

## Temporal and spatial variability of the resuspension coastal plume in southern Lake Michigan inferred from ADCP backscatter

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### Introduction

In August 1997, the National Oceanic and Atmospheric Administration (NOAA)-Coastal Ocean Program (COP) and National Science Foundation-Coastal Ocean Process (CoOP) funded a 5-year program to study “the impact of episodic events on the nearshore–offshore transport and evolution of biogeochemically important materials in the Great Lakes”. This program, Episodic Events: Great Lakes Experiment (EEGLE), being coordinated by the NOAA’s Great Lakes Environmental Research Laboratory (GLERL) in Ann Arbor, Michigan, is a 5-year study involving 17 government and academic research institutions and over 40 scientists. A 10-km wide plume of suspended material extending over 300 km along the southern shores of Lake Michigan was first observed in satellite imagery (MORTIMER 1988). Satellite observations during the last decade have shown annually recurrent plumes in southern Lake Michigan initiated by major winter–spring storms. Unfortunately, AVHRR satellite images suitable for observing the plume are visual images captured only during cloudless days, an infrequent occurrence during winter over the Great Lakes. The maximum plume events for the last 3 years, as determined from satellite images, are shown in Fig. 1. The plume often veers offshore along the eastern shore, which also coincides with the region of maximum long-term sediment accumulation in the lake (LINEBACK & GROSS 1972, EDGINGTON & ROBBINS 1990, EADIE et al. 1996). Preliminary estimates suggest that the particulate matter in the plume is in the range of 4 MMT, greater than the total annual load of fine sediments into Lake Michigan. These resuspension events also resuspend and transport large quantities of nutrients and contaminants. Therefore, southern Lake Michigan is an ideal location for studying internal recycling of biogeochemically important materials, ecosystem responses, and the cross-shore transport of these materials in the Great Lakes.

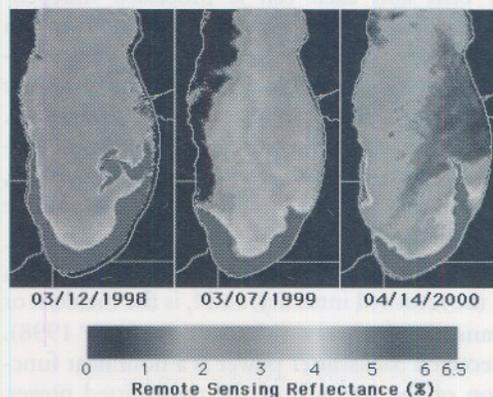


Fig. 1. Maximum plume events in southern Lake Michigan for each of the 3 field years, 1998, 1999, and 2000, as determined from available NOAA AVHRR satellite images. The dark grey band around the southern basin of the lake represents the plume.

During the three field seasons, as many as 24 moorings with single point measuring current meters were deployed during the fall and retrieved in the spring. In addition, five Acoustic Doppler Current Profiler (ADCP) moorings were deployed in the area where the plume generally moves offshore (Fig. 2). ADCPs provide a vertical profile of the current velocity and return echo intensity at discrete equally spaced depth cells through the water column. Recorded echo intensity data are used primarily as data quality indicators; however, correlations of the return echo and the concentration of particulate material in the water column are increasingly being explored (FLAGG & SMITH 1989, WEIERGANG 1995). Though the major emphasis of the EEGLE physical measurement program is to identify and quantify the physical processes responsible for the nearshore–offshore exchange during these episodic events, this paper presents qualitative information on the spatial

and temporal variability of particulate material as interpreted from the acoustic backscatter data during the 3-year field study.

### Results and discussion

An ADCP transmits acoustic pulses from a four-transducer assembly and receives a return signal reflected from scatterers in the water, such as plankton, sediment, or bubbles. The return echo is broken into successive segments or cells and each cell is processed independently. Parameters normally recorded by an ADCP are profiles of horizontal velocity, vertical velocity, error velocity, and echo intensity along with some 'housekeeping' parameters. Echo intensity, a measure of the returning signal strength reflected from suspended particles, is generally reported in terms of the volume scattering strength,  $S_v = 10 \log_{10}(I_R/I_I)$ , where  $S_v$  is the volume backscattering strength in dB,  $I_R$  is the returned intensity, and  $I_I$  is the incident or transmitted energy (MEDWIN & CLAY 1998). Received backscatter power is a nonlinear function of the strength of the transmitted power, properties of the individual receivers, the loss of

energy due to sound absorption, beam spreading, and the effective area of the reflecting particles. Each unit must undergo extensive calibration procedures, in order to obtain absolute backscatter values, i.e. values that are instrument-independent. These procedures are not routinely carried out. A first step for computing backscatter coefficient profiles is to adjust for the power attenuation losses due to beam spreading and water absorption and using 'typical' values for the ADCP model and frequency. To accomplish this, DEINES (1999) developed a working version of the sonar equation to estimate the relative backscatter coefficient profile. For details of the procedure, see DEINES (1999).

Vertically integrated backscatter values for 110 days, 01 January–20 April, for each of the three field seasons (1998, 1999, and 2000) are shown in Figs. 3a, 3b, and 3c. The plotted time series backscatter data are deviations from the mean for the 110 days. The dotted line at +10 dB was arbitrarily added to assist in visualizing the comparative strength of events between years. Also, a change of +10 dB represents an order of magnitude increase in scatterers. Wind speed and direction from the water treatment plant at St. Joseph, Michigan, or from a tower on the north breakwall of the St. Joseph Harbor are shown in the bottom two panels of each figure. Only two storms during the first year produced significant increases in backscatter, 09–11 January and 09–11 March, 1998 (Fig. 3a). Note that the signal increase at the two 40-m moorings (A02, A05) was about the same at the 20-m mooring sites. In contrast, 1999 had at least seven events that exceeded +10 dB above the mean in 20 m water depth (A01, A04), but episodes when the plume extended to the 40 m (A02 and A05) water depth were limited to only three events (Fig. 3b). The 2000 season continued the trend established the previous year – numerous short storm episodes that suspended large amounts of material near-shore (<30 m), but only occasionally extended to the 40 m depth (Fig. 3c). Backscatter variances in the latter 2 years at the 20-m sites were two to three times that of the 1998 variance. The offshore sites only saw increased backscat-

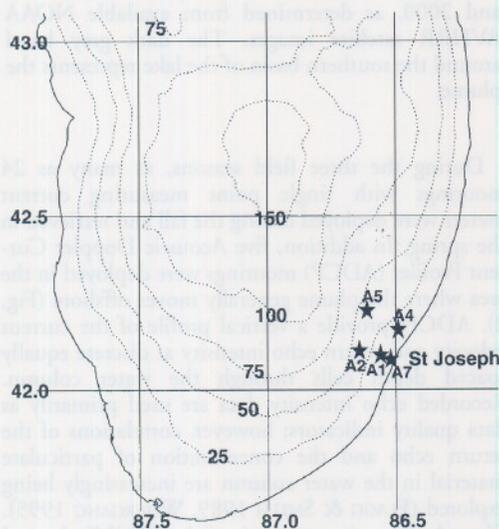


Fig. 2. Bathymetry of southern Lake Michigan and ADCP mooring locations. The isobaths are in meters.

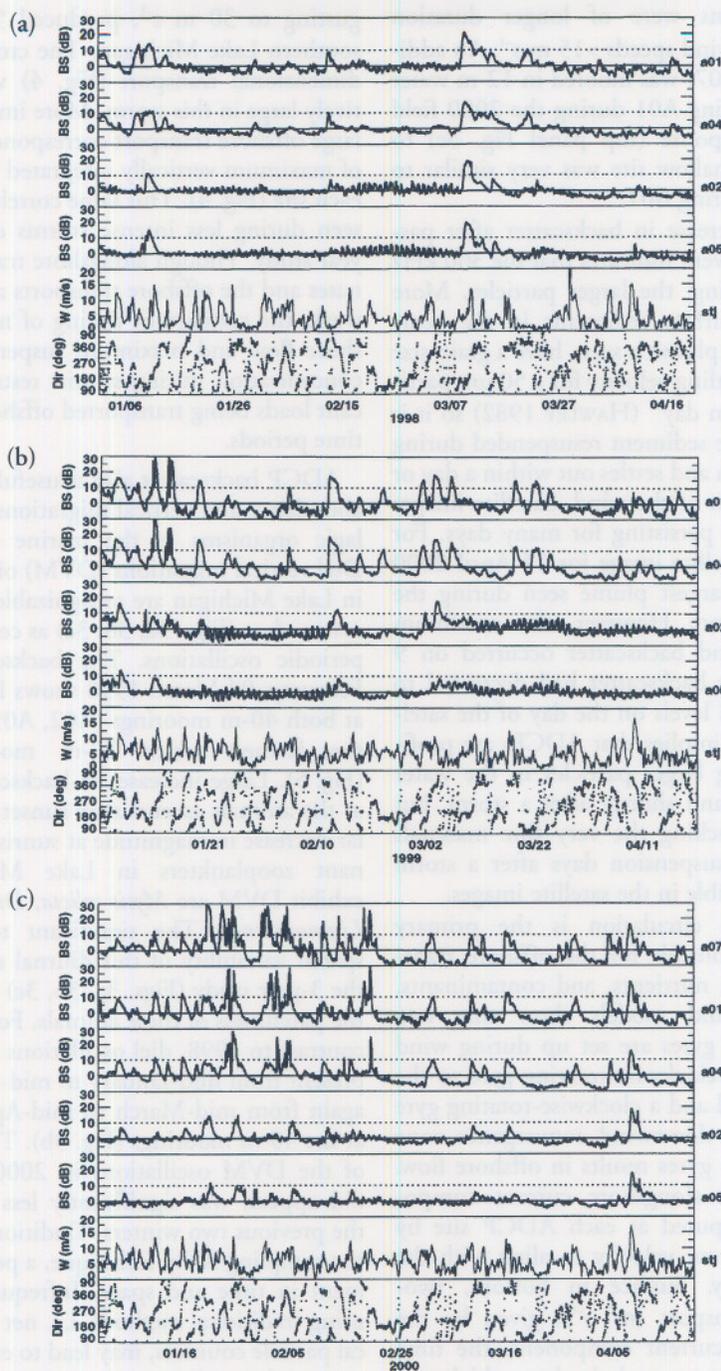


Fig. 3. Backscatter from ADACP sites A01 and A04 (in 20 m water depth), A02 and A05 (40 m water depth), and wind speed and direction from St. Joseph, Michigan, for 01 January–20 April (a) 1998, (b) 1999, and (c) 2000. Mooring A07 (12 m water depth) is included in the upper panel of (c).

ter when storms were of longer duration (24–36 h) and wind speeds  $>15 \text{ m s}^{-1}$ . An additional ADCP (A07) was moored in 12-m water inshore of mooring A01 during the 2000 field season. The response (top panel Fig. 3c) to storms at this shallow site was very similar to that seen at mooring A01.

The rapid decrease in backscatter after passage of a storm event indicates that the 300 kHz ADCPs are 'seeing' the larger particles. More than 80% of surface sediments in the near-shore, where the plume is seen, have a grain size  $>60 \mu\text{m}$ . The settling velocity for a  $50 \mu\text{m}$  particle is about  $40 \text{ m day}^{-1}$  (HAWLEY 1982) so it is assumed that the sediment resuspended during storms is  $>60 \mu\text{m}$  and settles out within a day or so, after cessation of the wind. Satellite images show the plume persisting for many days. For example, the satellite image for 14 April 2000 (Fig. 1) is the largest plume seen during the 2000 field season. However, the maximum wind velocity and backscatter occurred on 9 April 2000. The backscatter had decreased to near background levels on the day of the satellite image. This implies that ADCPs are proficient at tracking larger particles in the water column during and shortly after a storm, but less adept at tracking the very fine materials that remain in suspension days after a storm event and are visible in the satellite images.

Wind-induced circulation is the primary mechanism responsible for the offshore transport of particles, nutrients, and contaminants. Measurements and models show that two counter-rotating gyres are set up during wind events; a counterclockwise-rotating gyre to the right of the wind and a clockwise-rotating gyre to the left. The downwind convergence zone between the two gyres results in offshore flow. Cross-shore and alongshore current components were computed at each ADCP site by rotating the current velocity to align with the local bathymetry. Surface to bottom, two-dimensional transport ( $\text{m}^2 \text{ s}^{-1}$ ), given by the product of the current component, the time interval it represents, and the layer thickness, was calculated. The largest plume event occurred during the first field year on 9–11 March 1998. North-west winds of  $20 \text{ m s}^{-1}$ ,

produced  $5\text{-m}$  waves in southern Lake Michigan. The cross-shore two-dimensional transport (Fig. 4) was comparatively large in this storm. More importantly, the large offshore transport corresponds to the time of maximum vertically integrated backscatter at each site (Fig. 4). This same correlation was also seen during less intense storms during the 3-year study. Though alongshore transport dominates and the offshore transports are on average weak, the concurrent timing of maximum offshore flow and maximum suspended material concentration during storms results in significant loads being transported offshore over short time periods.

ADCP backscatter also is useful in studies of abundance and vertical migrations of mesopelagic organisms in the marine environment. Diel vertical migrations (DVM) of zooplankton in Lake Michigan are recognizable in the backscatter data (Figs. 3a, 3b, 3c) as consistent daily periodic oscillations. The backscatter for 18 February–04 March 1998 shows DVM activity at both 40-m moorings (A02, A05) and also at the farthest south 20-m mooring (A01) (Fig. 5). Large increases in backscatter are seen as the animals ascend after sunset, with a similar decrease in magnitude at sunrise. The dominant zooplankters in Lake Michigan that exhibit DVM are *Mysis relicta*, *Diaptomus*, and *Limnocalanus*. The significant temporal and spatial variability of this diurnal signal seen in the 3-year study (Figs. 3a, 3b, 3c) demonstrates the patchiness of these animals. For example, in contrast to 1998, diel oscillations in 1999 were present from mid-January to mid-February and again from mid-March to mid-April, but only at the 40-m moorings (Fig. 3b). The amplitude of the DVM oscillations in 2000, when they did appear, was significantly less than during the previous two winters. Traditional zooplankton sampling is, by technique, a point measurement in time and space. Infrequent sampling using traditional methods, i.e. net tows or optical particle counters, may lead to erroneous biomass and population estimates, and extrapolating these data to describe temporal and spatial characteristics in large lakes is in question. ADCPs have the potential to provide long-term

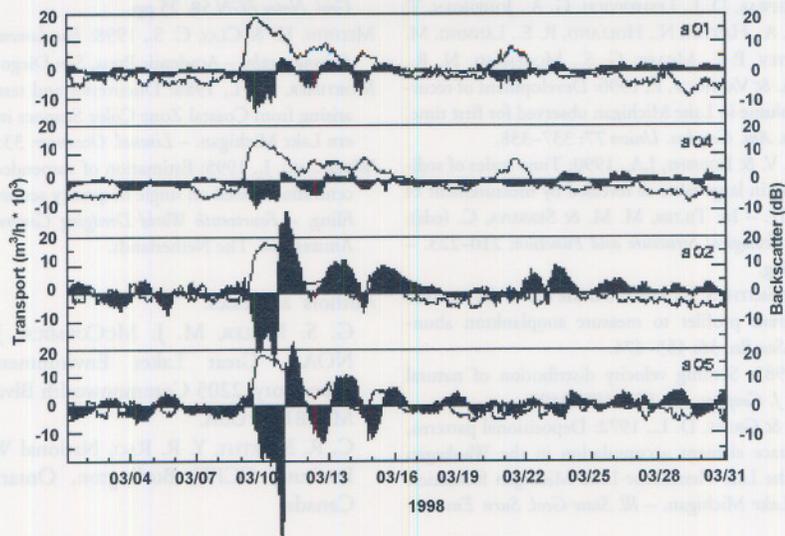


Fig. 4. Vertically integrated two-dimensional transport (denoted by the filled curve and left axis) with the corresponding backscatter (solid line and right axis) from four ADCP moorings during March 1998. Negative transport values correspond to offshore flow.

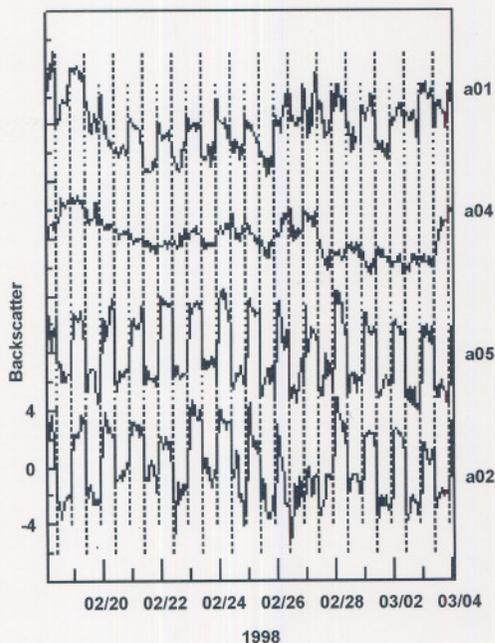


Fig. 5. February 18–March 04 1998 backscatter. Each data set has been offset by 8 dB for graphic separation. The dotted vertical lines mark the times of local sunrise and sunset.

temporal information on zooplankton that exhibit DVM behavior. Zooplankton data obtained from traditional net tows and optical particle counters will need to be correlated with concurrent backscatter data before quantitative estimates of zooplankton type and abundance can be attempted.

In summary, the acoustic return signal from ADCPs is an additional tool for estimating the spatial and temporal variability of suspended materials during the winter and spring season in southern Lake Michigan. ADCP current velocity and backscatter data have demonstrated that suspended materials are trackable during the episodic storm events. During storms, the maximum material resuspension and larger particles frequently coincide with maximum offshore flow, and this is a primary mechanism for the offshore transport and high deposition rate in south-eastern Lake Michigan.

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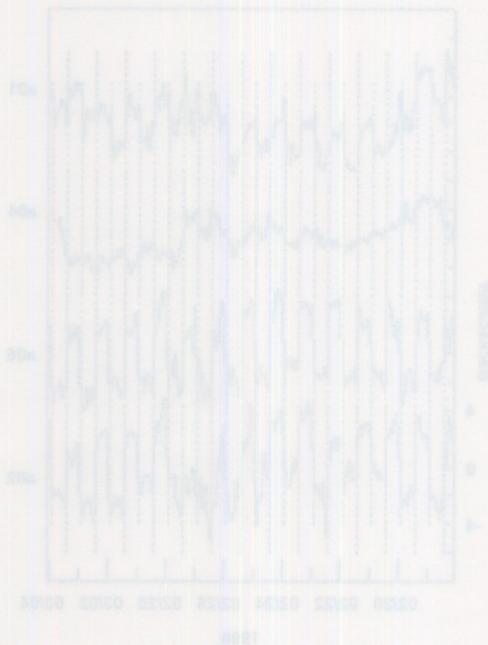


Fig. 5. February 18–March 04 1998 backscatter. Each data set has been offset by 5 dB for graphic separation. The dotted vertical lines mark the times of local sunrise and sunset.