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The Response of the Benthic Nepheloid Layer to a Downwelling Event

Nathan Hawley[1] and C. R. Murthy[2]

[1]*Great Lakes Environmental Research Laboratory*
2205 Commonwealth Boulevard
Ann Arbor, Michigan 48105

[2]*National Water Research Institute*
P.O. Box 5050
867 Lakeshore Drive
Burlington, Ontario L7R 4A6

ABSTRACT. *Time series observations of water temperature, current velocity, and water transparency were made at three elevations at a mooring in southwestern Lake Ontario over a 14-day period. Although a strong downwelling event occurred during the deployment, there was no indication of either local sediment resuspension or of downslope transport of suspended material. Our observations, when combined with those of Hawley and Lesht (1995), indicate that material is not supplied to the benthic nepheloid layer by either local resuspension or offshore transport during the stratified period. Although several authors have suggested that the maintenance of the benthic nepheloid layer during the stratified period requires the periodic supply of additional material after it is formed, the sources of this material are not well known. Some material is most likely supplied by the settling of material from the epilimnion, but an additional—as yet unidentified—source seems to be needed to explain the observed changes in both the thickness and the concentration of material suspended in the benthic nepheloid layer.*

INDEX WORDS: *Suspended sediments, Lake Ontario, nepheloid layer, particulate matter.*

INTRODUCTION

Although benthic nepheloid layers (BNLs) are commonly observed in the Laurentian Great Lakes, the processes responsible for their origin and maintenance are still the subject of debate. During the summer and fall, these layers are found just above the bottom in the deeper areas of all of the Great Lakes (Bell *et al.* 1980). They are characterized by an increase in light scattering (or equivalently, a decrease in light transmission) which is due mostly to an increase in the concentration of suspended material (Hawley and Zyrem 1990), although changes in particle characteristics may also be important (Mudroch and Mudroch 1992). These layers are also found in the ocean, where they are considered to be due to the resuspension of bottom material (McCave 1986). Based on observations made in Lake Michigan, Chambers and Eadie (1981) suggested that BNLs are originally established by currents associated with the offshore movement of the thermal bar during the spring, and that they are subsequently maintained by a combination of local resuspension and material transported downslope from the area where the thermocline intersects the bottom. Halfman and Johnson (1989) believed that the BNL in the western part of Lake Superior was maintained by a combination of local resuspension and density currents.

Scientists at the Canada Centre for Inland Waters have conducted several studies on the BNL in Lake Ontario. Sandilands and Mudroch (1983) documented the occurrence of the BNL throughout the lake, and noted the presence of biogenic material in suspended sediment collected from the BNL. They also found a direct correlation between the thickness of the BNL and water depth. In more recent studies, Mudroch and Mudroch (1992), and Mudroch *et al.* (1994) found that the chemistry of material suspended in the BNL differed from that of the the underlying sediments, and suggested that some of the suspended matter was not resuspended bottom material, but rather material settling from the epilimnion. They also found that in the western basin of the lake some of the suspended material was transported from Lake Erie via the Niagara River. Sly (1994a, 1994b) proposed a biogenic origin for the BNL. He argued that the particle size—and hence the particle fall velocity—of epilimnetic material decreased as it settled through the water column due to dissolution and degradation, and that this resulted in the accumulation of suspended material in the BNL. It seems likely that the material in the BNL has multiple origins, and that the relative importance of the various sources varies with location and time. In the western basin of Lake Ontario, both Mudroch and Mudroch (1992) and Oliver and Charlton (1984) calculated that a large percentage (40–60%) of the material suspended in the BNL was due to the resuspension of bottom material.

The findings in all of these investigations are based on indirect evidence; in none of the studies was sediment resuspension actually observed. The best way to identify a resuspension event is to correlate time series measurements of suspended sediment concentration and current velocity (or wave activity in shallow water), but to date the only such measurements in the hypolimnion of the Great Lakes are those of Hawley and Lesht (1995). They found no evidence of local resuspension in several months of observations from Lake Michigan, and suggested that the BNL is maintained by a combination of the vertical redistribution of material already in suspension and the downslope transport of additional material from the shelf during downwelling events. Although their data enabled them to document the first process, it was inadequate to document the second. This paper reports time series measurements of temperature, current velocity, and water transparency recorded during a downwelling event in Lake Ontario. We use these data to investigate the liklihood of downslope transport of suspended material during downwellings as a source of material to the BNL.

METHODS

The measurements were made as part of a program to investigate the role of bottom resuspension in the transport of contaminated sediments in Lake Ontario. As part of this study, three instrument moorings were deployed in Lake Ontario near Olcott, New York 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.

Details of the moorings are given in Table 1; the water depth at all of the stations is far too deep for direct surface wave action to affect the bottom during any but the most extreme storms. Two moorings were deployed by the Great Lakes Environmental Research Laboratory. One of these included two EG&G vector averaging current meters (VACMs); the second was an instrumented bottom-resting tripod with additional sensors mounted on the mooring wire. The latter mooring included a Marsh-McBirney 585 electromagnetic current meter and three Sea Tech transmissometers (25 cm pathlength). Temperature sensors (Yellow Springs thermistors) were co-located with the transmissometers. All of the sensors on both moorings were calibrated before and after the deployment. Velocities are accurate to 1 cm s^{-1} with a lower threshold of 2 cm s^{-1} for the VACMs and 0.2 cm s^{-1} for the electromagnetic current meter. Temperatures are accurate to 0.1°C and transparency readings to 0.001 v. When these moorings were recovered on 6 July 1993, it was discovered that (due to a leak in the pressure case) the tripod instruments had only worked for 15 days. Thus water transparency observations were only recorded from from 12 August through 27 August 1992.

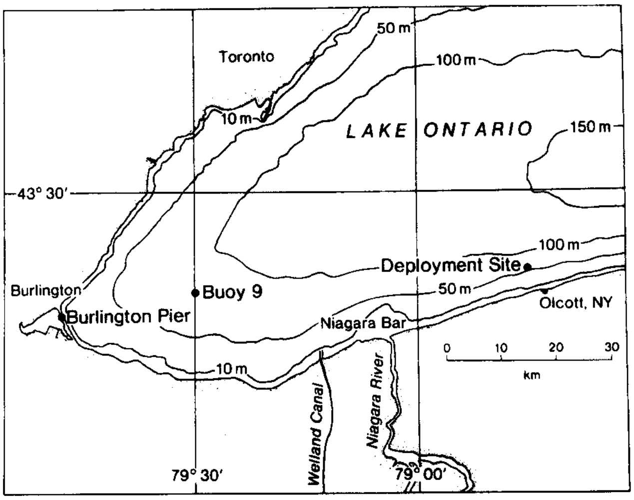

FIG. 1. Location of the moorings. Wind and wave observations were made at Buoy 9. The three moorings were all within 2 km of each other at the deployment site. The vertical profiles shown in Figures 2a and 2c were made in 30 m and 90 m of water on a transect running from Olcott through the mooring site.

The third mooring was deployed by the National Water Research Institute of Canada on 24 June 1992 and retrieved on 13 October 1992. This moor-

TABLE 1. Deployment data.

	EG&G Current Meters	Bottom Tripod	Neil Brown Current Meter
Deployed	12 August 1992	12 August 1992	24 June 1992
Retrieved	6 July 1993	6 July 1993	13 October 1992
Latitude	43°22.61′N	43°22.08′N	43°22.35′N
Longitude	78°45.24′W	78°45.75′W	78°46.38′W
Water depth	63 m	58 m	60 m
Current measurements			
Heights (mab)	5, 25	0.5	3
Sampling period	continuous 15 min avg	1 min avg per hour	continuous 20 min avg
Sampling rate	not applicable	1 Hz	1 Hz
Temperature measurements			
Height (mab)	5, 25	0.9, 5, 25	3
Sampling period	Continuous 15 min avg	1 min avg per hour	continuous 20 min avg
Sampling rate	not applicable	1 Hz	1 Hz
Transparency measurements			
Heights (mab)		0.9, 5, 25	
Sampling period		1 min avg per hour	
Sampling rate		1 Hz	

ing contained a Neil Brown acoustic current meter 3 meters above the bottom (mab) that recorded water temperature and current velocity throughout the deployment period. The meter was calibrated prior to deployment; the speeds are accurate to 0.5 cm s^{-1} with a lower threshold of 0.2 cm s^{-1}, and the temperature measurements are accurate to 0.1°C.

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), the weather observations 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 assuming a logarithmic velocity profile and a bottom roughness length of 0.02 cm.

Vertical profiles of water transparency and temperature were made using a Seabird CTD unit equipped with a 25 cm Sea Tech transmissometer. We attempted to construct an empirical equation relating the transmissometer measurements to the concentration of total suspended sediment, but since the resulting equation has an r^2 value of only 0.73 (we only had 14 data points) we have reported our results in terms of the beam attenuation coefficient (BAC), which has the units of m^{-1}. Since the attenuation coefficient is directly related to the concentration of suspended material, variations in its value can be qualitatively interpreted as reflecting changes in the suspended sediment concentration.

Box cores of bottom sediment were collected at the deployment site in August, 1992. Visual observations showed that the sediment was cohesive and was rather poorly sorted. The top 1 cm was analyzed for particle size by doing a wet sieving at 60 μm, sieving the sand fraction and doing a pipette analysis on the fine size fraction (Wang 1995). The sediment has a bimodal distribution with one peak in the very fine sand-coarse silt range and another in the fine clay range. Based on measurements made at the Niagara delta (Sly 1983) the annual sediment accumulation rate is probably about 1 mm per year, so the grain size distribution probably reflects the influence of different depositional processes over the past 10 years (Sly 1994a).

RESULTS

The sensors on the tripod operated only from 12 August through 27 August 1992 so we confine our analysis to this period. Profiles of temperature and water transparency made on a cross-shelf transect 3 days prior to the deployment of the tripod (9 August, Fig. 2a–2c) show that the lake was well-stratified with the thermocline 20–30 m below the surface. They also show that although a BNL did not exist nearshore, it was about 20 m thick near the deployment site (Fig. 2b). Further offshore the BNL was even more pronounced—it was both thicker (it extended through the entire hypolimnion) and had a larger maximum attenuation. A profile made when the tripod was deployed 3 days later (Fig. 2d) shows that the thermocline had risen about 10 m during that time and that the structure of the BNL had altered. Although both the total thickness and maximum attenuation remained about the same, the depth range over which the maximum attenuation was observed increased from about 4 to 10 m. This means that the BNL contained more suspended material on the deployment date than 3 days earlier. All of these profiles also show a surface nepheloid layer that extended to about the top of the thermocline. Unfortunately we have no profiles during the rest of the deployment.

Beginning at about midnight on 12 August (the tripod was deployed later—at 1400—on this day) strong winds blew from the northeast for 5 days (Fig. 3a). Winds from this direction are conducive to upwelling on the south shore of the lake (Mortimer 1980). On 17 August the winds reversed direction and blew from the southwest and northwest (which promotes downwelling on the southern shore and the formation of a coastal jet—Csanady and Scott 1974) until 22 August. After that the winds were light and variable.

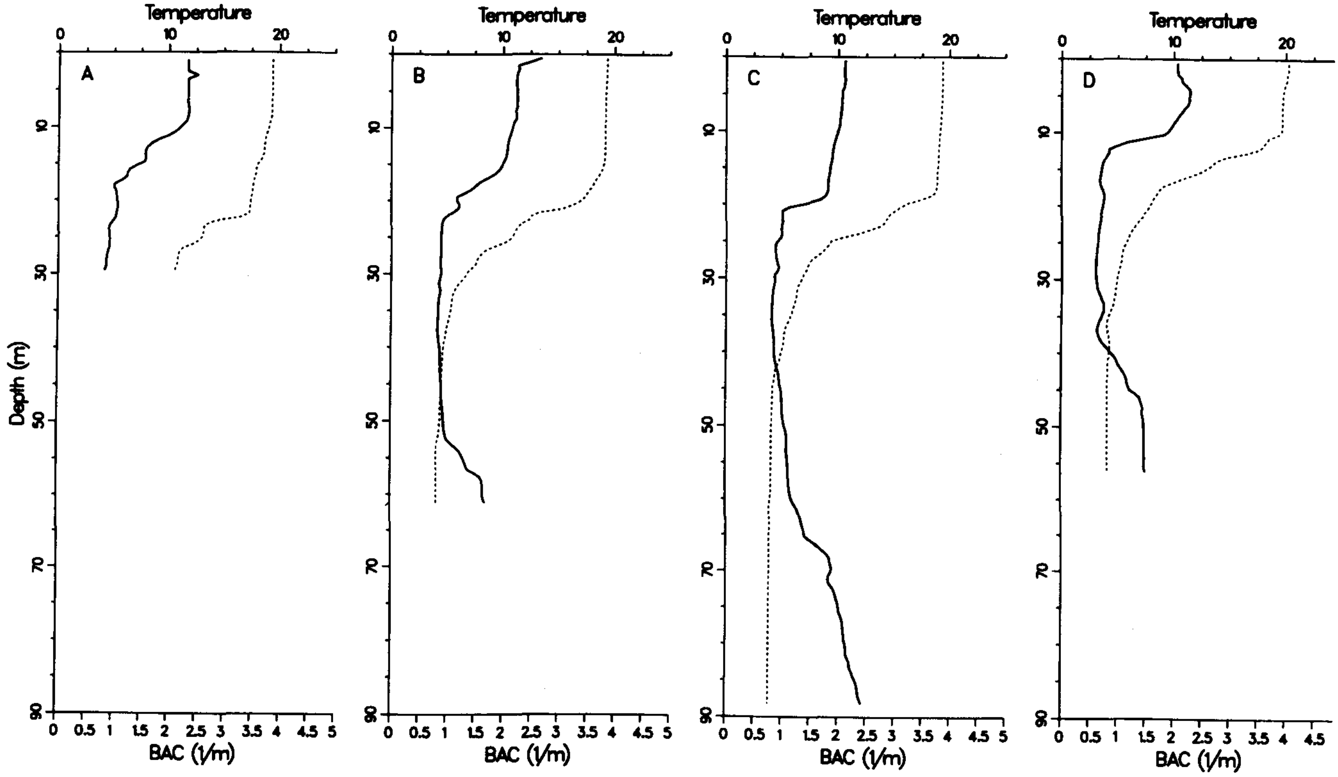

FIG. 2. Vertical profiles of beam attenuation (BAC, solid line) and temperature (dotted line).
A. Profile made in 30 m of water on 9 August.
B. Profile made in 60 m of water on 9 August.
C. Profile made in 90 m of water on 9 August.
D. Profile made at the tripod deployment site on 12 August.

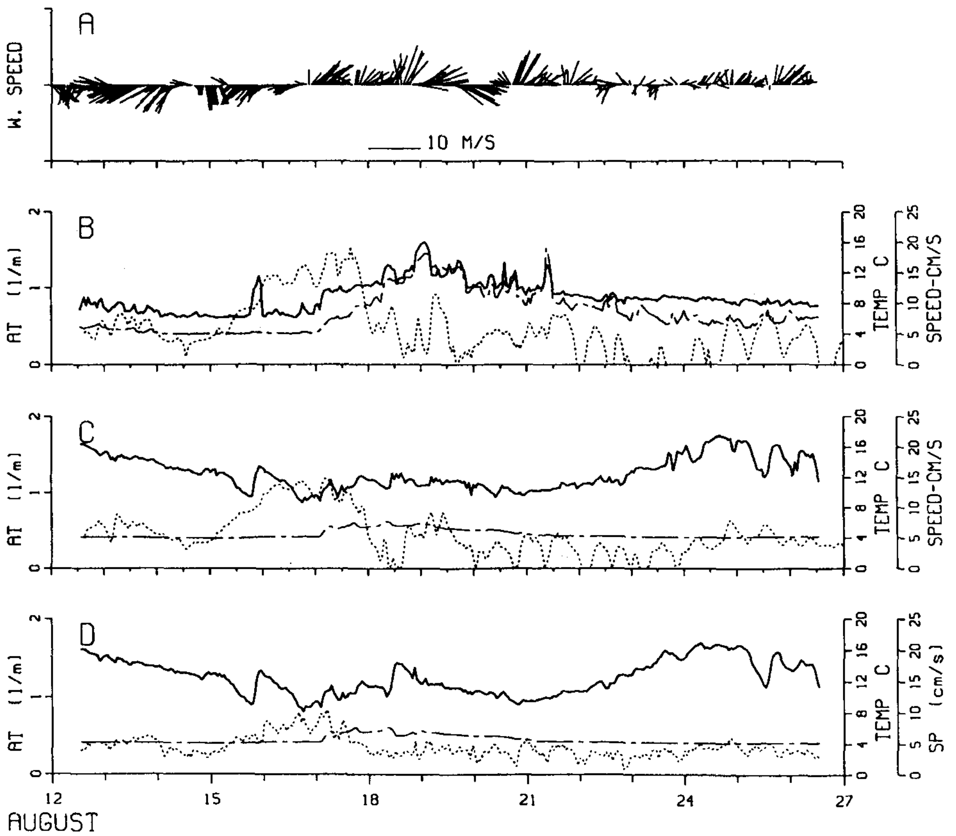

FIG. 3. Time series measurements made during the deployment. In Figures 3b, 3c, and 3d the beam attenuation is the solid line, the water temperature is the interrupted line, and the current velocity is the dotted line.
A. Wind speeds measured at buoy 9. The convention is that the winds blew in the direction of the lines, so during the first 5 days the wind blew mainly to the southwest.
B. Observations made at at 25 mab. The temperatures and beam attenuations were recorded by the tripod, the current speed by the EG&G current meter. Note the high correlation between the beam attenuation and the temperature from 17–22 August.
C. Observations made at 5 mab. The temperatures and beam attenuations were recorded by the tripod, the current speed by the EG&G current meter.
D. Observations made within the bottom meter by sensors mounted on the tripod. The temperatures and beam attenuation were recorded at 0.9 mab, the current speed at 0.5 mab.

The effects of the changes in wind direction are clearly visible in both the vertical profiles and in the temperature records. The decrease in the depth of the thermocline during the 3 days prior to the beginning of the deployment is consistent with the upwelling of cold bottom water, as is the increase in the amount of material suspended in the BNL (Bell and Eadie 1983). The decrease in the 25 mab temperature at the beginning of the deployment (Fig. 3b) is also consistent with upwelling. This upwelling apparently lasted until 17 August, when the increased temperatures at all three elevations clearly indicate the beginning of a downwelling event that lasted until 22 August. This is consistent with the change in wind direction on 17 August. After 22 August the temperature decreased to about

4.1°C at the two lower elevations but remained slightly higher (5–7°C) 25 mab.

Current speeds at all three elevations are less than 8 cm s^{-1} at the beginning of the deployment, but begin to increase at about noon on 14 August. They reach their maximum values on 16 and 17 August before decreasing on 17 and 18 August. This decrease in speed (which occurs 1 day after the downwelling begins) precedes a reversal in current direction at about noon on 18 August (Fig.4: The current velocities have been rotated so that up represents offshore flow.). The currents then change direction again at about noon on 22 August. This flow reversal is similar to those observed in the hypolimnion by Csanady and Scott (1974) during periods when coastal jets were present and is probably due to the propagation of an internal wave around the lake. After 22 August some indication of rotary motion (probably due to standing internal Poincare waves—a common feature in the lake's interior, Mortimer 1980) can be seen in the 5 and 25 mab current records. One interesting feature is the

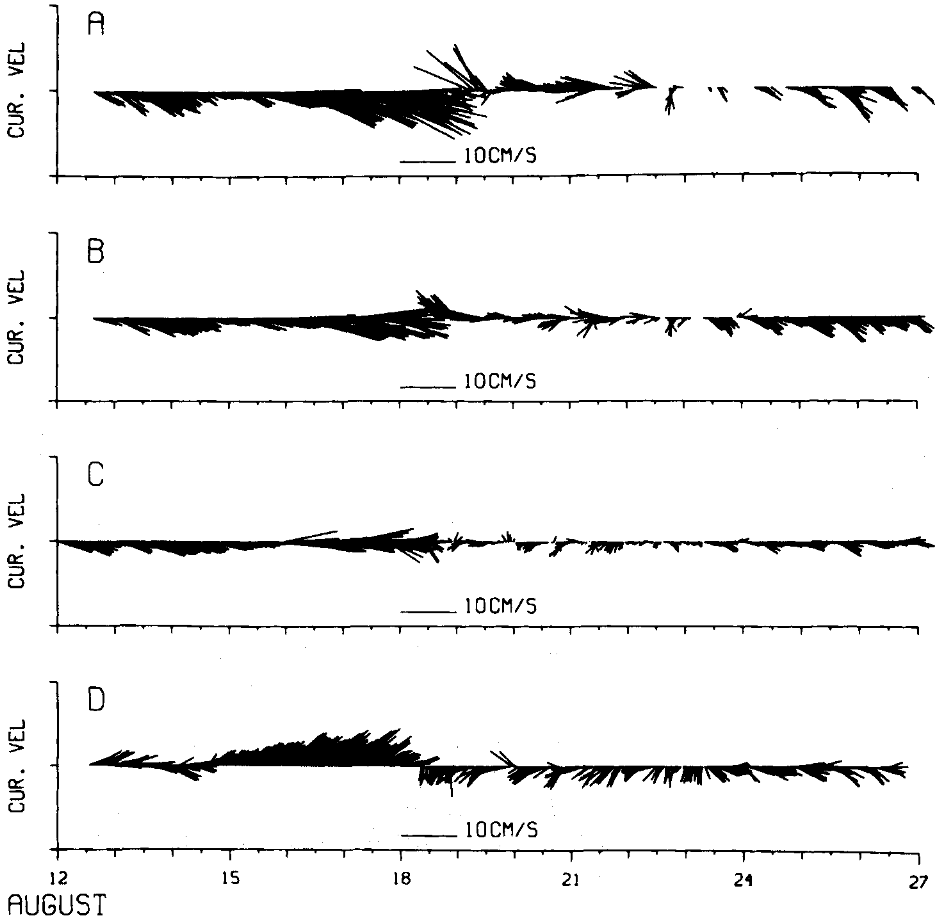

FIG. 4. ***Plots of the current velocities. The 25 and 5 mab measurements were made by EG&G current meters, the 3 mab measurements by a Neil Brown current meter, and the 0.5 mab measurements by a Marsh-McBirney 585 current meter. The currents have all been rotated 19° clockwise so that up represents an offshore current.***
A. 25 mab.
B. 5 mab.
C. 3 mab.
D. 0.5 mab.

change in current direction 0.5 mab beginning on 14 August. This change coincides with the increase in speed on that day, but there is no change in direction at the higher elevations. This difference is unexpected, but the good agreement of the current records during the rest of the deployment leads us to believe that the measurements are correct. Similar near-bottom observations were also reported by Simons and Schertzer (1989). This means that there must have been considerable shear in the bottom 3 m. It also means that from 14 to 18 August the flow has an offshore component at 0.5 mab, but an onshore component at the higher elevations.

Although the current speeds vary considerably, there is relatively little variation in the beam attenuations measured either at the two lower elevations (which were in the BNL) or at 25 mab (which probably was not). The range of observed attenuations is equal to a range of suspended sediment concentrations of only about 1–3 mg L^{-1}. There is also no correlation between the variations in the beam attenuation and the current speeds. If any local resuspension of bottom material had occurred, then we would expect to see a simultaneous increase in both the attenuation and the bottom current speed, but this does not occur at any time. The highest attenuations at the two lower elevations occur at the beginning and end of the records (when the current speeds are low) and while the increased attenuations at all three levels on 15 and 16 August resemble what we would expect to occur during a resuspension event, the increase in the attenuations actually precede the increase in bottom current speed. Attenuation values do increase at all three elevations during the downwelling episode (from 17 to 22 August), but their variation is correlated with changes in the temperature—not the current speed.

DISCUSSION

Chambers and Eadie (1981) suggested that resuspension of bottom material occurred during downwellings by a "rubbing" of the thermocline across the bottom due to the oscillatory motion of internal waves. Our observations do not support this hypothesis—we found no evidence of local resuspension either during the downwelling or later in the deployment. The maximum bottom stress due to current action is only 0.4 dyne/cm^2, and the maximum stress due to surface wave action is an order of magnitude less. This is probably not enough to resuspend the bottom sediment. Although there are no experimental measurements using material from our study site, Hawley's (1991) results from an in situ flume study show that a bottom stress of about 0.5 dynes/cm^2 was insufficient to erode bottom material from a location in Lake Ontario near Oswego, New York. Laboratory determinations of the critical shear stress for Great Lakes sediments also indicate that that a higher shear stress would be required to erode bottom material (approximately 1 dyne/cm^2, MacIntyre *et al.* 1990), while Sly's (1984) measurements of sediment shear strength in the Kingston basin give values of 1–10 dynes.

Nor do the attenuation measurements resemble those made during vertical mixing of the BNL as described by Hawley and Lesht (1995), who showed how changes in the vertical structure of the BNL could account for both decreased beam attenuations near the bottom and increased attenuations farther away from the bottom during periods of relatively high current speed. Our observations at 25 mab were probably not made in the BNL, so we cannot be sure, but the decreases in near-bottom beam attenuation seen on 16 and 17 August (when the current speed was increasing) do not much resemble the observations reported by Hawley and Lesht—the variations reported here are much smaller, and they occur over a shorter time period. If neither resuspension nor vertical mixing occurred, then by default the variations in beam attenuation are probably due to the advection of an inhomogeneous water mass past the sensors. We believe that this is the most likely explanation.

The attenuation variations at 25 mab from 17–22 August are undoubtedly due to the movement of the thermocline past the sensor. If the vertical profiles made on 12 August are used as a reference, then some mixing of the surface nepheloid layer further down into the water column is required to explain the observed temperature and attenuation changes, but it is clear that the changes in attenuation are associated with changes in temperature, not changes in the current velocity. The attenuation variations nearer the bottom are probably also due to advection associated with movement of the thermocline during this period. It is interesting to note that at the two lower levels the attenuation changes are directly correlated with the temperature changes until about the time of the flow reversal, after which they are inversely correlated. This may reflect a change in the structure of the BNL, but we have no way of assessing exactly what occurred.

If, as Hawley and Lesht (1995) have suggested, material is resuspended further inshore during downwelling events and then transported offshore, we would expect to see some indication of offshore transport during or after the downwelling. However, progressive vector diagrams of the current velocity (Fig. 5) show that offshore transport occurred only at 0.5 mab, and only from about noon on 14 August to noon on 18 August. Sediment transport diagrams—computed by multiplying the attenuation times the current velocity—are essentially identical to the water mass transports shown in Figure 5, so the only sustained episode of offshore sediment transport occurred at 0.5 mab between 14 and 18 August. Since the downwelling did not begin until 17 August, there is no indication that net downslope transport of sediment occurred either during or after the downwelling event. If any downslope transport did occur, it would have been primarily during the upwelling event that ended on 17 August. Since the 1 mab beam attenuation prior shows no significant increase during this period, it seems unlikely that any significant amount of material was transported offshore at any time during the deployment.

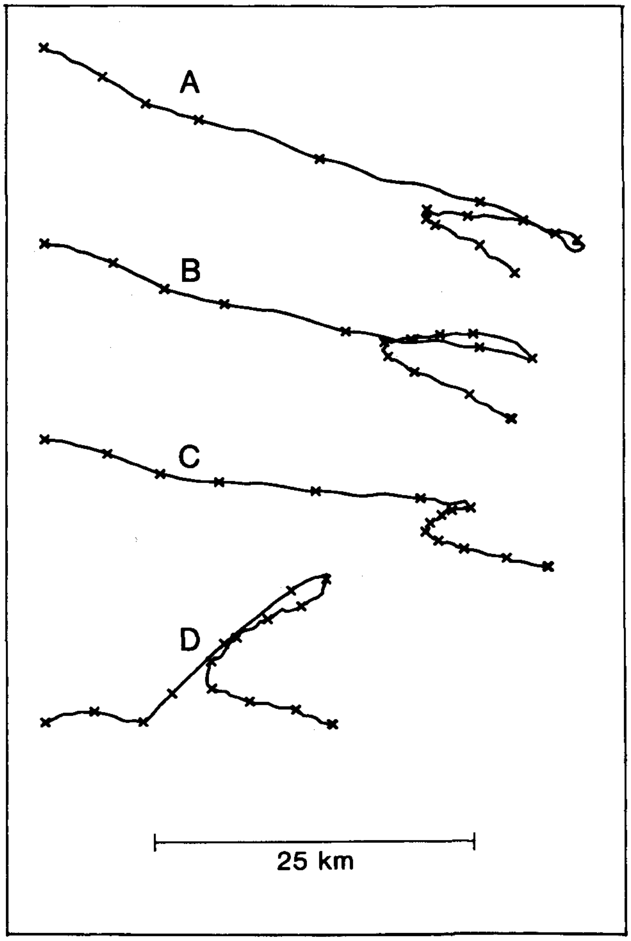

FIG. 5. ***Progressive vector diagrams of the current velocities. The currents have all been rotated 19° clockwise so that up represents offshore movement. All of the plots start at the left. The tick marks represent 24 hour intervals beginning at 1400 on 12 August.***
A. 25 mab.
B. 5 mab.
C. 3 mab.
D. 0.5 mab.

If neither local resuspension nor downslope advection of suspended material occurred during the downwelling described here, how likely is it that either of these processes occurs during other downwellings? The time series measurements of temperature and current velocity recorded at 3 mab (Fig. 6) allow us to compare this downwelling to others that occurred during the summer. Since both the temperatures and velocities recorded at 3 mab are very similar to those recorded at 5 mab at our site, we believe that we can use this record as an accurate indication of near-bottom conditions prior to 12 August. Vertical profiles made on both the deployment date (24 June) and on 20 July show that the lake was stratified and that a BNL was present, while the time series measurements of both temperature and velocity show that the downwelling discussed above was the most energetic downwelling up to that time. The temperature variations we observed at 25 mab are considerably greater than those observed by Csanady and Scott (1974) during two rather prominent downwellings during the summer of 1972, so it appears that the downwelling we observed was a vigorous one. If there was no additional material supplied to the BNL during this instance, it is unlikely that material was supplied during the less energetic downwellings that occurred earlier in the summer. Although either local resuspension or downslope transport may have occurred during the more energetic events that occurred in September, neither process appears to have been important during July and August. A progressive vector diagram of the currents shown in Figure 6 shows that the only sustained episode of offshore transport prior to September occurred from 13 to 18 July. However, the currents are quite weak (maximum stress was less than 0.5 dynes/cm^2), so it seems unlikely that any material was transported offshore during this time.

Over time scales of years, there is no doubt that

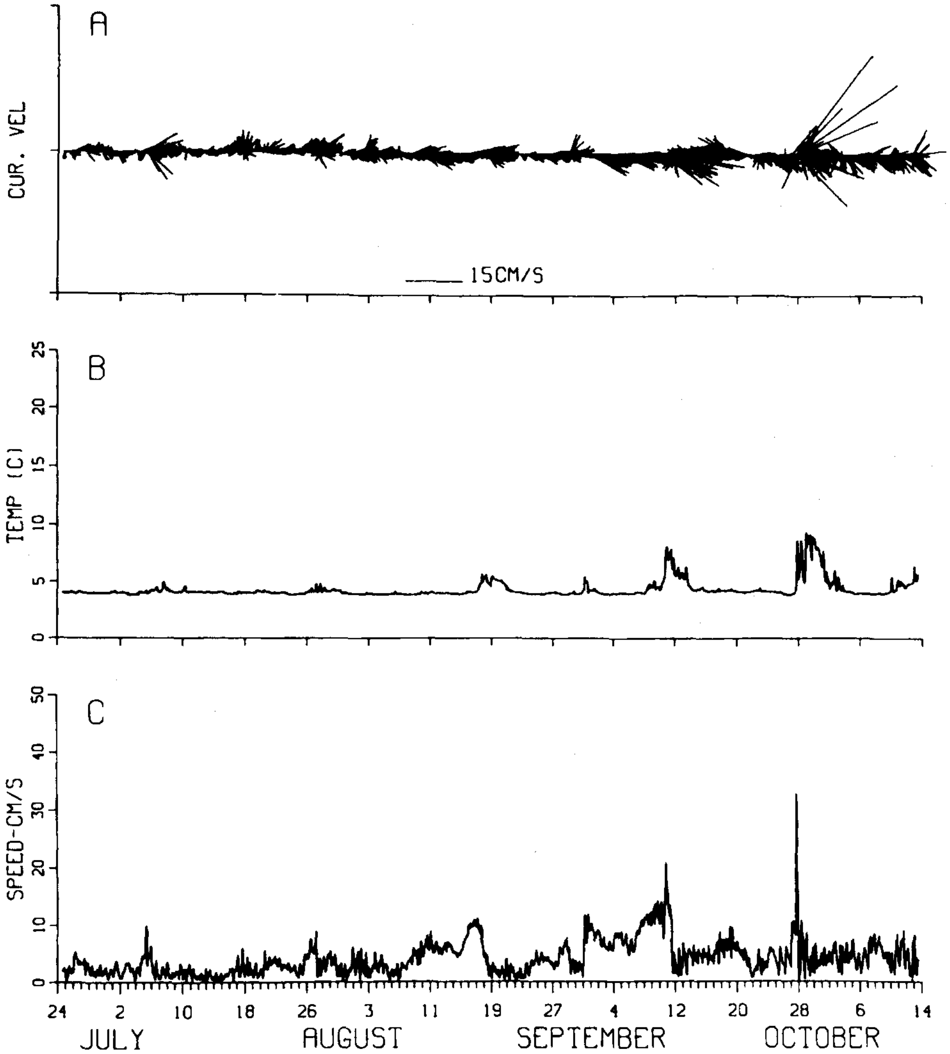

FIG. 6. Time series observations made at 3 mab from 24 June to 14 October.
A. Current velocities. These have been rotated 19° clockwise so that up represents offshore currents.
B. Water temperature.
C. Current speed.

offshore transport of material occurs. The documentation of the movement of sediment contaminated with Mirex between 1968 and 1977 is a case in point (Thomas and Frank 1987). Just when this transport occurs is still not clear, although there is a general consensus that it most likely occurs during the unstratified season (Robbins and Eadie 1991, Sly 1994a, Sly 1994b). Our observations support this consensus in a negative way, since we saw no evidence of offshore transport during the stratified period.

If there is no resuspension or offshore transport of material during the stratified period, how then is the BNL maintained, and what are the sources of the material? Geochemical studies of the material suspended in the BNL, and of that collected in sediment traps deployed at a station on the 70 m isobath about 10 km west of ours (station 210 in Oliver and Charlton 1984, Oliver *et al.* 1989, Mudroch and Mudroch 1992, and Mudroch *et al.* 1994), indicate that much of the material in the BNL was resuspended from the bottom. This material may have been resuspended during the formation of the BNL during the spring—the mechanisms for the formation of the BNL are still unknown—and subsequently kept in suspension by vertical mixing events as described by Hawley and Lesht (1995). Eadie and Robbins (1987) calculated an aggregate settling velocity of about 1 m per day for suspended material in Lake Michigan. If the BNL is 20 m thick, then if an episode of vertical mixing occurred about once every 3 weeks, the BNL could be maintained indefinitely once it is established; such an episode may have occurred just before we deployed our tripod. Vertical mixing however can only redistribute material already in suspension, it cannot increase the total amount of suspended material. Any explanation of the BNL must also account for the direct correlation between the thickness of the BNL and water depth. This was first documented by Sandilands and Mudroch (1983) and is also evident in Figure 2. Since it is clear that the total amount of material suspended in the BNL does vary with both time and location, additional material must be supplied after the BNL is established during the spring. One likely source is material settling downward from the epilimnion, thus accounting for the decreased water transparencies observed as the year progresses (Mudroch and Mudroch 1992). Another possible source—at least in the western basin—is sediment transported into the lake from Lake Erie (Mudroch and Mudroch 1992). However it is hard to see how material from either of these sources could account for the changes in the amount of suspended material shown in Figure 2, since the concentration of material settling from the epilimnion should be relatively constant over short times and distances and there was no major influx of material from Lake Erie. Some other—as yet unknown—source appears to be needed.

CONCLUSIONS

The actual processes responsible for the original formation of the BNL every year are still unknown, nor are the processes responsible for maintaining the BNL well understood. Our observations do not support the hypotheses that the BNL is maintained by either local resuspension or by the downslope transport of material during downwelling events—at least during the summer. It seems likely that episodes of vertical mixing help to keep material suspended in the BNL, but such episodes cannot explain the observed variations in the total mass of suspended material that are observed over both time and space. Some additional material is most likely introduced into the BNL by the settling of particles from the epilimnion. Another probable source—at least in the western basin—is material from Lake Erie. Neither of these sources however, appears to be able to explain all of the observed variations in the BNL. The actual transport pathways of suspended sediments in the Great Lakes are still not well understood, and will probably remain so until observations from a cross-shelf array of instrumented moorings are available.

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