J. Great Lakes Res. 22(3):707–721
Internat. Assoc. Great Lakes Res., 1996

Resuspension of Bottom Sediments in Lake Ontario During the Unstratified Period, 1992–1993

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ABSTRACT. *Time-series measurements of current velocity and water temperature made at a station in southwestern Lake Ontario between October 1992 and June 1993 are combined with analyses of material collected in a sequencing sediment trap moored at the same location. The results show that local resuspension of bottom material occurred several times during November and December. Analyses of total PCBs and Mirex concentrations were used to infer the origins of the material collected in the traps. Material collected during the fall has multiples sources; in addition to material already in suspension and bottom material resuspended from the immediate area, some material appears to be derived from the Niagara River delta. This is the first reported instance of bottom resuspension in the Great Lakes at depths below wave base during the unstratified period that has been confirmed by current velocity measurements.*

INDEX WORDS: *Resuspension, Lake Ontario, sediment transport.*

Introduction

During the past 15 years several investigators have used the results of sediment trap studies to infer the occurrence of sediment resuspension in the Great Lakes (Chambers and Eadie 1981, Charlton 1983, Eadie *et al.* 1984, Rosa 1985). This has been done by assuming that increased sediment fluxes measured near the bottom are due to episodes of local bottom resuspension. Differences in the chemical composition of the material collected in traps have also been used to develop models of material cycling in the lakes (Oliver and Charlton 1984, Oliver *et al.* 1989, Baker *et al.* 1991, Robbins and Eadie 1991). Most of these studies conclude that significant vertical mixing of sediments throughout the water column occurs during the unstratified period. In none of these studies, however, have any measurements of either current velocity or suspended sediment concentration been used to validate the interpretation of the trap data. Hawley and Lesht (1995) showed that changes in the vertical structure of the benthic nepheloid layer (BNL) can produce variations in sediment flux similar to those produced by resuspension episodes. This means that unless there are distinct differences between the composition of the bottom sediment and the material in the BNL, it may not be possible to identify resuspension events without simultaneous measurements of the current velocity and/or the suspended sediment concentration. Although several previous investigations have reported time-series measurements of current velocity and suspended sediment concentration in the Great Lakes (Lesht and Hawley 1987; Hawley and Lesht 1992, 1995; Hawley and Murthy 1995), to date bottom resuspension has only been reported at depths less than wave base (approximately 30 m). Although in two of these studies observations were made in water depths between 65 and 100 m (Hawley and Lesht 1995, Hawley and Murthy 1995), most of those observations were made when the water column was stratified. During the isothermal period (when bottom current speeds may be considerably greater) resuspension may occur at greater depths.

Rosa *et al.* (1983) were the first investigators in the Great Lakes to combine current velocity observations with sediment trap data. They reported that bottom resuspension occurred at a station in Lake

Ontario (water depth 72 m) when the current velocity increased from 2 to 4 cm s^{-1}. However their observations were made during the stratified period. In this paper we report the first concurrent current velocity and sediment trap measurements made during the unstratified period in the Great Lakes. We combine these data with chemical analyses of the bottom sediment and the trap material to identify episodes of bottom resuspension and to determine the likely origins of the trap material.

STUDY SITE AND METHODS

Measurements were made as part of a program to investigate the role of bottom furrows and seasonal bottom resuspension in the transport of contaminated sediments in Lake Ontario. As part of this study, instrument moorings were deployed in Lake Ontario near Olcott, NY during 1992 (Fig. 1). This site was chosen because it is within the area where coastal jets are likely to form (Csanady and Scott 1974) and because it is downstream of the Niagara River, which is a historical source of anthropogenic pollutants. Two moorings were deployed; details are given in Table 1. One mooring supported EG&G vector averaging current meters at 5 and 25 meters above the bottom (mab). Calibrations before and after the deployment show that the velocities are accurate to 1 cm s^{-1} with a lower threshold of 2 cm s^{-1}. Water temperatures were also recorded by the current meters; these are accurate to 0.1°C. The second mooring supported sediment traps at two elevations: 25 mab and either 5 or 7 mab. This mooring was deployed three times. During the first (summer) deployment two sets of two non-sequencing cylindrical sediment traps (10 cm inner diame-

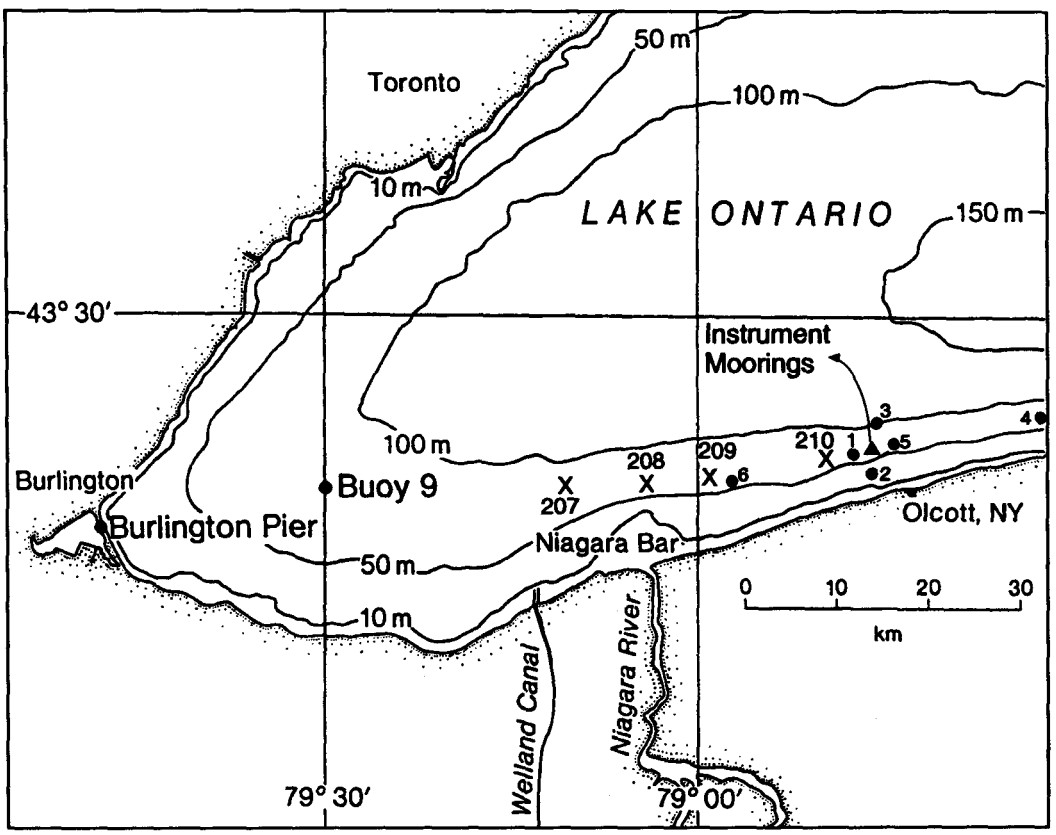

FIG. 1. Location of the moorings. Box core sites are numbers 1-6. Wind and wave observations were made at Buoy 9 and at Burlington Pier (wind observations only). Locations of the stations (207-210) occupied by other investigators and discussed in the text are also shown; the water depth at these stations is 70 m.

TABLE 1. Deployment information.

	EG&G Current Meters	Sediment Trap Deployment 1	Sediment Trap Deployment 2	Sediment Trap Deployment 3
Deployed	12 Aug 92	1 August 92	18 October 92	12 April 93
Retrieved	6 July 93	18 October 92	18 December 92	29 June 93
Latitude	43° 22.61′N	43° 22.17′N	43° 22.21′N	43° 22.28′N
Longitude	78° 45.24′W	78° 46.90′W	78° 46.90′W	78° 22.28′W
Water depth	63 m	59 m	57 m	63 m
Current and Temperature measurements				
Heights (mab)	5,25			
Sampling period	continuous 15 min avg			
Trap measurements				
Height (mab)		5	7	7
Trap diameter (cm)		10	15	15
Aspect ratio		6:1	7:1	7:1
Sample intervals		68 days	10 for 6 days 1 for 1.25 days	9 for 6 days 1 for 10 days 1 for 14 days
Height (mab)		25	25	25
Trap diameter (cm)		10	10	10
Aspect ratio		6:1	6:1	6:1
Sample interval		68 days	61 days	78 days

ter, aspect ratio 7:1) were deployed at each elevation, but an Indented Rotating Sphere Carousel sequencing trap (Peterson *et al.* 1993, inner diameter 15 cm, aspect ratio 6:1) was used at the lower level during the second (fall) and third (spring) deployments. The sequencing trap holds 12 sample bottles, each of which can be programmed to collect for a different length of time. A 6-day collection interval was used for all but the last sample during the fall deployment and all but the last two samples during the spring. A tripod instrumented with three transmissometers to measure the suspended sediment concentration was also deployed in August, but it failed after 2 weeks.

Box cores of bottom sediment were collected at the deployment site and at five other locations in August 1992. The top 10 cm of the cores were subsampled at 1 cm intervals and frozen until they were analyzed. Prior to analysis both the trap material and the box core subsamples were split into four parts. One part was dried and weighed to determine the particle mass, a second was used to determine grain size and total organic carbon content (TOC), and the other two were used to determine the Mirex and total PCB content. Internal standards were added to the samples prior to determining the concentration of Mirex and PCBs with a high resolution capillary gas chromatograph. Recoveries averaged 90%. Total PCBs were computed based on 15 major congeners. Total organic carbon was determined by dissolving the non-organic carbon in hydrochloric acid and then analyzing the remaining material with a CHN analyzer. Errors in the Mirex, TOC, and PCB concentrations are estimated to be ±20%. The duplicate

samples collected in the non-sequencing traps show an average variation in mass flux of 17%, so any variation in mass flux less than 20% can be explained by sample variability. Particle size was measured by wet sieving at 60 μm, sieving the sand fraction and measuring the fine fraction with a Coulter counter. A complete description of all of the analytical procedures is given by Wang (1995).

Weather and wave observations were obtained from a Canadian weather buoy located in the western end of the lake. (Fig. 1). In order to determine the wave parameters at other locations (including the deployment site) and between mid-November and mid-March (when the buoy was not deployed), weather observations recorded at Burlington Pier were used as input data to the GLERL wave model (Schwab *et al.* 1984), which calculates the significant wave height and the peak energy wave period. The good agreement between the observed and calculated wave parameters at the buoy (based on 5 months of observations) gives us confidence in the accuracy of the model results. The calculated wave parameters and linear wave theory were then used to calculate the bottom shear stress due to wave action. The bottom shear stress due to current activity was calculated from the 5 mab current data assuming a logarithmic velocity profile and a bottom roughness length of 0.02 cm.

Vertical profiles of water transparency and temperature were made at the beginning and end of each deployment with a Seabird CTD unit equipped with a 25 cm Sea Tech transmissometer. We attempted to develop a calibration equation relating the concentration of total suspended material to the beam attenuation measured by the transmissometer, but since the r^2 value of the regression is only 0.73 (we only had 14 observations) we have reported the beam attenuation coefficient instead. The attenuation coefficient is reported in units of m^{-1} and can be used as a qualitative measure of the concentration of suspended material, which we estimate to range between 0.5 and 10 mg L^{-1}.

RESULTS

In this paper we concentrate on the samples collected during the second and third deployments since the time resolution in the bottom trap is much better. We discuss the spring trap samples first since they show relatively little variation with either time or elevation above the bottom, and are therefore somewhat easier to interpret.

SPRING DEPLOYMENT

A vertical profile made on the deployment date (Fig. 2A) shows that the water was isothermal, and that only a thin BNL was present. By the end of the deployment the thermocline was well established, and the BNL was much thicker (Fig. 2B). A third profile taken 7 days after the traps were retrieved (Fig. 2C) gives an indication of the short-term variability that exists in the water column. The thermocline rose about 10 m, and the BNL increased in both thickness and concentration. Similar variations in the structure of the nepheloid layer have been observed in both Lake Michigan (Hawley and Lesht 1995) and in Lake Ontario (Hawley and Murthy 1995). The changes shown in Figures 2B and 2C are similar to those observed by Hawley and Murthy during an upwelling event.

The water temperatures, current velocities, and mass fluxes measured during the deployment are shown in Figure 3. The gradual increase in temperature is due to the warming of the lake during this period. It is hard to determine exactly when thermal stratification became established, but it seems to have been on about 5 June, since the temperatures at the two levels become less similar after this date. It is clear that stratification was established by 17 June. Thus all but the last one or two trap samples were collected during the unstratified period. Current velocities at the two levels are very similar, with maximum speeds of about 20 cm s^{-1}. This is sufficient to produce a bottom shear stress of about 0.6 dynes cm^{-2}. The maximum computed wave stress was only 0.02 dynes cm^{-2}, so surface wave effects were unimportant during this deployment. The current velocities show that the predominant transport direction is alongshore to the east with an onshore component, but there are several periods during which the flow is westward and/or offshore.

The sediment mass fluxes are fairly low and show relatively little variation either between the two elevations, or between the different samples collected in the bottom trap. This indicates that the material in suspension was mixed fairly uniformly through the water column throughout the deployment. The largest fluxes occurred between 18 and 30 April; the same time the bottom current speeds were also greatest. If the increased flux is due to local resuspension, then the current speeds can be used to calculate an estimate of the critical shear stress (between 0.3 and 0.6 dynes cm^{-2}, Fig. 4) needed to resuspend bottom material at the site. An-

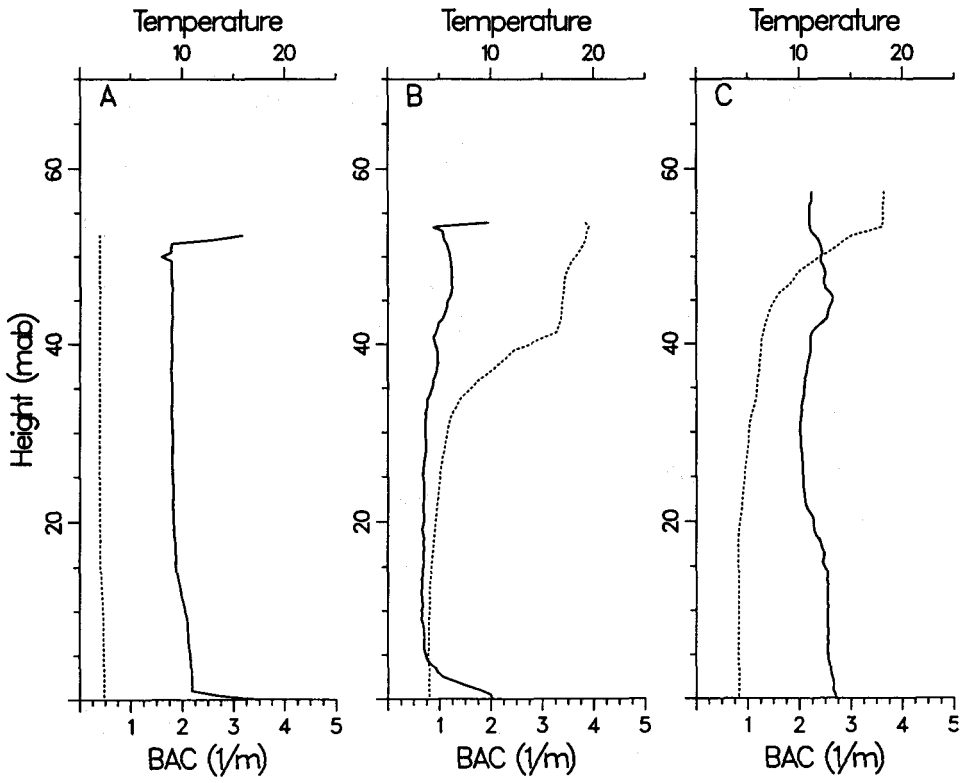

FIG. 2. Vertical profiles of beam attenuation (solid line) and temperature (dotted line) during the spring and summer of 1993. The traps were deployed on 12 April and retrieved on 29 June. A. Profile made on 12 April 1993. B. Profile made on 29 June 1993. C. Profile made on 6 July 1993.

other possibility is that the additional material came from vertical mixing of material already in suspension. If the structure of the BNL changes in a manner similar to that seen in Figures 2A and 2B, then there would also be an increased flux in the bottom trap. Lateral advection could also supply the additional material, but without additional information it is impossible to determine which of these processes actually occurred. Since the average fluxes measured at the two elevations are very similar, whatever process is responsible for the increased flux in the bottom trap probably was not limited to the bottom 7 m. The decrease in mass flux after 5 June may be because of a decrease in the flux of material from the upper water column due to the water density gradient at the thermocline.

The concentrations of the PCBs and Mirex in the trap material also show little variation (Table 2 and Fig. 4). The average concentration of both total PCBs and Mirex in the lower trap are about the same as those measured in the upper trap, and there is relatively little variation in the concentrations with time. This also indicates that the suspended sediment was well-mixed throughout the lower water column. There is a slight decrease in the PCB concentration during the period of maximum flux, but an analysis of variance shows that the difference is not statistically significant (at the 95% confidence level). The TOC concentration increases in the bottom trap throughout the deployment, which probably reflects increasing biological productivity in the upper water column during this period. TOC contents for suspended matter in surface waters are typically 10–20% (Charlton 1983), so the increase in TOC is consistent with increased production of this material with time. The higher TOC content in the upper trap

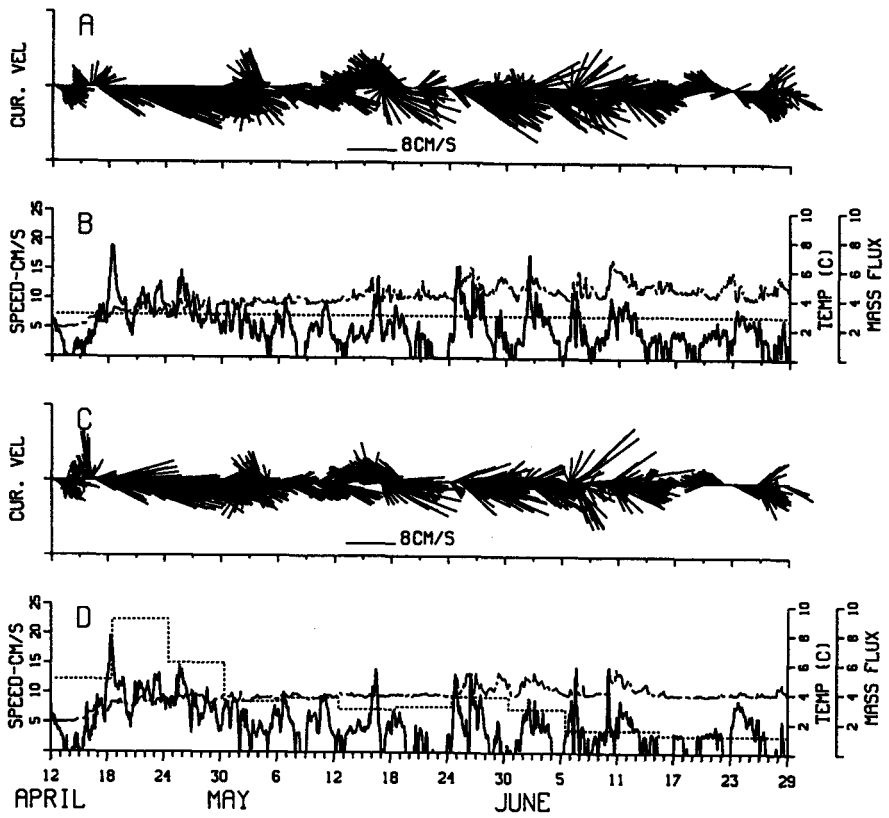

FIG. 3. Time-series measurements made during the spring 1993 deployment. A. Current velocity measured 25 mab. B. Current speed (solid line), water temperature (interrupted line), and mass flux (dashed line) measured 25 mab. C. Current velocity measured 5 mab. D. Current speed (solid line), water temperature (interrupted line), and mass flux (dashed line) measured 5 mab.

is consistent with this interpretation. Thus it seems that most of the trap material is probably derived from material already suspended in the lower part of the water column, with an increasing percentage of this material settling from the near-surface waters (at least until the thermocline is established).

FALL DEPLOYMENT

Profiles made at the beginning and end of the fall deployment are shown in Figure 5. Although the lake was still stratified at the beginning of the deployment, the fall breakdown of the thermocline was well advanced (Figs. 5A and 5B—the traps were deployed on 18 October). At the end of the deployment (Fig. 5C) the water was isothermal but a BNL was still present.

Sediment fluxes and time-series measurements of the water temperature and current velocity are shown in Figure 6. The temperature records show that the fall overturn was completed by about 2 November, which means that all of the bottom trap samples except for the first two or three were collected entirely during isothermal conditions. The generally falling temperatures after 30 October reflect the cooling of the lake during the early part of the winter. Currents at the two elevations are very similar and, as during the spring, show a predominant eastward and onshore transport. However, the current speeds are considerably greater than during the spring (note the difference in the scale), and reach 30 cm s^{-1} at 5 mab on several occasions. This is equivalent to a bottom shear stress of well over 1

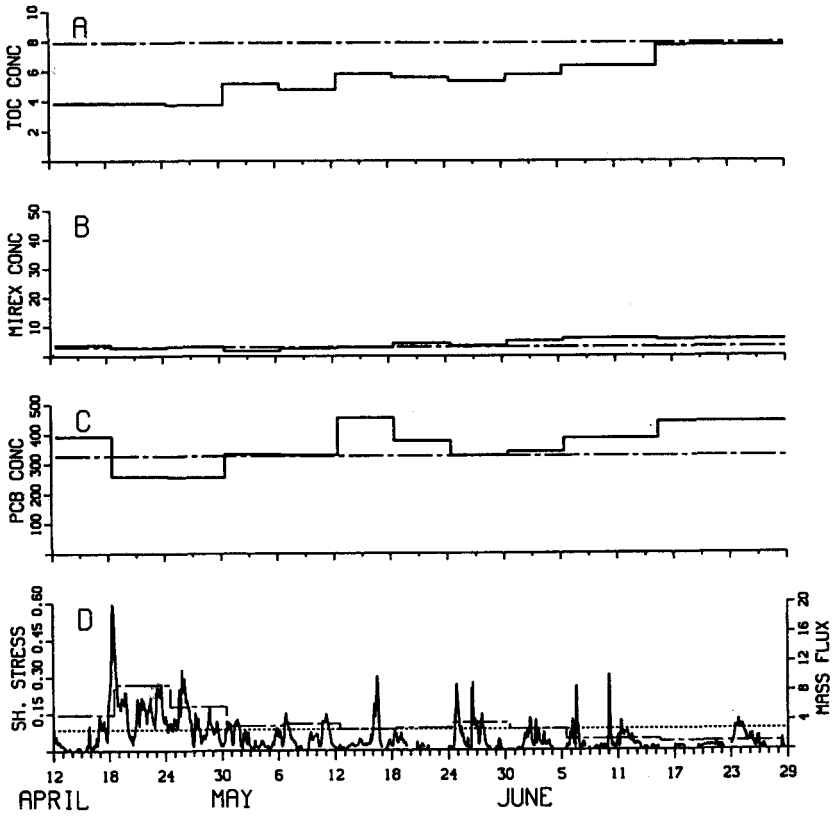

FIG. 4. Mass flux and contaminant concentrations from the trap samples collected during the spring 1993 deployment. A. Total organic carbon measured 7 mab(solid line) and 25 mab (interrupted line). B. Mirex concentrations measured 7 mab (solid line) and 25 mab (interrupted line). C. Total PCB concentrations measured 7 mab (solid line) and 25 mab (interrupted line). D. Current shear stress (solid line) and mass flux measured at 7 mab (interrupted line) and 25 mab (dashed line).

dyne cm^{-2} (Fig. 7). As was true during the spring, the effects of surface waves were negligible.

The sediment fluxes measured in the bottom trap vary widely during the deployment. The lowest fluxes are approximately equal to that measured 25 mab (and are about three times those measured during the spring) while the highest fluxes are almost an order of magnitude greater (again, note the difference in scale between Figs. 4 and 7). There are two distinct episodes of high mass fluxes. The first lasts from 5–17 November, includes the fourth and fifth sample intervals, and occurs at the same time as the maximum current speeds, while the second begins of 5 December and continues through the end of the deployment. There is, however, no consistent relationship between mass flux and shear stress. The sediment fluxes during the second high-flux episode are considerably higher than those during the first episode even though the peak current speeds are somewhat less, and the mass flux from 23–29 November is low even though the shear stress is fairly high. Even if a critical threshhold shear stress (a value below which no resuspension occurs) is subtracted from the calculated values (we tried a number of values between 0 and 1 dyne cm^{-2}) there is still no consistent correlation between the mass flux and either the average excess stress (calculated stress minus the threshold value) or the total excess stress. This suggests that processes other than local resuspension are at least partially responsible for the observed changes in mass flux.

TABLE 2. Chemical concentrations in trap material.

Trap Height	Collection Period	Mass Flux ($g/m^2/day$)	Total PCB (ng/g)	Mirex (ng/g)	TOC (%)
Summer 1992					
25 mab	12 Aug–18 Oct	6.01	343.70	2.35	5.78
5 mab	12 Aug–18 Oct	24.79	317.20	2.78	4.12
Fall 1992					
25 mab	18 Oct–18 Dec	8.63	172.00	5.93	3.66
7 mab	18–24 Oct	8.55	316.30	2.17	4.11
7 mab	24–30 Oct	6.32	308.10	2.30	4.10
7 mab	30 Oct–5 Nov	10.97	372.50	37.47	4.04
7 mab	5–11 Nov	34.97	173.20	1.86	3.57
7 mab	11–17 Nov	51.05	171.00	5.98	3.54
7 mab	17–23 Nov	9.68	282.60	3.17	3.93
7 mab	23–29 Nov	18.64	247.60	8.03	3.53
7 mab	29 Nov–5 Dec	30.64	230.10	36.79	3.57
7 mab	5–11 Dec	73.28	174.50	2.45	3.28
7 mab	11–17 Dec	76.85	173.00	2.92	3.14
7 mab	17–18 Dec	80.17	247.30	3.98	3.32
7 mab*	18 Oct–18 Dec	32.90	244.65	10.22	3.67
Spring 1993					
25 mab	12 Apr–29 June	2.86	326.50	3.05	7.90
7 mab	12–18 April	4.88	382.90	3.72	3.86
7 mab	18–24 April	8.95	259.00	2.70	3.85
7 mab	24–30 April	6.00	255.50	3.13	3.74
7 mab	30 Apr–6 May	3.38	332.60	1.73	5.16
7 mab	6–12 May	3.65	330.30	2.56	4.76
7 mab	12–18 May	2.88	455.60	2.93	5.82
7 mab	18–24 May	3.06	377.60	4.30	5.58
7 mab	24–30 May	3.74	328.60	3.46	5.34
7 mab	30 May–5 June	2.91	341.08	5.07	5.76
7 mab	5–15 June	1.52	385.70	5.88	6.35
7 mab	15–29 June	1.17	441.70	5.54	7.72
7 mab*	12 April–29 June	3.44	369.07	4.08	5.65

* indicates average values for the collection period

The contaminant concentrations (Fig. 7) also vary more widely than during the spring. The total PCB concentrations show the same inverse correlation with mass flux seen in the spring deployment, but this time the concentration in the bottom trap is always equal to or greater than that measured 25 mab. The range of concentrations measured is also slightly lower than that measured during the spring. This suggests that in addition to the material already in suspension, an additional source of material depleted in PCBs is responsible for the extra material collected during the high flux episodes, and that the bulk of the material in the upper trap was collected during these intervals.

Peak Mirex concentrations occur during sample intervals three and eight, and do not correlate with either the mass flux or total PCB concentration. In fact the mass fluxes during both of these intervals are relatively low. Nor do the Mirex concentrations show a consistent correlation with the current shear stress; interval three includes the highest stress calculated during the deployment, but the stress during interval eight is much less. It appears that the high Mirex concentrations are not due to local resuspen-

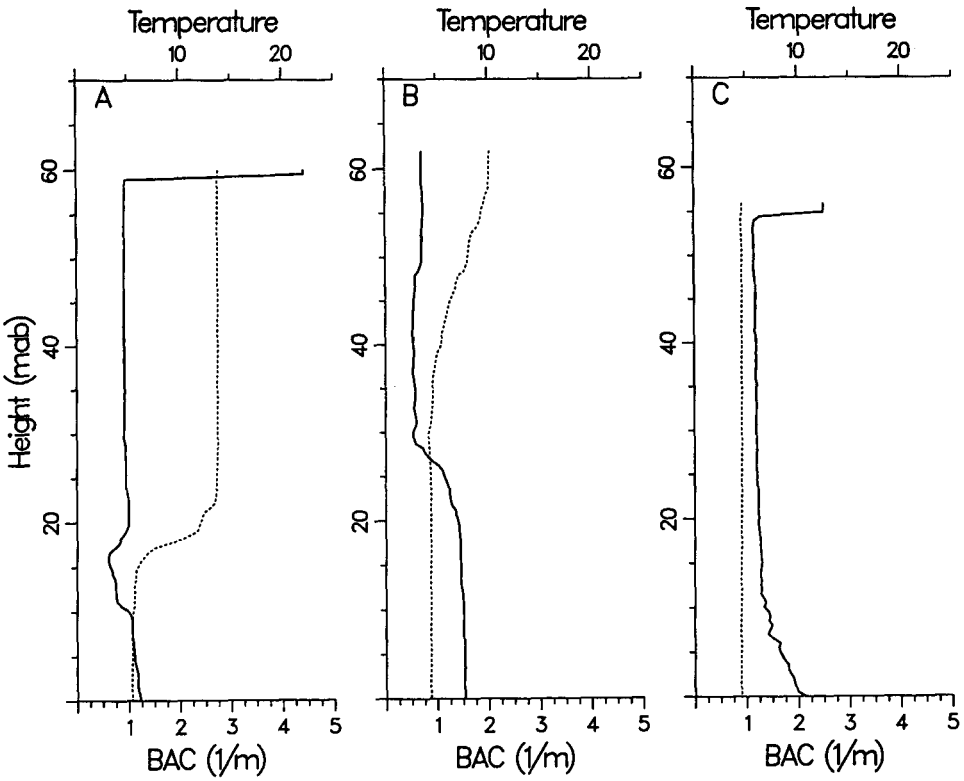

FIG. 5. Vertical profiles of beam attenuation (solid line) and temperature (dotted line) from the fall of 1992. The traps were deployed on 18 October and retrieved 18 December. A. Profile made on 13 October, 1992. B. Profile made on 16 October, 1992. C. Profile made on 18 December, 1992.

sion, and that another source of material is needed to explain the observations.

TOC concentrations show relatively little variation during the deployment. The average content at the two elevations is about the same, and there is little variation in the samples collected in the bottom trap. The concentrations are also less than those collected during the spring. This may be due to a decrease in biological productivity at this time of the year, or it may reflect the increased importance of material derived from other sources.

BOTTOM SEDIMENTS

Data from the top 1 cm of the box cores are shown in Table 3. TOC concentrations are lower than those measured in the traps, so if bottom material is resuspended, it could explain the lower TOC concentrations observed during the fall. Total PCB concentrations vary somewhat, but are generally greater than or equal to the concentrations measured in the traps. The Mirex concentrations are similar to those found in most of the trap samples, but are considerably less than the highest concentrations observed during the fall deployment. A more complete discussion of the box core data is given by Wang (1995), who concluded that box core 5 (the one taken at the deployment site) is in a non-depositional zone. The study site is probably located on the flank of the Whitby-Olcott Sill, which Thomas (1972) and Thomas *et al.* (1972) identified as a non-depositional area.

DISCUSSION

If the fall trap samples are divided into two groups based on their mass flux, an analysis of variance shows that the two groups have statistically

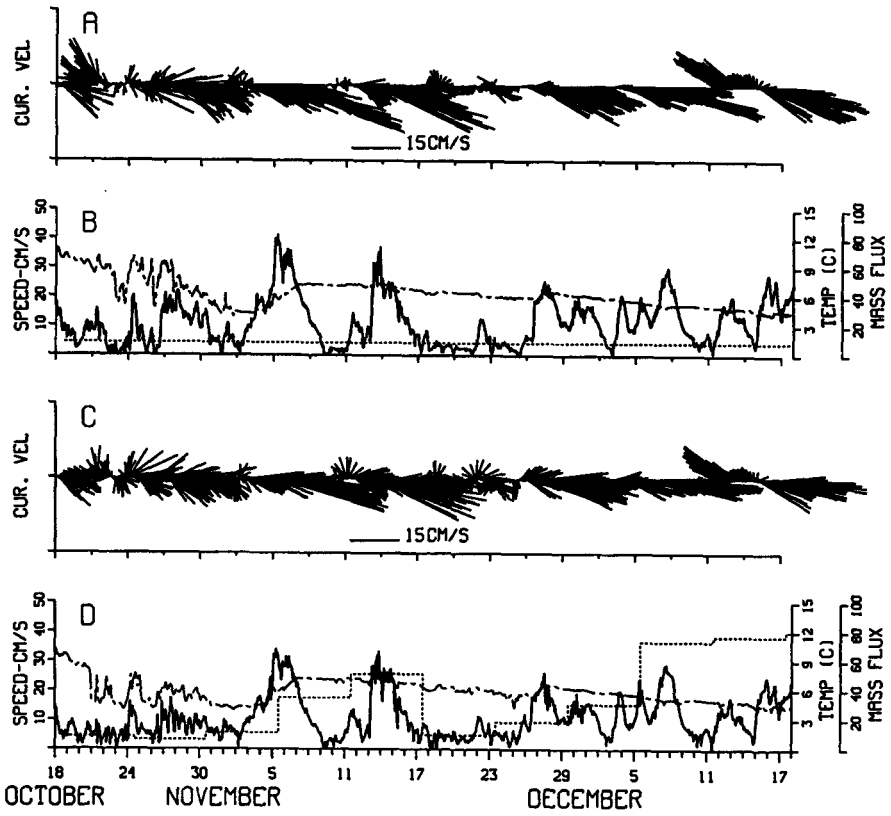

FIG. 6. Time-series measurements made during the fall 1992 deployment. A. Current velocity measured 25 mab. B. Current speed (solid line), water temperature (interrupted line), and mass flux (dashed line) measured 25 mab. C. Current velocity measured 5 mab. D. Current speed (solid line), water temperature (interrupted line), and mass flux (dashed line) measured 5 mab.

different (at the 95% confidence level) total PCB concentrations. The distinction between the low and high Mirex concentrations in the fall samples is also statistically significant. Thus it appears that at least three distinct sediment sources are needed to explain the fall trap results: a background material that is collected during quiescient periods, a second sediment high in Mirex (at least 35 ng g^{-1}), and a third sediment with a relatively low PCB concentration (about 150–200 ng g^{-1}) that is collected during the high flux episodes. In the discussion below we attempt to identify the sources of these sediments.

We believe that the material collected in the traps during the spring and during the low-flux intervals during the fall is primarily background material that was already suspended in the BNL. This material is most likely composed of particles that were previously introduced into the water column at various times and places and have been maintained in the water column by turbulent diffusion. The chemistry of this material is characterized by PCB concentrations of about 300–400 ng g^{-1} and Mirex concentrations of about 3–5 ng g^{-1}. Although it is difficult to compare our results with those from other investigations (due to differences in analytical techniques and changes in contaminant concentrations with time), our total PCB abundances are consistent with previous observations. At a site about 10 km west of ours (station 210, Fig. 1), Mudroch and Mudroch (1992) measured a total PCB concentration of 384 ng g^{-1} on the sediment suspended in the BNL. They also found that the material in the BNL was rela-

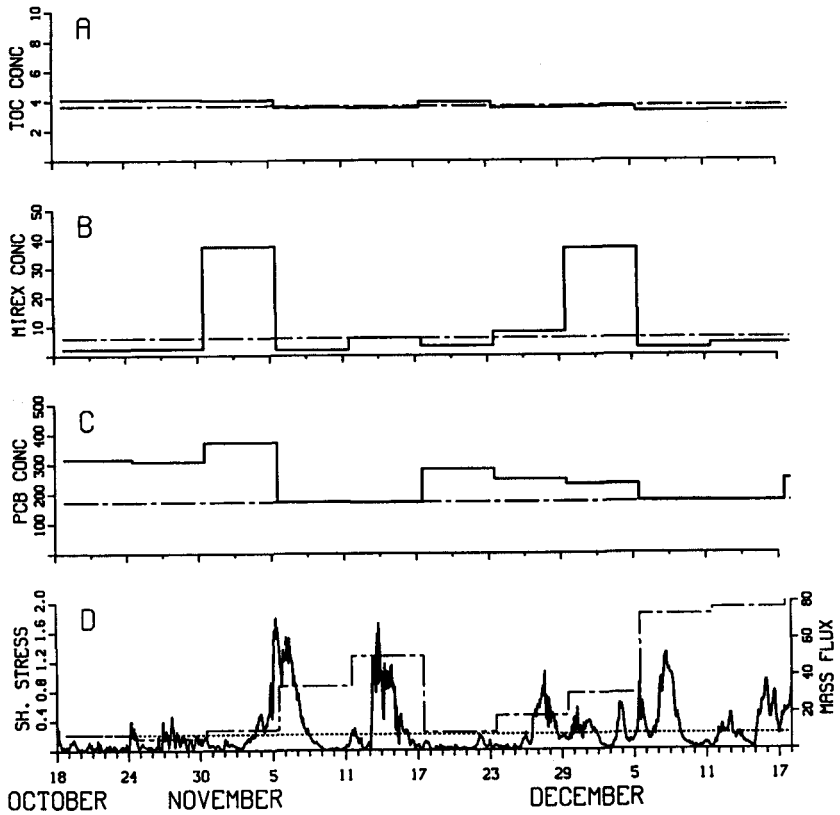

FIG. 7. Mass flux, total organic carbon, and contaminant concentrations from the trap samples collected during the fall 1992 deployment. A. Total organic carbon measured 7 mab (solid line) and 25 mab (interrupted line). B. Mirex concentrations measured 7 mab (solid line) and 25 mab (interrupted line). C. Total PCB concentrations measured 7 mab (solid line) and 25 mab (interrupted line). D. Current shear stress (solid line) and mass flux measured at 7 mab (interrupted line) and 25 mab (dashed line).

tively depleted in the lighter and more soluble PCBs relative to the congener distribution in the surface sediments; an observation that also applies to our trap samples (Brownawell *et al.* 1994). In a sediment trap study around the Niagara River delta (stations 207, 208, 209, and 210) Oliver *et al.* (1989) reported total PCB concentrations between 1,300 and 80 ng g^{-1}. Most of the Mirex concentrations in our trap material are also similar to those reported by previous workers from sediment traps at station 210 (5.9 ng g^{-1}, Oliver and Charlton 1984).

Vertical remixing of material already in suspension probably accounts for the heightened mass flux seen during the early part of the spring deployment since the contaminant concentrations are essentially constant. However, since this material would have the same composition as that collected during ambient conditions, we do not believe that remixing material already suspended in the BNL is the source of the additional material collected during the high flux episodes during the fall, or of the material with the high Mirex concentrations. There are several possible sources for the additional material: material introduced into the lake by the Niagara River and transported directly to the site, bottom material from the Niagara delta that has been resuspended and advected to the site, bottom material from else-

TABLE 3. Chemical concentrations in box core material.

Site #	Lattitude	Longitude	Water Depth (m)	Depth Interval (cm)	PCB Conc. (ng g^{-1})	Mirex Conc. (ng g^{-1})	TOC Conc. (%)
1	43°22.52′N	78°45.83′W	67	0–1	379.53	7.53	2.85
2	43°21.60′N	78°46.31′W	36	0–1	479.61	1.21	1.71
3	43°23.60′N	78°46.96′W	95	0–1	351.60	9.76	4.31
4	43°23.60′N	78°34.88′W	64	0–1	327.20	3.51	0.81
5	43°22.30′N	78°45.47′W	55	0–1	613.20	2.52	1.36
6	43°20.44′N	78°55.06′W	58	0–1	333.67	3.73	2.59

where in the lake that has been resuspended and transported to the site, and local bottom sediment resuspended into the water column.

Both the water discharge of the Niagara River (as measured at Buffalo by the U.S. Army Corps of Engineers) and the sediment concentration of that water (as measured at Niagara by the Niagara Falls Water District) show a large increase on 13–15 November. Winds during and after this period are from the southwest, which confines the plume to a narrow band along the shore to the east of the river mouth (Masse and Murthy 1990). If we assume that the current velocities measured at the site are representative of those between the river mouth and the trap site, then a progressive vector plot of the currents shows that the turbid water from the plume should reach the site prior to the end of the sampling period that ends on 17 November. This trap sample has a high mass flux, so turbid river water is a possible source for some of the material. Oliver and Charlton (1984) concluded that the plume influence could be seen at station 210, but since we have no measurements of either the total PCB or the Mirex concentration on particles suspended in the river, we cannot confirm their findings at our site. Kauss (1983) analyzed suspended material from the lower Niagara River and reported a PCB concentration of 136 ng g^{-1} and a Mirex concentration of 55 ng g^{-1}. These values are somewhat different from those collected in the bottom trap between 11 and 17 November, but there is no reason to assume that the concentrations have remained constant over 12 years. However, if river-derived particles are an important constituent of the material collected between 11 and 17 November, then another source of material with the same chemical characteristics is needed to explain the observations made both between 5 and 11 November and after 5 December. Particles in the river are derived mainly from Lake Erie, and their contaminant loads are somewhat different from that on particles found in Lake Ontario (Mudroch and Williams 1989), so it seems unlikely to us that there would be another source of material with the same composition. Although it is possible that river- derived particles transported directly to the site are an important source of trap material, we believe that other sources are more likely candidates.

Sediment resuspended at the Niagara delta and then advected to the site may be the source of the material with high Mirex concentrations. Although our box core data show no Mirex concentrations high enough to produce the abundances observed in the trap samples collected from 30 October–5 November and from 29 November–5 December, Oliver *et al.* (1989) found that surficial (0-3 cm) delta sediments at stations 207, 208, and 209 contained high concentrations of Mirex (36–65 ng g^{-1}). Calculated wave shear stresses at the delta have high values on 2 and 22 November (over 1 dyne cm^{-2}) so bottom sediment may have been resuspended by wave action on these days. A progressive vector plot shows that material resuspended on 2 November would reach the trap site prior to 5 November, but a similar calculation for material resuspended on 22 November indicates that it should reach the trap site before 29 November—one sample period prior to that when the high Mirex concentration is observed. Examination of the wind records shows however that instead of being mainly from the west, as they are between 2 and 5 November, the winds are from the east between 23 and 27 November. Winds from this direction push water in the delta area offshore and to the west (Masse and

Murthy 1990). Since Simons *et al.* (1985) showed that drogues released in the river mouth could escape from the eastward-flowing coastal jet for several days prior to being recaptured, it is possible that material resuspended at the delta might not arrive at the trap site until after 29 November. If material in the delta still has a high Mirex concentration, then the resuspension and transport of this material could explain the high Mirex concentrations observed during these two sample periods. Surficial PCB concentrations in the delta (Oliver *et al.* 1989, stations 207, 208, and 209) are slightly higher (between 380 and 530 ng g^{-1}) than those found in the traps during these two intervals, but those samples were collected in 1981. Unfortunately more recent concentration measurements of delta sediments are not available.

Since the bottom shear stresses during the fall are frequently rather high, local resuspension of bottom sediment is an obvious possible source of material during the high flux episodes. Although measurements of the shear strength of the local sediments are not available, MacIntyre *et al.* (1990) reported that a stress of about 1 dyne cm^{-2} was sufficient to erode bottom material from the Great Lakes. Our calculations show that this value was exceeded several times during the fall deployment. If local resuspension did occur, then we would expect the PCB concentrations in the trap material to be similar to those measured in the bottom sediments. However, our analyses of the bottom sediments both at the site and at surrounding locations show that the total PCB concentrations are somewhat higher than those in the trap material. If local resuspension is the source of the additional sediment, then there must be some mechanism that lowers the PCB concentration in the trap material. There are several possibilities: (1) the PCBs could be desorbed after the material is collected in the traps, (2) the material could be desorbed into the water column prior to collection, (3) there could be a grain size effect (large high-density particles with low PCB concentrations could be a higher percentage of the material collected during the high flux episodes), or (4) there could be a thin, easily-eroded, surface layer low in PCBs that we did not collect.

Several of these possibilities can be ruled out. Desorbtion after the trap material was collected seems unlikely since it should have occurred in all of the samples. Desorbtion into the water column also seems unlikely since Mudroch and Mudroch (1992) showed that the PCB concentration on particles in the benthic nepheloid layer was approximately 400 ng g^{-1}—considerably higher than the concentrations we observed during the high-flux episodes. It also seems unlikely that a surface layer was removed during the sampling since a box corer was used to collect the samples, and we were careful not to disturb the sediment-water interface when we sectioned the cores.

The most likely explanation is a grain-size effect. Particle size measurements show that although the amount of sand-sized material remained constant during all of the collection intervals, the fraction of material between 16 and 64 μm in diameter increased about 10-20% during the high flux episodes while the amount of clay-sized material decreased by a similar percentage. If the concentration of PCBs is greater on the clay-sized material than on the larger particles, this would explain the lower PCB concentrations during the high-flux periods. Although Mudroch and Mudroch (1992) found that the total PCB concentration on surface sediments at station 210 was slightly higher for particles between 64 and 13 μm than for finer material, their measurements were made on surficial (0-3 cm) sediment with a total PCB concentration of only 95 ng g^{-1}. The PCB concentration at our station is considerably higher, and the distribution could also be different. Given the high bottom stresses observed between 4 and 17 November, and 5 to 11 December, it seems likely that local resuspension occurred and that this material is the main source of the high fluxes observed during these periods. Although the low mass flux between 23 and 29 November is somewhat anomalous, it is not unique; similar "flow-events" have been observed in both Lake Michigan (Hawley and Lesht 1995) and in the deep sea (Gross and Williams 1991).

Another possible source of trap material is sediment from nearer shore that is resuspended by either wave or current action and then transported to the site. We have no current data from any inshore stations, but the calculated wave shear stress off Olcott, NY from nearer shore shows peaks on 2, 20, and 22 November, and on 10 and 11 December. Progressive vector diagrams show, however, that offshore transport only occurred between 11 and 15 December. Material resuspended nearer shore and then transported offshore could explain why the mass fluxes after 11 December are higher than those observed earlier—even though the shear stresses at the trap site are less.

CONCLUSIONS

Without time-series measurements of the suspended sediment concentration we cannot be certain, but we believe that there were at least two instances of local sediment resuspension during the fall deployment. Previous investigators have inferred bottom resuspension from trap measurements alone, but these are the first reported instances of bottom resuspension below wave base in the Great Lakes during the unstratified period that have been supported by current velocity measurements. Bottom resuspension occurred in response to the increased near-bottom current velocities during these periods which were, in turn, generated by the passage of storms across the lake. Wind observations made at Burlington Pier show that wind speeds over 50 km hour^{-1} were recorded several times during the fall deployment period. Speeds of this magnitude are not uncommon; the peak speed recorded during the winter (approximately 60 km hour^{-1}) occurred in March, and there were several other storms that were at least as intense as those during the fall deployment. An analysis of 30 years of wind records (Transport Canada 1991) shows that the most severe storm during the winter of 1992-1993 (the one in March) is in no way exceptional—it was a typical "storm of the year." Thus it seems likely that bottom resuspension occurs fairly commonly during the unstratified period at this site.

The trap material collected during the fall is probably a combination of material from several different sources: material already suspended in the water column, material derived from the Niagara delta, local bottom material that was resuspended, and material from further inshore that was resuspended and then transported to the trap site. During the spring, when the flow conditions were less energetic, material already suspended in the BNL was probably the primary source of trap material. Unfortunately, we cannot confirm our conclusions since there are no data on the contaminant concentrations in the possible source regions during our study period. If we were to repeat this study, we would make sure that these measurements were made.

ACKNOWLEDGMENTS

We thank the crews of the R/V *Lake Guardian* and the CSS *Limnos* for assistance during the deployment and retrieval of these moorings, and the technical staff of the Great Lakes Environmental Research Laboratory for calibrating the instruments. The Canada Centre for Inland Waters provided the weather data from Burlington Pier and from buoy #9. Andrew Piacente of the U.S. Army Corps of Engineers provided the flow data and Charles Gonzalez of the water facilities service of the City of Niagara New York provided the turbidity data for the Niagara River. We thank F.M. Boyce, M.N. Charlton, and P.G. Sly for their reviews of the manuscript. This work was partially funded by N.Y. State Sea Grant contract NA90AADSG078. This is GLERL contribution 996.

REFERENCES

Baker, J.E., Eisenreich, S.J., and Eadie, B.J. 1991. Sediment trap fluxes and benthic recycling of organic carbon, polycyclic aromatic hydrocarbons and polychlorobiphenyl congeners in Lake Superior. *Environ. Sci. Technol.* 25:500–509.

Brownawell, B., Flood, R.D., and Wang, X. 1994. The role of seasonal resuspension in contaminant cycling in Lake Ontario. *Great Lakes Res. Rev.* 1:29–35.

Chambers, R.L., and Eadie, B.J. 1981. Nepheloid and suspended particulate matter in south-eastern Lake Michigan. *Sedimentology* 28:439–447.

Charlton, M.N. 1983. Downflux of sediment, organic matter and phosphorus in the Niagara River area of Lake Ontario. *J. Great Lakes Res.* 9:201–211.

Csanady, G.T., and Scott, J.T. 1974. Baroclinic coastal jets in Lake Ontario during IFYGL. *J. Phys. Ocean.* 4: 524–541.

Eadie, B.J., Chambers, R.L., Gardner, W.S., and Bell, G.L. 1984. Sediment trap studies in Lake Michigan: resuspension and chemical fluxes in the southern basin. *J. Great Lakes Res.* 10:307–321.

Gross, T.F., and Williams, A.J. III. 1991. Characterization of deep-sea storms. *Marine Geol.* 99:281–301.

Hawley, N., and Lesht, B.M. 1992., Sediment resuspension in Lake St. Clair. *Limnol. Oceanogr.* 37:1720–1737.

_____, and Lesht, B.M. 1995. Does local resuspension maintain the benthic boundary layer in Lake Michigan? *J. Sediment. Res.* 65A:69–76.

_____, and Murthy, C.R. 1995. The response of the benthic nepheloid layer to a downwelling event. *J. Great Lakes Res.* 21:641–651.

Kauss, P.B. 1983. Studies of the trace contaminants, nutrients, and bacteria levels in the Niagara River. *J. Great Lakes Res.* 9:249–273.

Lesht, B.M., and Hawley, N. 1987. Near-bottom currents and suspended sediment concentration in southeastern Lake Michigan. *J. Great Lakes Res.* 13:375–386.

MacIntyre, S., Lick, W., and Tsai, C.H. 1990. Variability

of entrainment of cohesive sediments in freshwater. *Biogeochem.* 9:187–209.

Masse, A.K., and Murthy, C.R. 1990. Observations of the Niagara River thermal plume (Lake Ontario, North America). *J. Geophys. Res.* 95:16097–16109.

Mudroch, A., and Mudroch, P. 1992. Geochemical composition of the nepheloid layer in Lake Ontario. *J. Great Lakes Res.* 18:132–153.

_____, and Williams, D. 1989. Suspended sediments and the distribution of bottom sediments in the Niagara River. *J. Great Lakes Res.* 15:427–436.

Oliver, B.G., and Charlton, M.N. 1984. Chlorinated organic contaminants on settling particulates in the Niagara River vicinity of Lake Ontario. *Environ. Sci. Technol.* 18:903–908.

_____, Charlton, M.N., and Durham,, R.W. 1989. Distribution, redistribution, and geochronology of polychlorinated biphenyl congeners and other chlorinated hydrocarbons in Lake Ontario sediments. *Environ. Sci. Technol.* 34:200–208.

Peterson, M.L., Hernes, P.J., Thoreson, D.S., and Lee, C. 1993. Field evaluation of a valved sediment trap. *Limnol. Oceanogr.* 38:1741–1761.

Robbins, J.A., and Eadie, B.J. 1991. Seasonal cycling of trace elements, ^{137}Cs, ^{7}Be, and $^{239+240}Pu$ in the Great Lakes. *J. Geophys. Res.* 96:17081–17104.

Rosa, F. 1985. Sedimentation and sediment resuspension in Lake Ontario. *J. Great Lakes Res.* 11:13–25.

_____, Nriagu, J.O., Wong, H.K., and Burns, N,M. 1983. Particulate flux at the bottom of Lake Ontario. *Chemosphere* 12:1345–1354.

Schwab, D.J., Bennett, J.R., and Liu, P.C. 1984. Application of a simple numerical wave prediction model to Lake Erie. *J. Geophys. Res.* 89:3586–3592.

Simons, T.J., Murthy, C.R., and Campbell, J.E. 1985. Winter circulation in Lake Ontario. *J. Great Lakes Res.* 11:423–433.

Thomas, R.L. 1972. The distribution of mercury in the sediments of Lake Ontario. *Can. J. Earth Sci.* 9: 636–651.

_____, Kemp, A.L.W., and Lewis, C.F.M. 1972. Distribution, composition and characteristics of the surficial sediments of Lake Ontario. *J. Sediment. Petrol.* 42:66–84.

Transport Canada. 1991. *Wind and wave climate atlas III.* Transportation Development Centre, Policy and Coordination Group, Ottawa, Canada.

Wang, X. 1995. Seasonal resuspension of contaminated sediments in southern Lake Ontario. M.S. thesis, Department of Marine Environmental Science, State University of New York at Stony Brook, Stony Brook, NY.

Submitted: 4 April 1996
Accepted: 8 July 1996