 2A). There was, however, a continued decrease in the occurrence of pronounced temperature gradients ($> 1°C \cdot m^{-1}$) within Long Point Bay into October.

Diurnal variation in surface water temperatures was often evident from May to August, being detectable when winds were relatively calm (Fig. 3). This daily warming–cooling cycle approximated a sine curve with a period of 24 h. Minimum daily lake water temperatures occurred at dawn (approximately 0600 h) while maximum temperatures were recorded at about 1800 h. The amplitude of temperature change was 1–4°C, but more commonly varied between 1.5 and 3.0°C.

Mean April–November surface water temperature (2-m depth) for the 13 y of study was 13.8°C. The lowest and highest annual mean temperatures (April–November) were 12.8°C (1972) and 15.1°C (1983), respectively (Table 1). Although seasonal temperature patterns in 1971 and 1980 were quite different, mean April–November temperatures for these 2 y were identical (Table 1).

Mean April–November water temperatures were positively correlated to mean air temperatures for the same period ($r = 0.800$). Relatively warm surface water temperatures were recorded during 1983 although air temperatures were only average. This warm lake temperature in 1983 was partly due to the preceding winter which was one of the mildest in recent history (Assel et al. 1984) (Table 1). The water temperature to air temperature relationship improved if the extent of lake warming above the winter base temperature (mean January–February temperature) was used in the regression ($r = 0.851$):

$$\text{Water Temperature} = 1.00(\text{Air Temperature}) + 0.300 \quad (n = 13)$$

Discussion

The nearshore waters in the Nanticoke region of Long Point Bay are subject to frequent variations in temperature during the lake warming cycle, from mid-May to mid-August. Tempera-

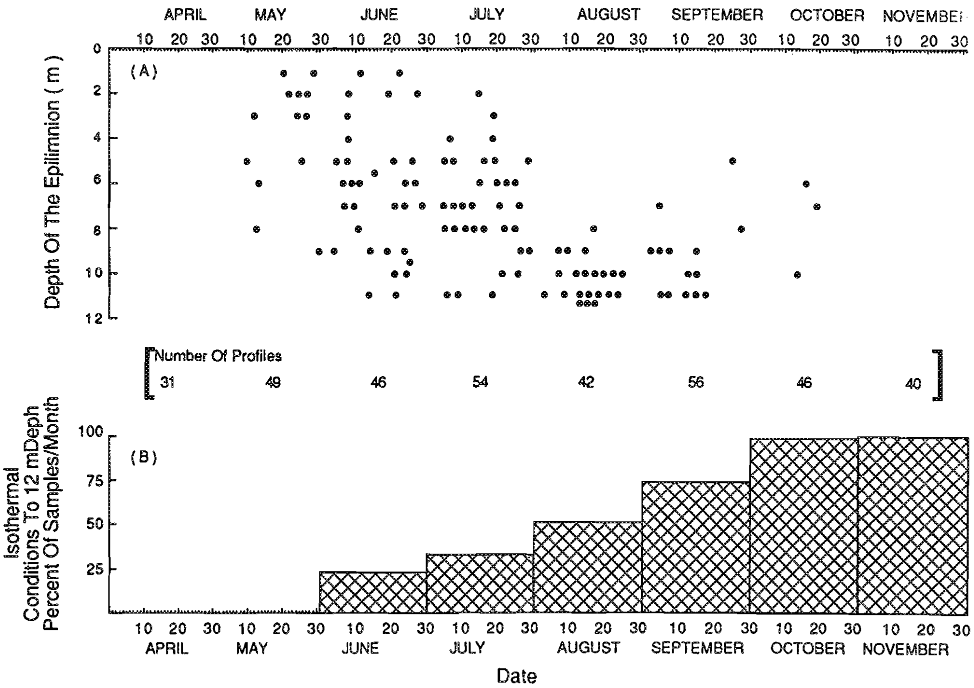

FIG. 5. Results of vertical temperature profiles for the years 1971–83 indicating the presence of a temperature gradient (> 1°C per m) within the 12-m depth (A), and frequency of profile measurements in which Long Point Bay was isothermal to the 12-m depth (B).

ture excursions due to upwellings and to short-term temperature fluctuations, both of which are wind-induced, are common at this time of the year. However, the number of upwellings that occurred in a given year varied, ranging from zero to eight over the years 1971–83.

Warm epilimnetic waters occupy Long Point Bay by mid-August, although there are occasional intrusions of the thermocline into the Bay, between the bottom (12-m depth) and the 8-m depth. As the lake warms, wind-induced turbulence contributes to the rate and overall extent to which the epilimnion deepens. Associated with this mixing is an increase in the stability imparted to the lake surface stratum as the heat content of the lake increases. The epilimnion in the Eastern Basin of Lake Erie usually extends beyond the 15-m depth by mid-August and pronounced stratification exists in deeper offshore regions of the lake (Burns 1976; Kerman et al. 1977; Lam et al. 1983). After mid-August, but prior to fall cooling, the energy associated with even the most severe winds fails to result in the total displacement of the warm surface waters within the relatively shallow reaches of Long Point Bay. However, the strong winds responsible for initiating upwelling also tend to be less frequent and less sustained in mid-summer. Ivey and Patterson (1984) similarly reported the absence of upwellings in the Central Basin of Lake Erie during the period of strong thermal stratification.

The importance of wind direction in initiating upwelling was related to the thermal stability of Long Point Bay. The initial set-up of east-directed currents by winds from the southwest quadrant was often sufficient to result in Ekman-type upwelling during the early stages of the lake warming cycle or in the fall. In the summer, however, upwelling occurred when the source of the strong winds shifted from the southwest to northwest quadrants. This shift results in substantial direct stress being applied to surface waters in an offshore direction. It should be noted however, that upwelling did not result from all occurrences of wind patterns that fit the above two descriptions. In addition to local wind conditions, upwellings can propagate into the region from disturbances at other points around the lake (Simons and Schertzer 1987).

The time taken for warmer surface water to return to the nearshore zone was also related to thermal stability. The short recovery times, typically 2–4 d, in the summer suggests that distinct water masses are replaced during both upwelling and downwelling. Thus, there is a rapid return to the stable energy condition represented by thermal stratification, once the winds that propagated the upwelling subside. Longer recovery periods typical of spring upwellings occur at a time when the lake is weakly stratified, suggesting a gradual mixing of water masses following upwelling.

Longer recovery periods following both spring and summer upwellings resulted from the persistence of winds that had initiated the upwelling. A more rapid return to ambient temperatures tended to be associated with the movement of a high pressure system into the region, identified by a substantial decrease in wind strength and by a clock-wise rotation in wind direction. The downwelling process did not result from a reversal in the direction of strong winds.

The nearshore environments of large lakes are dynamic systems, influenced by meterological conditions. In this study we have characterized the natural variability in lake water temperature within Long Point Bay. Abrupt temperature changes, resulting from upwellings and related short-term temperature fluctuations, occur frequently and irregularly but only during the period of lake warming. This temporal pattern is attributed to the development of thermal stability within the Eastern Basin of Lake Erie and to the relatively shallow topography of Long Point Bay. Less pronounced temperature changes result from the daily warming and cooling of lake surface waters and from annual variations in atmospheric warming. Understanding the sources and extent of natural variability in the physical environment, which is influenced to a considerable extent by wind-induced mass water movements, is an essential first step in attempting to determine the natural or anthropogenic factors that affect other components of the aquatic environment.

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