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Observations of Nepheloid Layers Made With an Autonomous Vertical Profiler

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ABSTRACT. *An autonomous vertical profiler was deployed at a site in 55 m of water in southern Lake Michigan during the late summer of 2001. Profiles of temperature and water transparency were made hourly between 1 and 40 meters above the bottom for about 23 days (568 profiles). The temperature observations show that the depth of the thermocline changed in response to both near-inertial internal waves and to upwelling and downwelling events. The transparency measurements show the presence of both an intermediate nepheloid layer located near the base of the thermocline and a benthic nepheloid layer at the bottom. The layers were usually separated by a region of clearer water, but during one upwelling event they merged together. Changes in both the intermediate nepheloid layer and the benthic nepheloid layer occurred in response to changes in the thermocline depth. The total amount of material suspended in both the bottom 40 m and in the benthic nepheloid layer varied by over 50%. The source of the additional material appears to be local resuspension events caused either directly or indirectly by near-inertial internal waves.*

INDEX WORDS: *Lake Michigan, nepheloid layer, vertical profiler, internal waves.*

INTRODUCTION

Nepheloid layers are a common feature in both the Great Lakes and the world's oceans. The layers are identified by optical or acoustic measurements and are caused primarily by increased concentrations of material suspended in the water column. Several types of nepheloid layers have been described: benthic nepheloid layers (bnl) are defined as extending upward from the bottom until a minimum attenuation is reached in the middle of the water column (McCave 1986), intermediate nepheloid layers (inl) occur at mid-depths and are usually associated with thermoclines or pycnoclines, and surface nepheloid layers (snl) occur near the surface.

In Lake Michigan the bnl is commonly present in the hypolimnion during the stratified period and is also found to a lesser degree during the unstratified period. Several investigators have proposed theories for the origin and maintenance of the bnl in the Great Lakes. These include local resuspension (Chambers and Eadie 1981, Sandilands and Mudroch 1983, Rosa 1985, Baker and Eisenreich 1989, Halfman and Johnson 1989, Mudroch and Mudroch 1992), downslope advection of nearshore material (Halfman and Johnson 1989), and settling of biogenic material (Sly 1994). Although time series measurements of both current velocity and water transparency are required to test these hypotheses, none were made in any of these studies.

However the results of several such time series studies have recently been reported. Hawley and Lesht (1995) analyzed several months of time series observations in Lake Michigan in water depths of 65 to 100 m and found no instances of bottom resuspension. They suggested that the bnl was maintained by a combination of vertical mixing and the offshore transport of material during downwelling events. Although Hawley and Lesht speculated that internal wave action supplied at least some of the energy for vertical mixing, their data were insufficient to document their speculation. Hawley and Murthy (1995) found no evidence of either resuspension or downslope transport during a downwelling event in Lake Ontario. More recently, Lee and Hawley (1998) examined the effects of upwelling and downwelling events on the bnl in Lake

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Michigan. They too found that material was not directly supplied to the bnl during downwelling events. In all of these studies variations in both the thickness of the bnl and the concentration of material suspended within it were observed, but no obvious physical forcing was identified.

The time series measurements in the investigations described above were made once per hour at only a few heights above the bottom. Although useful, these observations have several limitations. First, the hourly interval means that shorter-term processes will probably be missed, and certainly will be difficult to interpret. Second, the limited number of elevations sampled means that there is little vertical resolution available. Simple questions, such as how much material is suspended within the bnl and how this amount varies with time, cannot be answered except at a few times when vertical profiles were made from aboard a ship. Third, the fixed positions of the sensors means that they may or may not always be in the same water mass. Sensors near the thermocline may move in and out of the hypolimnion as the depth of the thermocline varies, while sensors closer to the bottom could move in and out of the bnl as its thickness increases and decreases. Such movement can considerably complicate the interpretation of the time series data.

In order to avoid some of the problems listed above, an autonomous vertical profiler has been designed and constructed. The profiler makes repeated measurements of temperature and water transparency as a function of depth. Data from the first deployment of this unit are presented here. No current velocity measurements were made, so it is not possible to interpret the data completely, but the results suggest a possible mechanism for the origin and maintenance of nepheloid layers in the Great Lakes.

METHODS AND SITE DESCRIPTION

The autonomous vertical profiler (Fig. 1) is constructed of standard 140 mm (5.5″) diameter Type 1 PVC pipe 11 mm (7/16″) thick with machined end caps. The unit is 2.2 m long, weighs 40 kg in air,

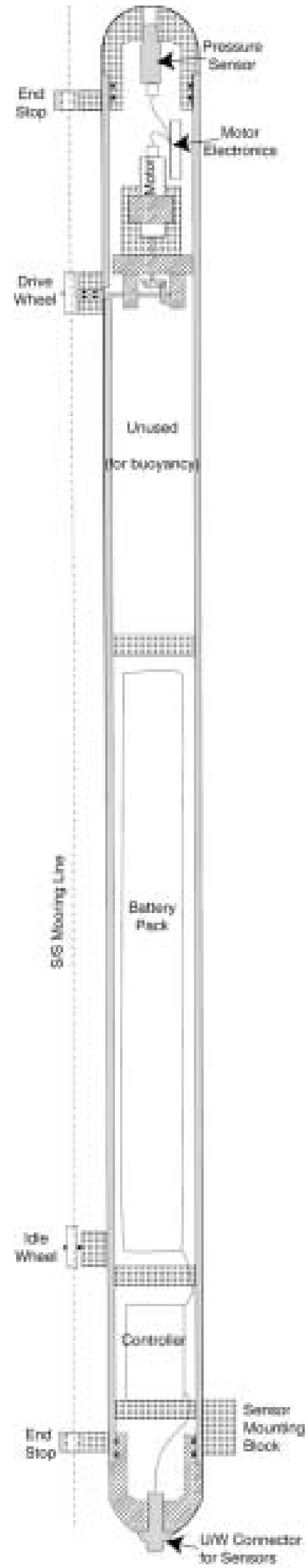

FIG. 1. Schematic drawing of the autonomous vertical profiler. S/S is stainless steel. The transmissometer and temperature sensor are attached horizontally to the sensor mounting block near the base of the profiler. The pressure sensor is mounted in the top.

and is neutrally buoyant in water. A drive pulley powered by a 12 v electric motor (49.42 mN-m output torque, 5,400 rpm under no load) connected to a 93:1 gear reducer drives the unit up and down a 6.35 mm (1/4″) stainless steel mooring cable. Upward and downward excursion is limited by rubber stops attached to the cable. The profiler is controlled by a Tattletale data logger and control unit that records the data onto a 15 megabyte compact flash disk memory card. The profiler ascends and descends at about 0.15 m/s and can sample at rates up to 2 Hz. Power is provided by two separate battery packs: one 12 v 10 ampH stack powers the control unit, and another eight stacks wired in parallel run the motor. The motor is mounted in the housing with the drive shaft parallel to the long axis of the profiler, so a 90° gear coupling is needed to drive the drive pulley. During development this arrangement caused the motor to bind under load until a flexible coupling was installed.

The speed of the profiler (as determined from the pressure readings) was monitored constantly. If the speed was less than 0.03 m/s for more than 8 s, the motor was turned off until the time for the next cycle. This ensured that the motor was not running during the time intervals between profiles, and also ensured that the motor would turn off if an obstruction on the wire stopped the profiler. No obstructions (other than the mechanical stops at the top and bottom) were encountered during the deployment.

The pressure sensor used is a Celesco SG strain gauge with a maximum range of 70 m (100 psia) and an accuracy of 0.35 m. The temperature sensor is a Seabird SBE 3F. This model has an accuracy of 0.001°C and a response time of 0.5 s. Water transparency was measured with a Sea Tech transmissometer (0.25 m pathlength). The output voltage was measured to 0.001 v over a nominal 5 v range. These voltages were converted to beam attenuation coefficient (bac) with an equation supplied by the manufacturer. The bac has the units of 1/m and is a measure of the concentration of suspended material. The pressure sensor is mounted inside the top end cap while the transmissometer and temperature sensors are located about 0.2 m from the bottom of the unit (Fig. 1). The profiler was not designed to measure current velocity, since measurements of velocity throughout the water column can be measured with an independently moored acoustic doppler current profiler.

The profiler was deployed in 55 m of water near Muskegon, MI (Fig. 2) on 31 July 2001. Previous work at this site during the stratified period in 1995

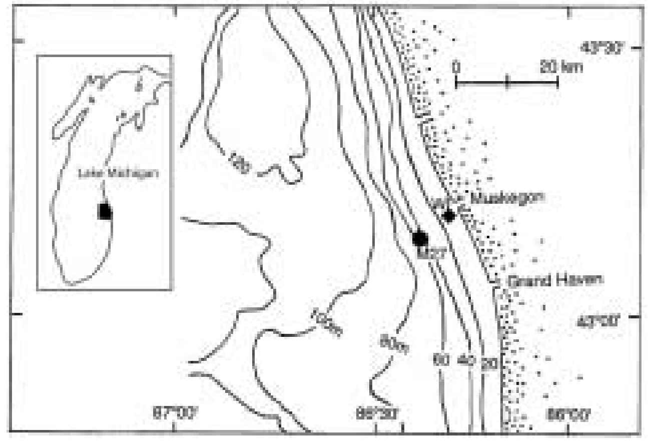

FIG. 2. Location of the deployment site (M27) and the water intake station (WI). Nomad buoy 45007 is located approximately 60 km to the southwest.

and 1998 (Hawley unpublished data) shows that both benthic and intermediate nepheloid layers were present at this site, and that near-inertial internal waves occurred frequently. Bottom contours in this area (which is near the northern edge of the southern basin of the lake) run roughly parallel to the shoreline. Depth increases relatively slowly to about 30 m, then increases more rapidly to about 80 m before the relatively flat lake bottom is reached. The mooring site was located about midway down the steeper slope between 30 and 80 m. Bottom sediment at this site is a silty sand with a mean diameter of 0.16 mm (Hawley and Lee 1999).

The profiler was programmed to make a profile once an hour between stops located 1 m and 40 m above the bottom (mab). This interval was chosen so that the effects of near-inertial internal waves (which have a period of 17.6 h) on the bnl could be investigated. A total of 568 profiles were made (through 23 August) before the batteries wore out. Since this deployment was designed to test the reliability and endurance of the profiler, an acoustic current profiler was not deployed. Although data were recorded during both the up and down casts, only the data from the up casts are presented here. For presentation purposes the data were binned at 1 m intervals.

Boyce *et al.* (1989) reviewed the seasonal thermal cycle of the Great Lakes and described the various physical processes that occur. Circulation in the lake is driven by the wind, but (because of Lake Michigan's size) rotational forces are important. The lake is stratified from June to November, with a warm epilimnion separated from the colder hypolimnion water (temperature near 4°C) by a thermocline 10 to 20 m thick. A two-layer circulation system is set up, with the epilimnion responding directly to the wind stress. This causes upwelling and downwelling events to occur as the thermocline tips. On the eastern side of Lake Michigan, winds to the north cause downwelling of surface waters, while winds to the south induce upwelling of colder bottom water. These disturbances may then propagate counter-clockwise around the lake as internal Kelvin waves (Mortimer 1980, Boyce *et al.* 1989). The amplitude of these waves decays with distance from shore, so their effects are seen only within a few km of the shoreline.

Farther offshore the winds generate quasi-standing internal Poincaré waves. These waves have periods close to the local inertial period (about 17.6 h) so they have been called near-inertial waves. These internal waves (which have a roughly circular motion in the horizontal plane) occur in both the epilimnion and the hypolimnion throughout the stratified period (approximately June to November). The effects of these waves can be seen in temperature records since the thermocline depth at a given point varies with the phase of the wave (except at the wave nodes where there is no vertical movement).

RESULTS

Wind speeds observed at a meteorological station in Muskegon were light (less than 10 m/s) and variable during the deployment (Fig. 3a). The strongest winds occurred on 17 August and were from the south, but there were also sustained winds to the north between 6 August and 10 August. Water temperature measurements (Fig. 3b) made at the Muskegon water station (the water intake is 3 mab in 16 m of water, Fig. 2), show that the winds generated downwelling events beginning on 5 August and 17 August, while upwellings occurred on 3 and 10 August. The effects of both near-inertial internal waves and another downwelling event can also be seen at the beginning of the deployment.

Data from NDBC buoy 45007 (located near the center of the southern basin about 60 km southwest of the deployment site) show that waves were small during the deployment—the wave height was greater than 1 m on only five occasions (Fig. 3d). Turbidity data from the water intake (Fig. 3c) show that local resuspension of bottom material occurred only between 16 and 20 August and on 22 August.

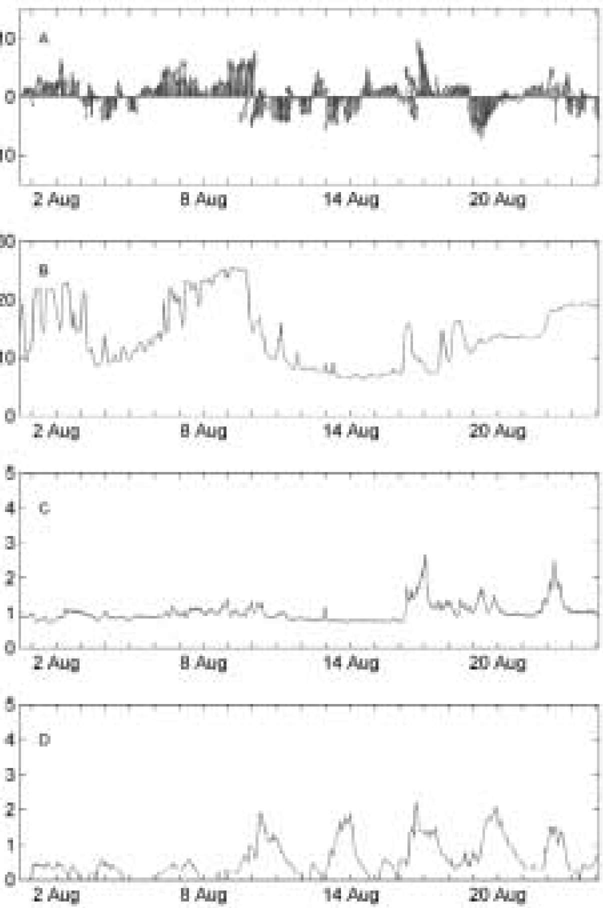

FIG. 3. Weather and water intake data during the deployment. The second tick mark on the horizontal axis is 2 August. A. Wind speed and direction recorded at Muskegon B. Water temperature at the Muskegon water intake. C. Beam attenuation coefficient at the water intake. D. significant wave heights at NDBC buoy 45007.

Bottom stresses due to surface wave action would not cause local resuspension at the deployment site (maximum stresses were much less than 0.001 N/m^2).

Data from the profiler are shown in Figure 4. Although the profiler did not make observations in the epilimnion, the temperature data clearly show the vertical movement of the thermocline due to both near-inertial waves (the shorter-term variations), and the upwelling and downwelling events observed at the water intake. Fourier analysis of the temperature data shows a distinct peak at 17.6 h (the inertial period of the lake) at all depths, so the effects of near-inertial waves were present throughout the water column. The data also show that slightly warmer (> 4.5°C) water was present at the bottom on 7 to 11 August, 19 August, and 23 August. This was due to the offshore movement of the thermocline during the downwelling events.

When examined as a function of depth, the beam attenuation coefficients show two distinct maxima: an inl between 30 and 40 meters above bottom (mab), and a bnl near the bottom. The inl occurs near the base of the thermocline and moves up and down with it. Most of the suspended material is concentrated between the 6° and 12° isotherms (the white lines in Fig. 4b), although at the beginning of the deployment some material is present deeper in the water column. The inl is present throughout the deployment until 19 August, after which it disappears. Fourier analysis of the bac data shows a peak at the inertial period for elevations above 25 m, but not closer to the bottom. The inl is most evident during the downwelling events at the beginning of the deployment and on 5 to 10 August, but is also evident during the upwellings.

The bnl is not very well-developed during this deployment (in 1995 bac values ranged up to 8 1/m, Hawley in preparation), so it is hard to define where the top of the bnl is, but since a region of clearer water (bac < 1.0 1/m) exists most of the time between the inl and the bottom, this bac value has been used to define the extent of both the inl and bnl. The bnl is most well-developed during the upwelling event that began on 10 August, but is absent after 19 August. Peak bac values occurred during episodes on 10 and 11 August and 13 and 14 August (when bac values near the bottom exceeded 1.8 1/m), Since there is no correlation between increased bac values and the occurrence of surface waves, it is unlikely that local resuspension by surface waves maintains the bnl. Although Fourier analysis of the near-bottom (less than 25 mab) bacs shows no peak at the inertial period, at times the growth and decay of the bnl is related to the phase of the near-inertial internal waves. The data collected between 7 August and 15 August (Fig. 5) clearly show that the development of the bnl is at a maximum when the thermocline is elevated and at a minimum when the thermocline deepens, but both the thickness of the bnl and the concentration of suspended material varied substantially from wave to wave.

Data from the profiles made at 4-hour intervals on 13 and 14 August (Fig. 6 and Table 1) show how the bnl can change over short time periods. In Table 1 the equation given by Hawley and Zyren (1990) was used to calculate the amount of suspended material (in a m^2 column) from the bac readings

$$\mathrm{TSM} = (\mathrm{bac} - 0.5)/0.53 \qquad (1)$$

where TSM is the concentration of suspended material (mg/L). Hawley and Zyren found that this equation can be used to convert beam attenuation to the concentration of suspended material throughout the southern basin of Lake Michigan regardless of the time of year, station location, or depth below the surface, and more recent measurements made during 1998 to 2000 confirm its validity. The amount of material in the inl could not be calculated since the top of the inl was always at elevations greater than 40 mab. Although the total amount of material suspended in the bottom 40 m remained fairly constant over the 2 days, both the thickness of the bnl and the amount of material suspended within it varied considerably. At noon on 13 August (Fig. 6a) the bnl was 10 m thick, but because the maximum attenuation (1.06 1/m) is only slightly greater than the minimum (0.95 1/m), it is almost impossible to distinguish the bnl from the overlying water. Four hours later (Fig. 6b) the bnl is more apparent although its thickness had decreased. Four hours after that (Fig. 6c) the bnl was still only 11 m thick but the concentration of material had increased and a strongly stepped profile was present. In another 4 hours (Fig. 6d) the profile was much smoother, the thickness of the bnl had increased to 21 m, and although the average concentration of suspended material decreased, the total amount of material in the bnl increased by about 40%. Although the average concentration was essentially the same 4 hours later (Fig. 6e), the thickness of the bnl decreased by about 50%, and in another 4 hours (Fig. 6f), the bnl disappeared completely. These variations show that material is not just being redistributed within the bnl, but rather that the total amount of suspended material changes with time. These changes may be due to local resuspension and diffusion upward of bottom material (Figs. 6b, 6c, and 6d) followed by settling of the material (Figs. 6e and 6f), but without any current velocity measurements it is impossible to confirm this hypothesis. The profiles also illustrate the difficulty in defining where the top of the bnl is—in several cases (Figs. 6c,6d, and 6e) the bnl appears to extend up to 25 or 30 mab, but deciding exactly where it ends is almost impossible. McCave (1986) defined the top of the bnl as the elevation at which the water reached a minimum bac, but in many of the profiles this difference is ex-

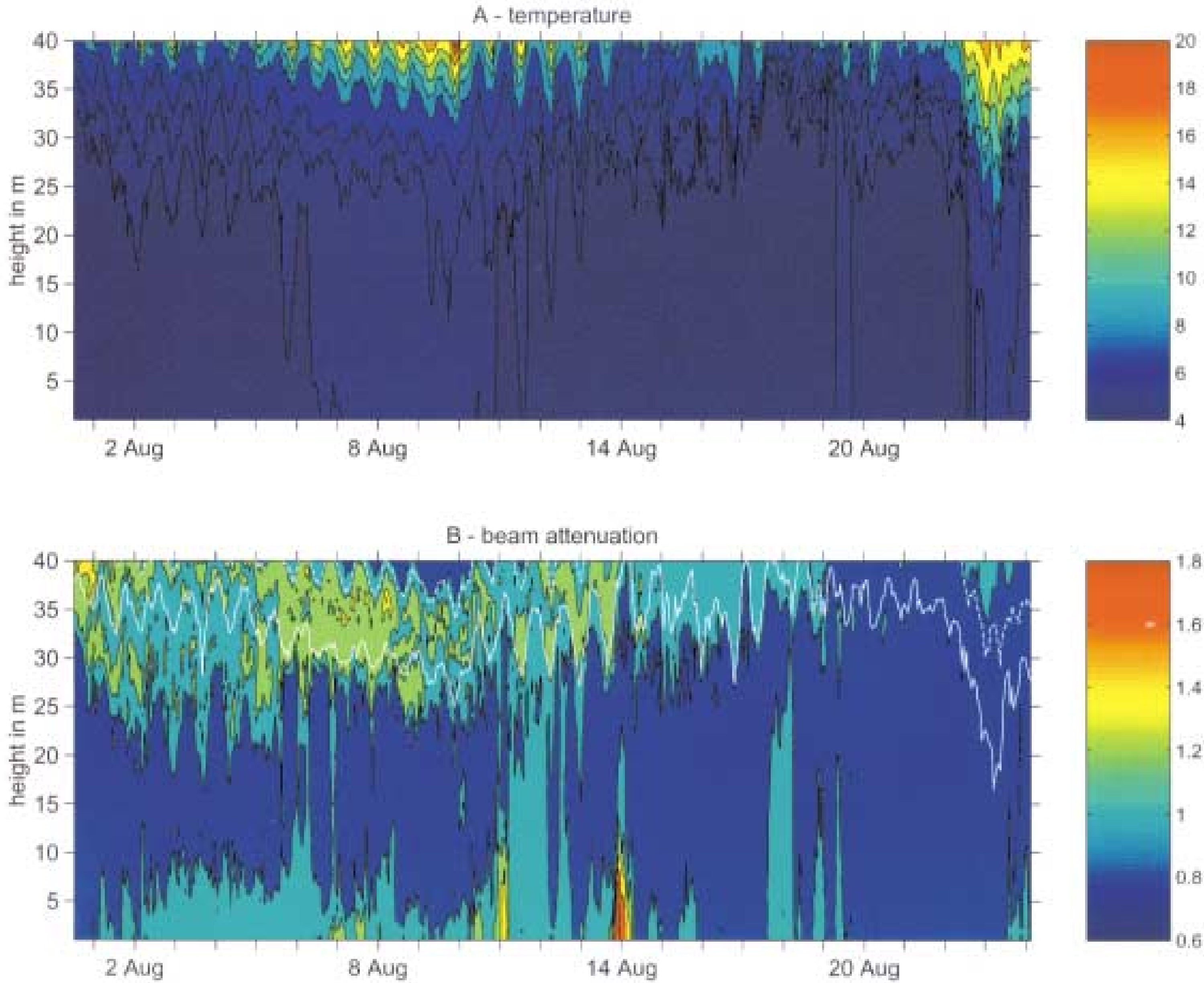

FIG. 4. Data from the vertical profiler. The second tick mark on the horizontal axis is 2 August. A. Water temperature. Contours are at 4.5, 5, 6, 8, 10, 12, 14, 16, 18, and 20°C. B. Beam attenuation coefficient. Contours are at 0.8, 1.0, 1.2, 1.4, 1.6, and 1.8 1/m. The white lines are the 6°C (solid) and 12°C (dashed) isotherms.

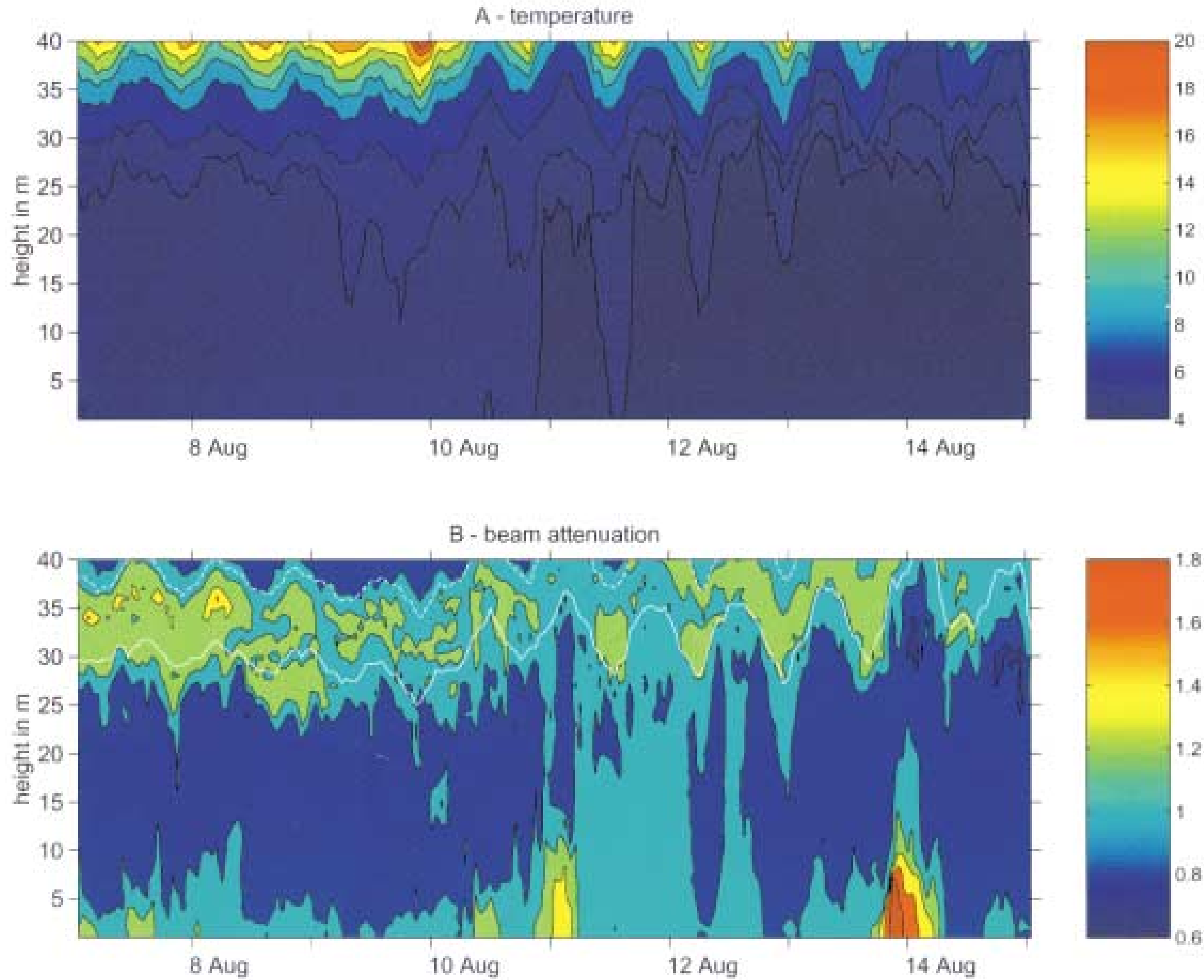

FIG. 5. Data from the vertical profiler. A. Water temperature. Contours are at 4.5, 5, 6, 8, 10, 12, 14, 16, 18, and 20°C. B. Beam attenuation coefficient. Contours are at 0.8, 1.0, 1.2, 1.4, 1.6, and 1.8 1/m. The white lines are the 6°C (solid) and 12°C (dashed) isotherms.

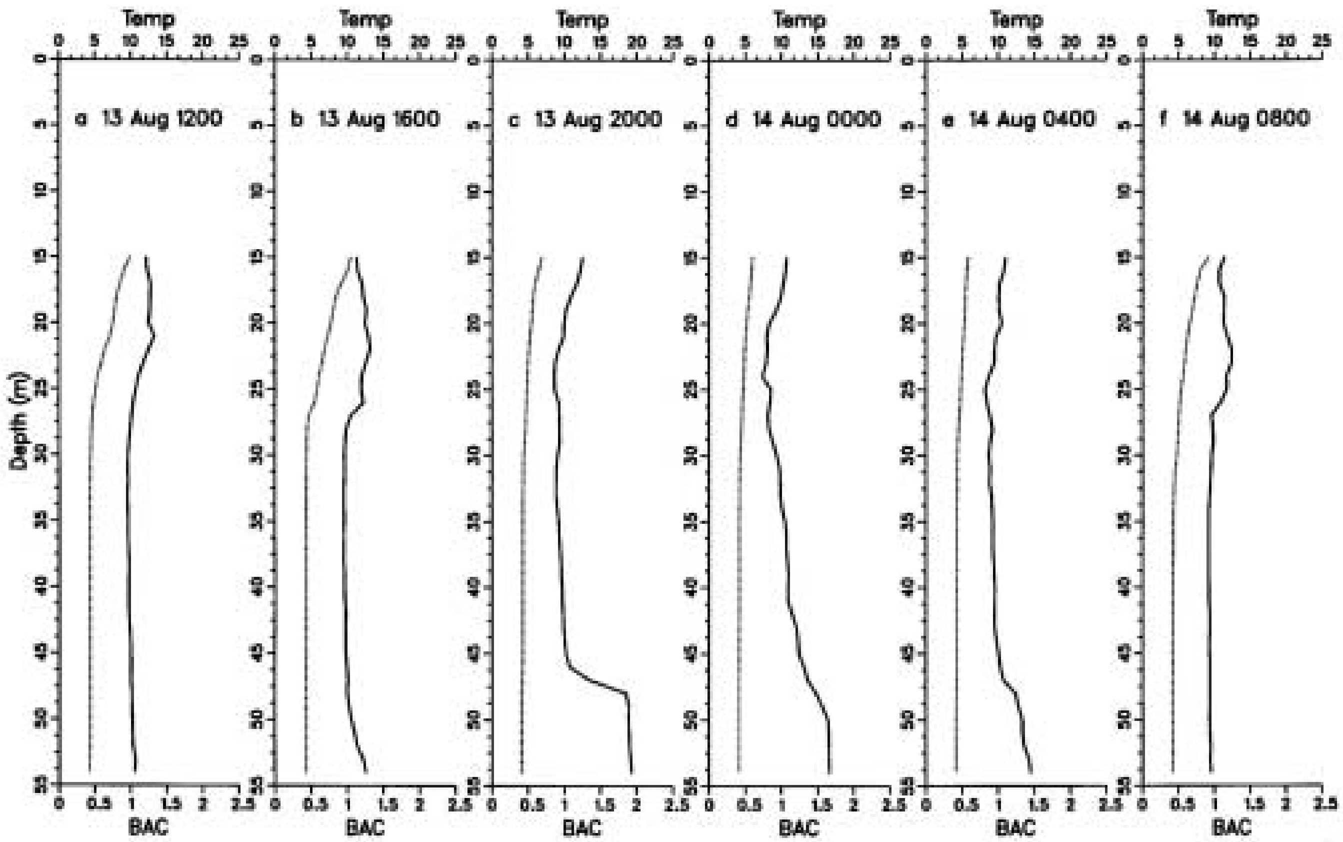

FIG. 6. Vertical profiles of bac(heavy solid line, units are 1/m) and temperature (lighter line, units are °C) made at 4-hour intervals.

tremely small (Figs. 6a and 6f). The thicknesses of the bnl listed in Table 1 increase if the same calculations are done using McCave's criterion, but the general pattern remains the same.

Over the entire deployment the total amount of material in the bottom 40 m also varied substantially—from 27 g to over 55 g in a m^2 column. Although the total amount of material in the inl cannot be calculated, the variability in the inl up to 40 mab was considerable—during the deployment the amount of material suspended within it varied between 0 g and 20 g (in a m^2 column extending from 25 to 40 mab on 8 August).

DISCUSSION

The data show that both the inl and the bnl respond to changes in the depth of the thermocline

TABLE 1. Characteristics of the benthic nepheloid layer (bnl) on 13–14 August.

	Total Suspended Material g	Thickness of bnl m	Material Suspended in bnl g	Concentration of material in bnl g/m^3
13 Aug—1200	41.9	10	9.8	1.0
13 Aug—1600	43.2	6	7.2	1.2
13 Aug—2000	48.8	11	23.1	2.1
14 Aug—0000	46.3	21	31.9	1.5
14 Aug—0400	39.2	10	14.2	1.4
14 Aug—0800	37.9	0	0.0	0.0

on at least two time scales—the inertial period of 17.6 h, and a longer time scale (measured in days) associated with upwelling and downwelling events. Responses at longer and/or shorter time scales may also occur but were not observed. Although the response of the inl to the near-inertial waves appears to be rather passive (it merely moves up and down with changes in the depth of the thermocline), there may be a more active response to upwelling and downwelling events, with more material accumulating in the layer during downwelling periods. More observations will be necessary before this relationship can be confirmed. In contrast with the inl, the bnl appears to respond more to changes associated with near-inerital wave action than to upwelling and downwelling events. In at least two instances (10 and 11 August and 13 and 14 August) the bnl grew considerably during periods when the thermocline was elevated and then diminished as the thermocline depth increased. However the response of the bnl to near-inertial wave action was not consistent, which suggests that while near-inertial wave action is associated with the processes controlling the growth of the bnl, it is not directly responsible.

The total amount of material suspended in both the bottom 40 m and in the bnl changes with time, but the source of the additional material is not clear. Without any current velocity data it is impossible to be sure, but the changes may be due to local resuspension by short-term events (less than an hour in duration) followed by settling of the material. The changes in the vertical profiles of bac shown in Figure 6 are more consistent with this interpretation than if the event was due to advection (in which case one would expect a more uniform distribution of suspended material as a function of both height and time). The cause of the resuspension does not seem to be surface wave activity since the largest surface waves do not coincide with the maximum development of the bnl. Resuspension may have been caused by increased current velocities, but Hawley and Lee (1999) reported current-induced resuspension at this station only when the winds were considerably stronger (greater than 15 m/s) than during this deployment. It seems most likely that the resuspension was caused (at least indirectly) by internal wave action. Puig *et al.* (2001) also observed a correlation of increased bottom concentrations with decreased temperatures at the inertial period, and ascribed those changes to resuspension of bottom material by the breaking of near-inertial internal waves as they progressed up the continental shelf (Cacchione and Drake 1986). There have also been observations of the resuspension of bottom material by solitary internal waves generated by currents impinging on the continental shelf (Bogucki *et al.* 1997, Johnson *et al.* 2001), and similar processes may occur in Lake Michigan. These solitary waves typically have periods of several minutes, so they are unlikely to be detected by hourly measurements.

The observations suggest that material may be exchanged between the inl and bnl during short-term mixing events such as the one on 11 and 12 August. Material in the inl appears to be primarily biogenic in origin (since filtered water samples collected from this layer leave a green residue on the filters), but no systematic analysis of material in this layer has been performed. Harrsch and Rea (1982) speculated that the inl was due to a concentration of fine-grained material caused by decreased settling velocities at the base of the thermocline. The composition of the material in the bnl is more varied. Mudroch and Mudroch (1992) examined the material in the bnl in Lake Ontario and found that its composition changed from location to location; in some cases it was primarily biogenic in origin while in others much of it was similar to material on the bottom. Shaffer (1988) made observations at a station in 160 m of water in southern Lake Michigan and found significant enrichment of allochthonous material in the bnl. Since it appears that material may be exchanged between the inl and bnl, it is not surprising that the composition of the bnl should be complex, reflecting perhaps contributions from different sources at different times and locations. Short-term mixing processes similar to those seen here may in fact be responsible for much of the exchange of materials between the epilimnion and hypolimnion, but additional observations at other sites will be required to confirm this hypothesis.

CONCLUSIONS

An autonomous vertical profiler was deployed successfully for approximately 23 days at a site in 55 m of water in southern Lake Michigan. A total of 568 vertical profiles were made of temperature and water transparency (bac) between 1 and 40 m above the bottom. The resulting data have distinct advantages over previous time series measurements since they allow one to determine changes in the vertical structure of these parameters in some detail. The results presented here show clearly that the intermediate nepheloid layer moves up and down in response to changes in the depth of the thermocline. The data also show that changes in the bnl are also associated with vertical movement of the thermocline in response to both near-inertial internal waves and to upwelling and downwelling events. The total amount of material suspended in both the bottom 40 m of the water column and within the bnl changes substantially with time, so suspended material is not merely redistributed vertically, but is actively resuspended and deposited even during intervals when no storms occurred. The cause of the resuspensions are not known, but it seems likely that they are generated either directly or indirectly by near-inertial internal wave action. A deployment of the profiler in conjunction with continuous measurements at several elevations of current velocity, temperature, and water transparency should allow the precise origin of the increased turbidity episodes to be determined, while deployments of the unit at other locations and in different water depths will allow us to determine how widespread the processes observed at this site are.

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