J. Great Lakes Res. 30(2):301–309
Internat. Assoc. Great Lakes Res., 2004

A Comparison of Suspended Sediment Concentrations Measured by Acoustic and Optical Sensors

Nathan Hawley*

Great Lakes Environmental Research Laboratory
2205 Commonwealth Boulevard
Ann Arbor, Michigan 48105

ABSTRACT. *Simultaneous acoustic and optical measurements of suspended sediment concentration were made during five deployments in southern Lake Michigan. The sensors gave similar results when bottom resuspension was the main cause of changes in suspended sediment concentration, but during the stratified period, when a nepheloid layer was present and large-scale zooplankton movement occurred, the sensors gave quite different results. Since the two types of sensors are most sensitive to particles of different sizes, the simultaneous deployment of acoustic and optical sensors may allow the response of different sized particles to similar forcings to be identified. Care, however, must be taken when comparing suspended sediment concentrations derived from optical and acoustic observations.*

INDEX WORDS: *Suspended sediment measurement, optical sensor, acoustic sensor, Lake Michigan.*

INTRODUCTION

Optical sensors have long been used in the Great Lakes to track changes in the concentration of material that is resuspended and transported by the fluid flow (Hawley and Lesht 1995, Lee and Hawley 1998, Hawley and Lee 1999, for example), but the use of acoustic sensors for this purpose is relatively recent. Miller *et al.* (2002) reported that the backscatter signal strength from 300 khz and 1,200 khz acoustic current profilers could be used to identify episodes of sediment resuspension at stations located in 20 and 40 m of water in southeastern Lake Michigan. Based on the apparent settling time of the particles being measured, Miller *et al.* concluded that the profilers were "seeing" the resuspension and settling of sand-sized material. Miller *et al.* also noted that the profilers recorded the diel migration of zooplankton during portions of the deployments. This latter observation was confirmed by Miller (2003) who found that acoustic profilers could be used to track the diel migration of zooplankton in Traverse Bay. Miller also found that the profilers recorded the presence of a layer of particles between the 6° and 10° isotherms that moved up and down in response to changes in the depth of the thermocline. This layer has also been identified in optical measurements (Hawley and Muzzi 2003).

Since acoustic sensors are most sensitive to much larger particles than optic sensors (Lynch *et al.* 1997), there is a question as to whether acoustic observations of suspended sediment are tracking the same particles as those observed in optical measurements. Data are reported here that show that in some cases optical and acoustic measurements give similar results, while in other settings the results are quite different.

STUDY SITES AND METHODS

Simultaneous measurements of the concentration of suspended sediment were made using both optical and acoustic sensors during five deployments in southern Lake Michigan between 1998 and 2002 (Fig. 1 and Table 1). The shallow water (less than 20 m) at the South Haven and M15 stations allows surface waves to frequently resuspend bottom material at these sites. Bottom material at these stations (Table 2) is mostly fine (diameter between 0.125 and 0.250 mm) and medium (0.250–0.500 mm) sand. The greater water depth (over 50 m) at M27 makes it much less likely that surface wave action could resuspend the bottom material. About a third of the bottom sediment is silt (diameter less than

*Corresponding author. Nathan.Hawley@noaa.gov

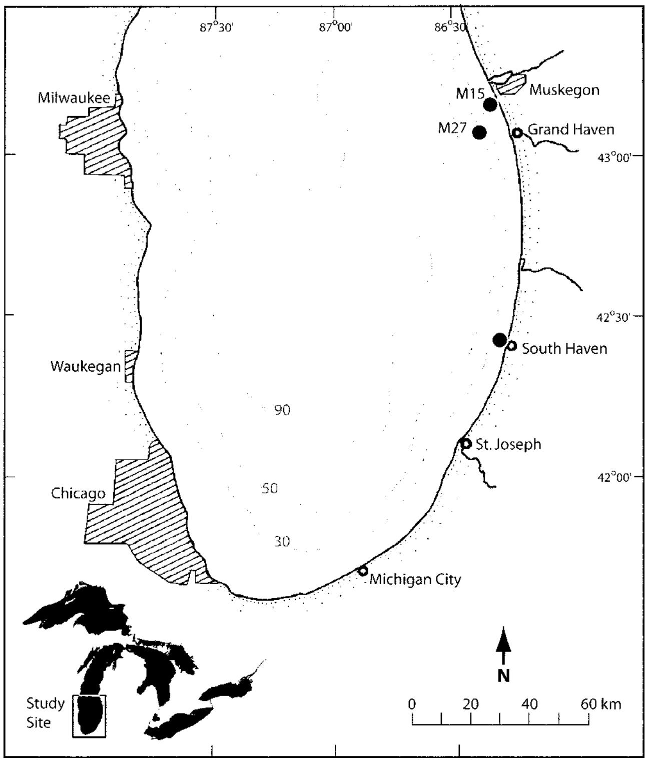

FIG. 1. Location of deployments. Contours are in m. Two deployments were made at M27 and at M15, and one deployment at South Haven.

0.062 mm); the rest is a mixture of very fine (0.62–0.125 mm), fine, and medium sand.

Optical measurements of the suspended sediment concentration were made using a Sea Tech transmissometer. This instrument measures the percent transmission of an infrared beam (wave length 660 nm) over a 0.25 m path length. Measurements were made at slightly different elevations (Table 1), but always less than 1 meter above the bottom (mab). The output voltage was recorded on a nominal 5 volt scale and converted to beam attenuation coefficient using an equation supplied by the manufacturer. Measurements were made for one minute each half hour at a sampling frequency of 1 hz. Hawley and Zyren (1990) showed that in southern Lake Michigan the attenuation is linearly related to the concentration of material suspended in the water, and that the calibration equation does not alter significantly with time of year, station location, or water depth. The response of the transmissometer to changes in particle concentration is quite sensitive to the particle size of the suspended material. Baker and Lavelle (1984) found that the attenuation measured at a given concentration was 15 times greater for particles with a mean diameter of

TABLE 2. Size distributions of bottom sediment.

Size fraction	South Haven	M15	M27
.5–1 mm	8.37%	1.05%	7.9%
0.25–0.50 mm	57.05%	24.31%	26.9%
0.125–0.25 mm	33.95%	57.44%	16.8%
0.062–0.125 mm	0.63%	17.18%	12.0%
0.031–0.062 mm	–	0.02%	13.1%
0.016–0.031 mm	–	–	7.8%
0.016–0.008 mm	–	–	6.4%
0.004–0.008 mm	–	–	5.6%
0.002–0.004 mm	–	–	3.1%
< 0.002 mm	–	–	0.4%

TABLE 1. Deployment information for the 5 stations, mab is meters above bottom.

Station	Deployed/ Retrieved	Latitude	Longitude	Water Depth	Mean particle diameter	Height of transmis-someter	Height of velocity sensor
M27 summer 1998	22 Jul– 2 Aug	43°09.90′N	86°25.67′W	59 m	0.088 mm	0.90 mab	0.22 mab
South Haven Fall 1999	15 Oct– 17 Nov	42°24.23′N	86°19.68′W	18.5 m	0.31 mm	0.84 mab	0.17 mab
M15 spring 2000*	7 Apr– 30 May	43°12.26′N	86°21.15′W	14.8 m	0.21 mm	0.83 mab	0.20 mab
M15 fall 2000	13 Sep– 15 Oct	43°12.23′N	86°21.32′W	15.9 m	0.21 mm	0.90 mab	0.15 mab
M27 summer 2002	31 Jul – 24 Aug	43°10.95′N	86°26.36′W	51.7 m	0.088 mm	0.83 mab	0.18 mab

* 18 hours of data missing on 8–9 May

0.008 mm than for particles with a mean diameter of 0.048 mm, but that there was little further decrease as the particle size increased to 0.106 mm.

Measurements of the current velocity were made with a SonTek 5 mhz acoustic current meter. Observations were made at either 2 or 4 hz for between 8 and 29 minutes each half hour. The velocity measurements were made at slightly different elevations above the bottom, but were always less than 0.25 mab (Table 1). The current speed and signal strength for the first minute of each burst are used in this analysis. The signal strength (converted to backscatter intensity using an equation provided by the manufacturer) can be used to determine the concentration of suspended material, but (as with the transmissometer) the signal is sensitive to particle size. The instrument used here has a maximum sensitivity to particles with a diameter of about 0.100 mm (SonTek 1997). For smaller particles the sensitivity decreases as a function of the particle size to the fourth power, and is essentially zero for particles smaller than 0.002 mm (SonTek 1997). The sensitivity also decreases for larger particles, but in this case the decrease is a linear function of the particle size. One-minute temperature averages were also computed each half-hour from the temperature data recorded by the current meter.

Paroscientific pressure sensors were used to measure wave activity during each deployment. Samples were recorded at either 2 or 4 Hz for 17 minutes each half hour. The significant surface height and peak energy period were computed using the method described by Hawley *et al.* (in press). Vertical profiles of temperature and water transparency were made at the beginning and end of each deployment with a Seabird SBE-25 profiling unit equipped with a Sea Tech transmissometer.

Power spectra were computed using a 512 point Hanning window with 25% overlap. Wavelet spectra were computed using the Morlet wavelet and a program developed by Torrence and Compo (1998). The bottom shear stress was computed from the measured waves and currents using the method of Li and Amos (2001).

RESULTS

Vertical profiles made at the beginning and end of the deployment near South Haven show that the water was essentially isothermal, and that there was no benthic nepheloid layer present. The time series data (Fig. 2a) show that a series of storms occurred during the deployment. During these storms the bottom stress due to the combined action of waves and currents reached values as high as 7.5 Pascals. Increases in both the optical attenuation and acoustic backscatter occurred when the bottom stress exceeded about 0.1 Pascals. This is the value needed to resuspend particles with a diameter of about 0.15 mm (using Li and Amos's formula), but at this site there is a very limited amount of material this size. However the bottom stresses increase very quickly to values exceeding 0.5 Pascals, which is the stress required to resuspend material with a diameter of 0.25 mm. Thus during the storms the bottom stresses almost always reached values higher than those required to suspend much of the bottom material (a stress of 3.3 Pascals is needed to resuspend 0.5 mm particles). There are also two episodes (on 17–18 October and 24 October) when increases in both the attenuation and backscatter occurred even though the bottom stress was less than 0.1 Pascals. Similar increases have been identified previously by Lee and Hawley (1998) during upwelling events, and the temperature data (not shown) show that upwellings occurred during these intervals.

Although both the optical attenuation and the acoustic backscatter increased during the storms, the backscatter strength varied considerably more. The differences in the response of the sensors to the resuspension events is due to a combination of at least three factors. First, although Hawley and Zyren (1990) showed that optical attenuation is a linear function of suspended sediment concentration, the same is not true for the backscatter intensity, which is known to be a non-linear function of sediment concentration (Hay 1983, SonTek 1977). Fugate and Friedrich (2002) found that the backscatter for a similar instrument varied with the logarithm of the concentration, and plots of the backscatter against both the attenuation and the bottom stress suggest that a similar relationship occurred during this deployment. Unfortunately no independent measures of sediment concentration are available during any of the deployments to calibrate the signal strength recorded by the current meter. The second factor is the different heights of the sensors above the bottom. Calculations of the vertical distribution of sand-sized material as a function of bottom stress (using Rouse's distribution, 1937) show that resuspended bottom material would be strongly stratified near the bed during the storms that occurred, so the current meter should record much higher concentrations of material than the transmissometer. The third factor is the greater sensitivity of the current meter to sand-sized material than the transmissometer. It is impossible to sort out the contributions of these three factors with the data available—the important fact is that the two sensors responded in a similar manner. Since both signals increased when the stress exceeded 0.1 Pascals, and both signals decayed to background levels at about the same time after the stress decreased, it is likely that the two sensors were tracking the same population of particles.

Similar results were obtained during the fall deployment at M15 (Fig. 2b). As at South Haven, the water was isothermal, and no benthic nepheloid layer was present. Although the peak bottom stress was somewhat less than at South Haven, resuspension occurred several times. As occurred during the South Haven deployment, both the optical attenuation and acoustic backscatter increased when the bottom stress exceeded about 0.1 Pascals, and both signals returned to background levels at about the same time after the stress diminished, so it is likely that the two sensors tracked the same particle population.

The water was isothermal and no benthic nepheloid layer was present during the spring 2000 deployment at M15, but the results are somewhat different. Peak bottom stresses were much lower (a maximum of about 0.8 Pascals), but were still high enough to resuspend bottom material. Although there are corresponding increases in the backscatter, the attenuation only increased during the event on 13–15 May. During other (relatively) high stress episodes, the increase in attenuation either preceded (8 April) or lagged (23 April) the increase in bottom stress. The largest increase in attenuation occurred on 22–24 May, when both the attenuation and the acoustic backscatter increased in the absence of any increase in bottom stress. The differences in behavior of the attenuation and the backscatter indicate that the two sensors are not always tracking the same particle populations. The changes in backscatter intensity are due to the resuspension and deposition of bottom material, but although the bottom stresses were sufficient to resuspend sand from the bottom, they were probably insufficient to mix the resuspended material up to the level of the transmissometer. If this is what happened, then the attenuation readings are probably tracking the movement of finer-grained material. Some of this material may have been derived from the bottom sediment, but at least some of it appears to have had another (unknown) source.

The water was stratified and a benthic nepheloid layer was present during both deployments at M27 (Fig. 3), and the deeper water and lack of storms caused bottom stresses that were quite low and entirely current driven. There are no obvious resuspension episodes during either deployment, and the changes in optical attenuation and acoustic backscatter signal strength are relatively small and show little correlation with each other. Power spectra of the data (Fig. 4) show that in 1998 the changes in both attenuation and current speed had a periodicity of about 17.6 h (the inertial period of the lake), while changes in backscatter intensity had a periodicity of slightly longer than a day. This daily periodicity is likely due to the diel migration of zooplankton, as previously reported by Miller *et al.* (2002) and Miller (2003). However, because the observations were made near the bottom, the pattern is reversed from that reported by Miller. In the data reported here, there is an increase in signal strength during the day—when the zooplankton congregate near the bottom—and a decrease during the night—when they migrate toward the surface to feed. There is also a short interval at the end of the 1998 deployment when for some unknown reason the signal strength varied over a 12 hour period. This can be seen in the power spectra as well.

The changes in the optical attenuation during the deployment are due to changes in the benthic nepheloid layer. Hawley and Muzzi (2003) and Hawley (2003) have noted that both the thickness of the benthic nepheloid and the concentration of the suspended material within it respond to the inertial oscillations that are common in the lake during the stratified period. These oscillations are an important feature of the lake circulation during the summer, and although the precise mechanism is unknown, apparently affect both the thickness of the benthic nepheloid layer and the concentration of material suspended within it.

In addition to a peak at the inertial period, the power spectrum of the attenuation during the 2002 deployment also shows a large peak at about 24 h—in fact this peak is larger than the one at the inertial period (this peak can also be seen to a lesser extent in the 1998 data). Wavelet analysis of the attenuation signal shows that this periodicity was most prominent between 5–8 August and between 17–20 August, while the inertial periodicity was most prominent between 31 July–5 August and 8–12 August, so the attenuation readings alternated between recording changes in the bnl due to inertial wave action and recording some other movement. The 24 h periodicity could be due to the diel migration

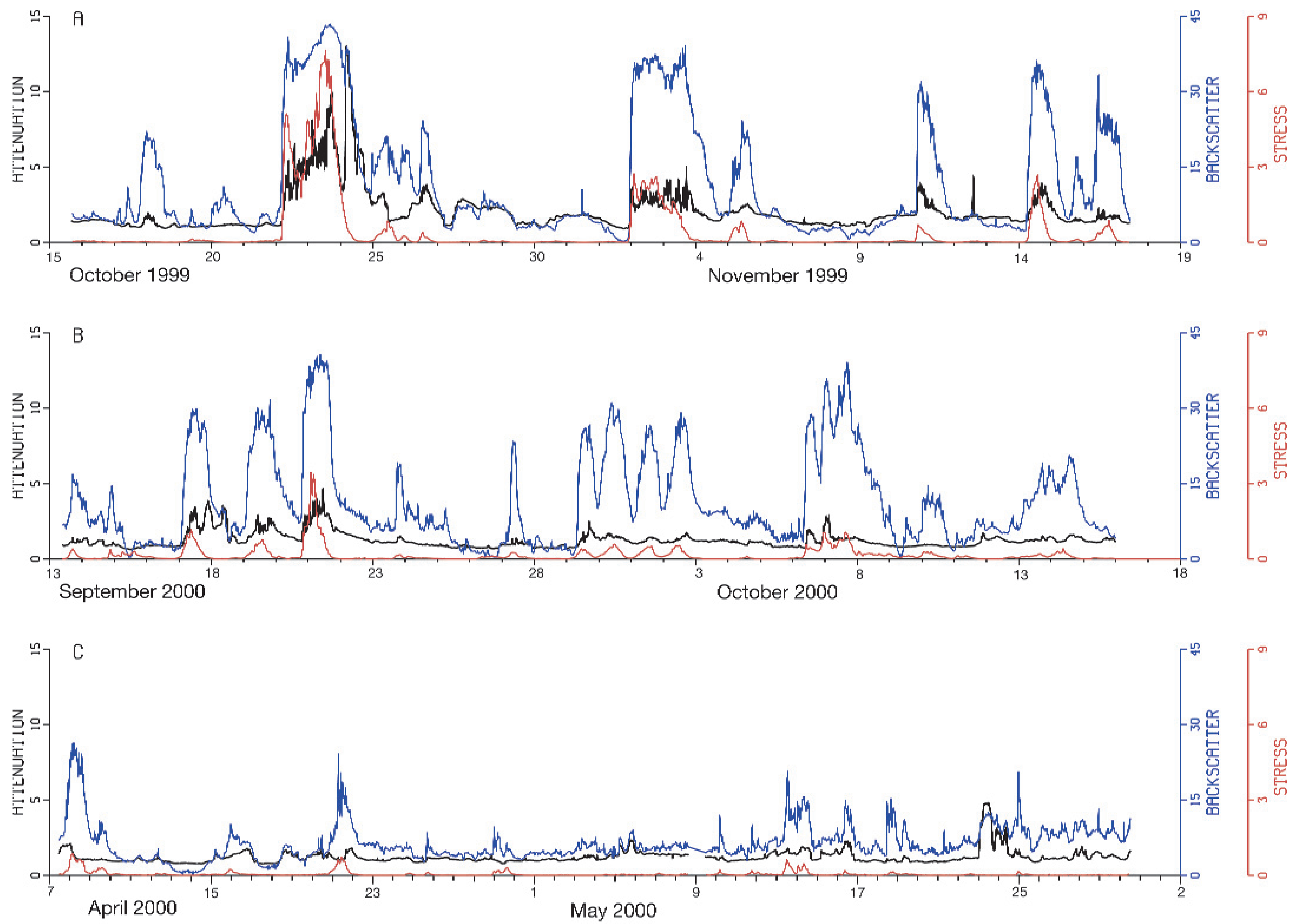

FIG. 2. Time series observations. The color of the axis corresponds to the color of the line on the plot. Black is optical attenuation (m^{-1}), blue is acoustic backscatter intensity (db), and red is bottom stress (Pascals). A. Observations at South Haven. B. Observations at M15 during the fall of 2000. C. Observations at M15 during the spring of 2000.

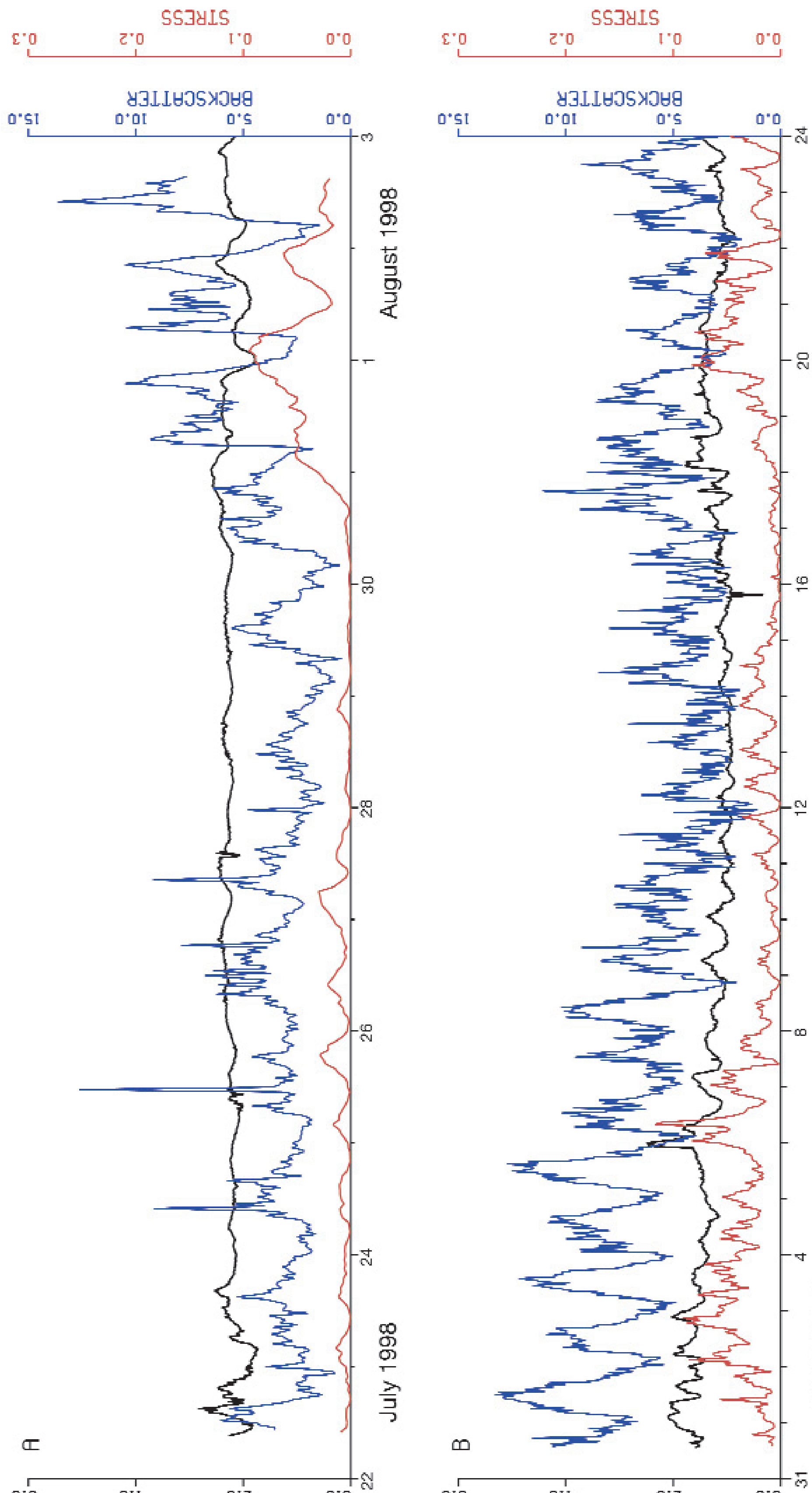

FIG. 3. Time series observations. The color of the axis corresponds to the color of the line on the plot. Black is optical attenuation (m^{-1}), blue is acoustic backscatter intensity (db), and red is bottom stress (Pascals). A. Observations at M27 during 1998. B. Observations at M27 during 2002.

recorded by the backscatter signal, but examination of the time series records (Fig. 3) shows that the peaks in the attenuation records do not coincide with the peaks in the backscatter signals. Since the transmissometer is most sensitive to very small particles, and since the peaks in attenuation do not coincide with the peaks in backscatter intensity, it is unlikely that the 24 h signal is due to zooplankton migration. It seems more likely that the 24 h periodicity is due to a combination of the inertial signal and the attenuation peaks that occurred on (6 and 18 August) during these two intervals.

DISCUSSION

The results clearly show that in some circumstances the optical and acoustic measurements give similar results (in the sense that both sets of measurements respond to the same events), and that in other circumstances the results differ considerably. The absence of both a benthic nepheloid layer and any large scale biological movement during the two fall deployments means that the only large changes in suspended sediment concentration are due to the resuspension events that occurred, and that the two sensors tracked the same particle population. Similar results have been reported from marine settings for both fine (Holdaway *et al.* 1999) and sand-sized particles (Osborne *et al.* 1994). In these cases the differences between the acoustic and optical signals could be used to infer information about the response of different sized particles to a particular forcing (Green *et al.* 2000, Fugate and Friedrichs 2002) and to determine the characteristics of the particle size distribution (Lynch *et al.* 1994), but only if additional information is collected to calibrate the sensors. During the two summer deployments, when both a benthic nepheloid layer and large-scale biological activity were present, the sensors' responses were dominated by these phenomena. Since the two sensors are most sensitive to different sizes of material, the observations made by them were quite different. In these circumstances the different sensors respond to the movement of different populations of particles, so the results can be used to identify different causes of particle transport. Conditions during the spring de-

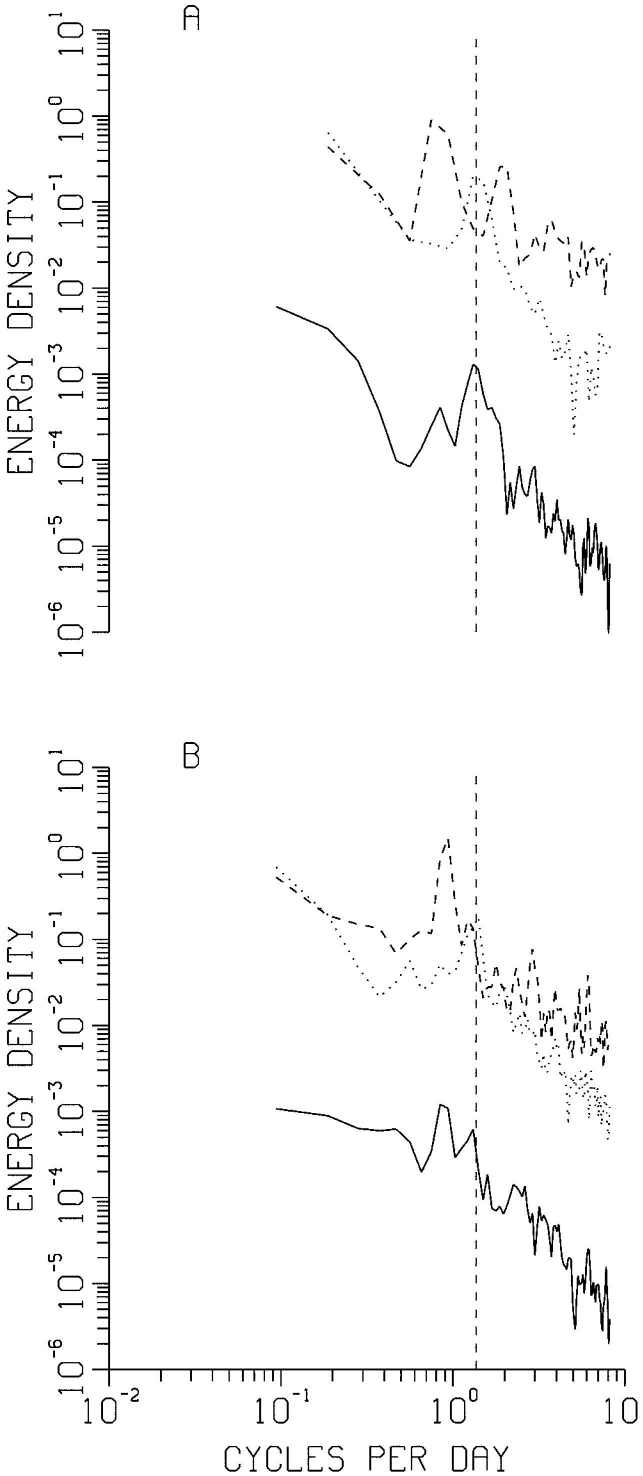

FIG. 4. Power spectra of the parameters during the summer deployments. The solid lines are the power spectra for the optical attenuation, the dashed lines are the power spectra for the acoustic backscatter intensity, and the dotted lines are the power spectra for the bottom current velocity. The dashed vertical lines indicate the inertial period (17.6 h) of the lake. A. Data from 1998. B. Data from 2002.

ployment were intermediate between these two end members, so the interpretation of the different sensor responses is difficult, but it appears that the acoustic signal recorded changes due to the resuspension of bottom material while the optical sensor recorded changes in the finer-grained material.

Since the acoustic current profilers used by Miller work at lower frequencies (300 and 1,200 khz) than the current meter used in this study, they should be most sensitive to even larger particles (1.6 mm for the 300 khz unit and 0.4 mm for the 1,200 khz, SonTek 1997). Since both the current profilers and the optic sensors detect the layer of material that exists near the base of the thermocline (the intermediate nepheloid layer of Hawley and Muzzi 2003), this layer is probably composed of particles covering a wide range of sizes since it is unlikely that the profilers can detect the particles seen by the optical sensors. It may be that the particles detected by the two sensors react differently to movements of the thermocline, but simultaneous observations will be required to determine whether or not this is the case.

One advantage of using acoustic sensors to track sediment movement is that the longer wavelengths allow observations to be made over a much greater spatial range. A single acoustic current profiler can make observations over as much as several hundred meters, but optical sensors can record information over only a few meters at best. However this limitation can be circumvented by moving the optical sensor while it is recording. In the future the combination of a vertical profiler (similar to that described by Hawley and Muzzi 2003) in combination with a current profiler may allow simultaneous observations of the movements of different sized particles over a wide range of depths, thus allowing the determination of how different sized particles react to the same physical forcing. Interpretation of such data, however, will require that the limitations of the different sensors (in particular the possible response of the acoustic sensors to biological as well as physical forcings) be kept in mind.

CONCLUSIONS

Simultaneous acoustic and optical observations of suspended sediment show that in some cases the two sensors give similar results, and that in other cases the results vary considerably. Differences in the sensor responses can be attributed to a number of factors including the position of the sensors relative to the bottom, the different response of the sensors to different sized particles, and the linearity of the sensors' response to changes in particle concentration. The two sensors gave similar results when there was only one cause of sediment movement (in these cases, resuspension by storm action), but the responses of the sensors can differ significantly if a nepheloid layer is present or biological activity occurs. Simultaneous deployment of acoustic and optical sensors will allow the response of different-sized particles to the same forcing to be investigated.

ACKNOWLEDGMENTS

The assistance of Ron Muzzi, Terry Miller, and the crew of the RV *Shenehon* are gratefully acknowledged. Wavelet power spectra software was provided by C. Torrence and G. Compo, and is available at URL: http://paos.colorado.edu/research/wavelets. This is GLERL contribution # 1299.

REFERENCES

Baker, E.T., and Lavelle, J.W. 1984. The effect of particle size on the light attenuation coefficient of natural suspensions. *J. Geophys. Res.* 89:8197–8203.

Fugate, D.C., and Friedrichs, C.T. 2002. Determining concentration and fall velocity of estuarine particle populations using ADV, OBS, and LISST. *Continental Shelf Research* 22:1867–1886.

Green, M.O., Bell, R.G., Dolphin, T.J., and Swales, A. 2000. Silt and sand transport in a deep tidal channel of a large estuary (Manukua Harbour, New Zealand). *Marine Geology* 163:217–240.

Hawley, N. 2003. *Observations of the intermediate and benthic nepheloid layers in southern Lake Michigan during the summer of 1995*. NOAA Technical Memorandum GLERL-124. Ann Arbor, MI.

_____, and Lee, C.-H. 1999. Sediment resuspension and transport in Lake Michigan during the unstratified period. *Sedimentology* 46:791–805.

_____, and Lesht, B.M. 1995. Does local resuspension maintain the benthic boundary layer in Lake Michigan? *J. Sediment. Res.* A65:69–76.

_____, and Muzzi, R.W. 2003. Observations of nepheloid layers made with an autonomous vertical profiler. *J. Great Lakes Res.* 29:124–133.

_____, and Zyren, J.E. 1990. Transparency calibration for Lake St. Clair and Lake Michigan. *J. Great Lakes Res.* 16:113–120.

_____, Lesht, B.M., and Schwab, D.J. in press. A comparison of observed and modeled surface waves in southern Lake Michigan and the implications for models of sediment resuspension. *J. Geophys. Res.*

Hay, A.E. 1983. On the remote acoustic detection of suspended sediment at long wavelengths. *J. Geophys. Res.* 88:7525–7542.

Holdaway, G.P., Thorne, P.D., Flatt, D., Jones, S.E., and Prandle, D. 1999.

Comparison between ADCP and transmissometer measurements of suspended sediment concentration. *Continental Shelf Research* 19:421–441.

Lee, C.-H., and Hawley, N. 1998. The response of suspended particulate material to upwelling and downwelling events in southern Lake Michigan. *J. Sediment. Res.* 68:819–831.

Li, M.Z., and Amos, C.L. 2001. SEDTRANS96: the upgraded and better calibrated sediment-transport model for continental shelves. *Comput. Geosci.* 27:619–645.

Lynch, J.F., Irish, J.D., Sherwood, C.R., and Agrawal, Y.C. 1994. Determining suspended sediment particle size information from acoustical and optical backscatter measurements. *Continental Shelf Research* 14:1139–1165.

_____, Gross, T.T., Sherwood, C.R., Irish, J.D., and Brumley, B.H. 1997. Acoustical and optical backscatter measurements of sediment transport in the 1988–1989 STRESS experiment. *Continental Shelf Research* 17:337–366.

Miller, G.S. 2003. Mysis vertical migration in Grand Traverse Bay, Lake Michigan, observed by an acoustic doppler current profiler. *J. Great Lakes Res.* 29:427–435.

_____, McCormick, M.J., Saylor, J.H., Murthy, C.R., and Rao, Y.R. 2002. Temporal and spatial variability of the resuspension coastal plume in southern Lake Michigan inferred from ADCP backscatter. *Verhand. Internat. Verein. Limnol.* 28:513–518.

Osborne, P.D., Vincent, C.E., and Greenwood, B. 1994. Measurement of suspended sand concentrations in the nearshore: field intercomparison of optical and acoustic backscatter sensors. *Continental Shelf Research* 14:159–174.

Rouse, H. 1937. Modern conceptions of the mechanics of fluid turbulence. *Trans. Am. Soc. Civil Engin.* 102:463–554.

SonTek. 1997. *SonTek doppler current meters, using signal strength data to monitor suspended sediment concentration*. SonTek application Note, San Diego, CA.

Torrence, C., and Compo, G.P. 1998. A practical guide to wavelet analysis. *Bull. Am. Meteorol. Soc.* 79:61–78.

Submitted: 18 August 2003
Accepted: 6 March 2004
Editorial handling: R. Peter Richards