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NEAR-BOTTOM CURRENTS AND SUSPENDED SEDIMENT CONCENTRATION IN SOUTHEASTERN LAKE MICHIGAN

Barry M. Lesht
*Atmospheric Physics Program
Environmental Research Division
Argonne National Laboratory
Argonne, Illinois 60439*

Nathan Hawley
*Great Lakes Environmental Research Laboratory
National Oceanic and Atmospheric Administration
2205 Commonwealth Boulevard
Ann Arbor, Michigan 48105*

ABSTRACT. In a study of sediment transport at the edge of the coastal shelf (28 m depth) in southeastern Lake Michigan we used an instrumented tripod to make continuous observations of horizontal current velocity, temperature, and turbidity within 1 meter of the bottom for 4 weeks during October 1981. The concentration of total suspended material (TSM) 0.9 m above the bottom varied from 1 to 5 mg/L in response to coastal upwelling, surface waves, and currents that exceeded 0.28 m/s (0.7 m above the bottom) on occasion. Advection of the Grand River plume also contributed significantly to the variations in the observed TSM concentration. Currents near the bottom were well correlated with surface winds and, although upwelling currents transported sediment upslope, the net horizontal sediment flux during the period of observation was west-southwestward, almost directly offshore. The magnitude of the horizontal sediment flux was approximately 1,000 times the magnitude of the vertical flux estimated from sediment traps deployed as part of earlier studies. We infer that local resuspension occurred roughly 20 percent of the time and the critical mean flow speed (at 0.7 m) for resuspension of the local silty sands was estimated to be about 0.18 m/s.
ADDITIONAL INDEX WORDS: Upwelling, sediment transport, temperature, turbidity, sediment-water interfaces.

INTRODUCTION

Sediment resuspension in the Great Lakes has been inferred from satellite photographs (Sheng and Lick 1979), transmittance profiles (Bell and Eadie 1983, Sandilands and Mudroch 1983), and sediment traps (Wahlgren and Nelson 1976, Chambers and Eadie 1981, Eadie *et al.* 1984, Rosa 1985). Although the physical resuspension of sedimented material is recognized as an important mechanism in the process of recycling and transportation of contaminants in lacustrine and marine systems, very few direct observations of this phenomenon have been made in the Great Lakes. As a consequence, the exact conditions under which resuspension occurs in these waters are largely unknown, and efforts to predict or to parameterize resuspension, or to evaluate estimates of the magnitude of resuspension made from indirect observations (e.g., sediment traps) have suffered.

In general, sediment transport (including resuspension; the entrainment of bottom sediments into the water column) occurs in response to movement of the overlying water. It is well known from laboratory studies that when the horizontal shear stresses associated with near-bottom currents exceed some threshold value, bottom sediments will become entrained and move with the flow (Miller *et al.* 1977). Threshold values derived in the laboratory are seldom useful in the field, however, both because the threshold values depend in a complicated way on the sediment composition and because the bottom shear stresses, which control the transport processes, are very difficult to estimate in the field in a way that permits comparison with laboratory values. Indeed, the most relevant sediment transport criteria might be best determined empirically from field observations. This technique has been applied successfully in several different marine environments (Young and Southard 1978, Wimbush and Lesht 1979, Lesht *et al.* 1980).

The essence of the empirical technique is to make long-term (several-week duration) *in situ* observations of physical conditions (water currents, temperature, etc.) near the sediment-water interface and then relate these observations to sediment transport. Typically, sediment movement is monitored using time-lapse photography or, as in the case described here, inferred using an optical transmissometer. Analysis of these data is usually directed toward determining an internally consistent set of criteria for predicting the onset and magnitude of sediment transport. Often, another goal of studies of this sort is to collect detailed information about the processes responsible for moving the sediment, making it possible to determine under what conditions and how frequently local sediment transportation may be expected to occur.

The purpose of the study reported here was to make simultaneous observations of near-bottom turbidity and currents in southeastern Lake Michigan (Fig. 1) during a period when the thermocline could be expected to impinge upon the bottom. This condition was of particular interest because of the suggestion (Chambers and Eadie 1981) that "rubbing" of the thermocline on the bottom resuspends sediments that supplement the benthic nepheloid layer found in the deeper waters offshore. Our objectives then, were 1) to document the occurrence of local changes in suspended sediment concentration that might be related to resuspension, 2) to estimate the direction and magnitude of horizontal sediment flux, including any upslope transport that might be associated with coastal upwelling, and 3) to estimate a local threshold criterion for initiation of sediment resuspension.

METHODS

This study was conducted using an instrumented tripod designed for exploratory work in the Great Lakes. The tripod is made of aluminum and configured in the form of a triangular prism 1.5 m on a side (Fig. 2). The sensors mounted on the tripod during the experiment reported here included a two-axis electromagnetic current meter (Marsh-McBirney model 512) 0.7 m above the bottom, a low-power beam transmissometer (SeaTech, 0.25 m path) 0.9 m above the bottom, and a solid state temperature probe (Analog Devices AC2626-K4) 1.3 m above the bottom. The instrument heights are reported here with respect to the base of the tripod. During retrieval, divers observed that the tripod had not settled more than a few centimeters into the sediment.

The analog signals produced by the sensors were low pass filtered (2 s time constant), then digitized every 0.879 s and averaged over 15-min periods using a microprocessor data acquisition system (DAS) of our own design (Williams *et al.* 1983). The data were stored on magnetic tape. Information about the tripod's orientation on the bottom (geomagnetic direction and tilt) and about the state of the electronic packages (battery state of charge and reference voltages) were also recorded every 15 min.

Each sensor was tested for long-term stability and temperature dependence in a temperature controlled water bath. The current meter was calibrated by towing in a 25-m tank at The University of Chicago. The temperature sensor was calibrated with a mercury thermometer read to 0.1°C and adjusted for bias in an ice-water mixture. The transmissometer was calibrated in terms of total suspended material (dry weight) using water samples obtained from the experiment location which were subsequently filtered through preweighed glass fiber filters. These concentration values were regressed against optical attenuation calculated from transmittance values measured at the same time and depth of water collection using an instrument identical to the one on the tripod. The resultant calibration function is linear (Fig. 3) in the range of expected concentrations.

Because optical attenuation is a sensitive function of suspended particle size distribution (Baker and Lavelle 1984), unequivocal calibration of a transmissometer for use in natural systems, where the size distribution of suspended particles might be expected to change with time, is very difficult. The degree to which this will be a problem will depend on the spatial and temporal inhomogeneity of the study area. We found little difference between the calibration function based on samples taken at the tripod location and on one based on samples taken later the same day from a station

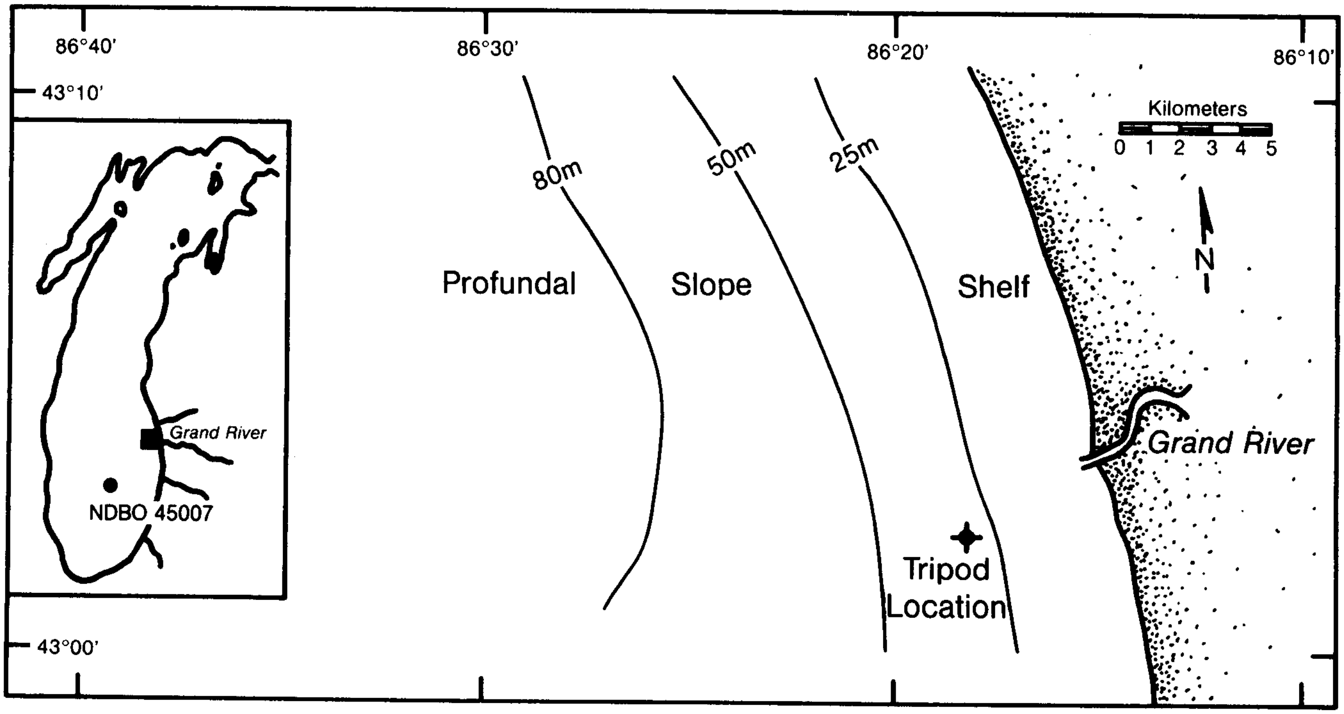

FIG. 1. Map of Lake Michigan offshore of Grand Haven, Michigan (after Eadie et al. *1984), showing location of the instrumented tripod during October 1981. The bathymetric zones are from Chambers and Eadie (1981). Location of NDBO buoy 45007 is shown on the inset map.*

much farther offshore in 102 m depth. The calibration function shown in Figure 3 is based on the combined data.

Given the 5-V full-scale limitation of the analog to digital converter, the 12-bit digitization of the signals corresponds to electronic resolution limits of 0.02°C in temperature, 1.5 μg/L in total suspended material, and 0.00015 m/s in current velocity. Actual instrument uncertainty is, of course, higher. We estimate the precision of the temperature, transmissometer, and current measurements to be 0.1°C, 0.5 mg/L, and 0.005 m/s, respectively.

Since so little is known about bottom currents and sediment transport in the Great Lakes, this experiment was intended to provide basic information that could be used to guide the design of later studies. Accordingly, emphasis was placed on long-term measurements of basic variables rather than on more detailed high-frequency observations. The DAS can accommodate high-frequency sampling schemes (up to 20 Hz) but only at the expense of experiment duration.

The tripod was deployed on 30 September 1981 in 28 m of water at 43° 02'N, 86° 16'W, approximately 5 km offshore of Grand Haven, Michigan (Fig. 1). This location is south of the mouth of the Grand River, just above the boundary between the nearshore shelf region and the steeper coastal slope. Although deployed just above the coastal slope, the onboard orientation sensors showed that the tripod was tilted a negligible amount (1.4°) from horizontal during the experiment. The bottom sediment at this location consists of silty sand (modal grain size 0.096 mm). The tripod was recovered on 27 October 1981. All sensors operated normally and 649.5 h of data were recorded.

RESULTS AND DISCUSSION

Time series of total suspended material (TSM), horizontal current speed, and water temperature obtained during the experiment are shown in Figure 4. All three series show considerable variability consistent with the dynamic nature of the edge of the coastal shelf during stratified conditions. Fifteen-minute average flow speeds measured

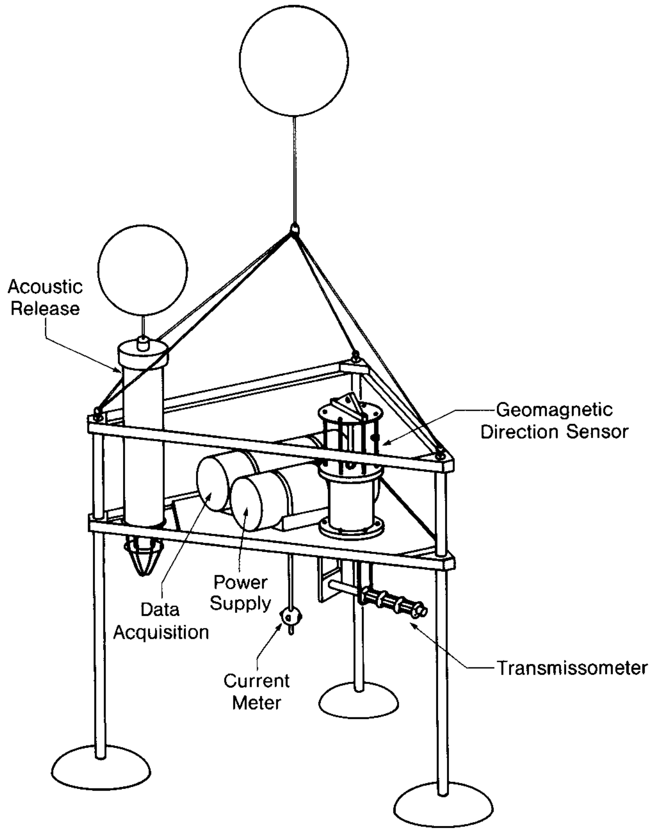

FIG. 2. Sketch of the instrumented tripod used in this study showing the position of the major sensors.

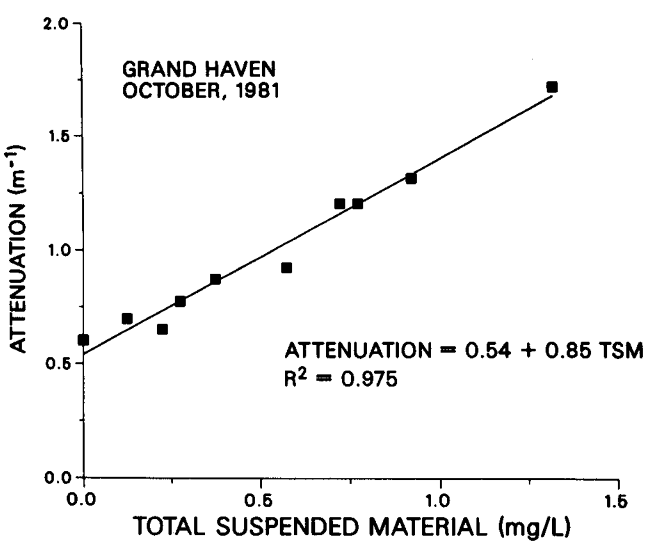

FIG. 3. Relationship between optical attenuation and total suspended material determined from samples taken in the study area on the day of deployment.

0.7 m above the bottom varied from 0 to over 0.28 m/s. Major temperature changes associated with coastal upwelling occurred twice during the experiment, and several instances of rapid changes in the concentration of TSM also occurred. Turbidity and temperature data collected by the city of Grand Rapids, Michigan, at the potable water intake located approximately 10 km to the southeast of the tripod, show a pattern very similar to that observed at the tripod, indicating that the observations reported here are probably representative of conditions elsewhere along the eastern shore. The temperature pattern is also remarkably like that presented by Bell and Eadie (1983, their Fig. 4).

Mean Current Flow – Upwelling

The relationship between winds and currents in Lake Michigan is well established (Mortimer 1975) and the occurrence of coastal upwelling on the eastern shore after the onset of north or northwest winds has been documented by Noble and Wilkerson (1970) and by Mortimer (1971). During October 1981 both major upwelling events (2 October and 6 October) were preceded by approximately 24 h of north-northwest winds. Bottom currents were southward, aligned with the wind, in the 12–18 h immediately before the upwelling. The rapid drops in temperature were associated with currents moving almost directly eastward (upslope). The southward component of the currents strengthened and became dominant again several hours after the initial drop in temperature.

A detailed view of the major upwelling events that occurred on 2 October and 6 October (Fig. 5) shows that increases in TSM appear to be related to the increases in current speed that were observed in the 24 h prior to the sudden drop in temperature and change of flow direction that typify the upwellings. In both cases TSM dropped as the colder water moved onshore, although the TSM peak observed on 2 October occurred shortly after the onset of the upwelling, possibly the result of increased turbulence that may be associated with the passage of the cold water front.

Water temperature remained near 5°C for 2 days following the upwelling of 2 October before beginning a gradual warming. Warming began approximately 4 days after the onset of the 6 October event but at a much slower rate. The reduction in warming rate and the apparent absence of major upwelling events after 6 October is probably due to deep-

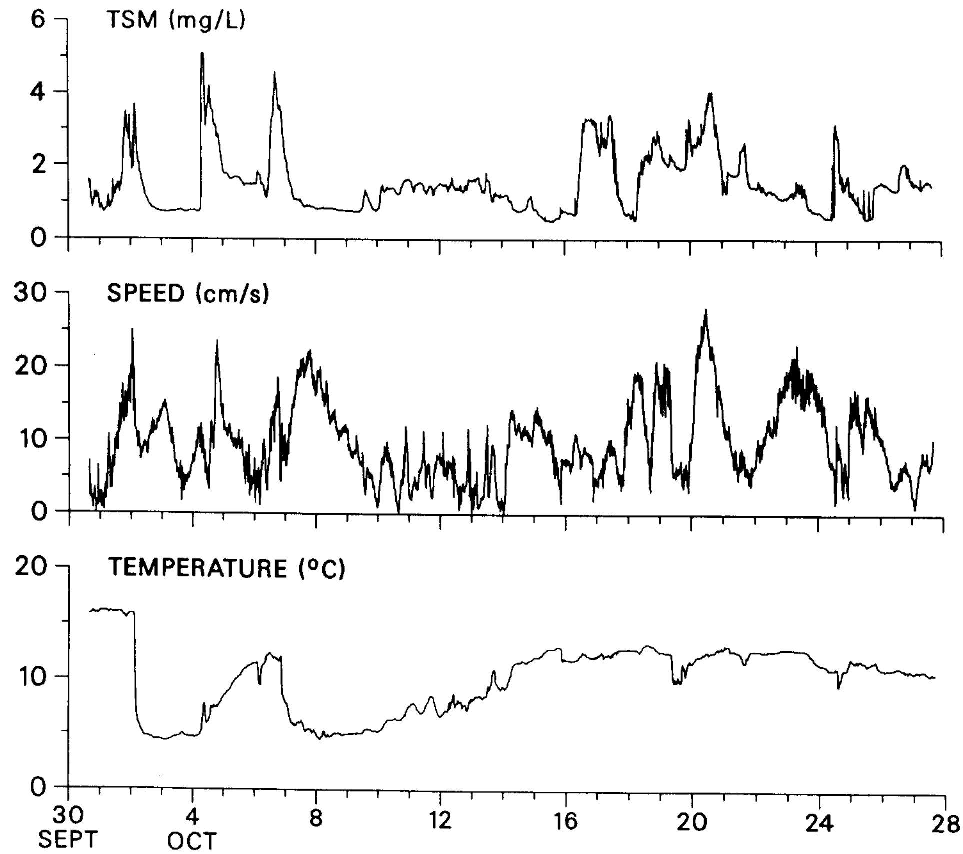

FIG. 4. Time series of total suspended material (TSM), horizontal current speed, and temperature within one meter of the bottom, 30 September - 28 October 1981.

ening of the thermocline beyond the 28-m depth at the experiment location. Smaller temperature changes associated with upwelling conditions, albeit in the presence of a reduced vertical temperature gradient, occurred several times later in the month. These too are associated with increases in TSM.

Prediction Function for Changes in Local Suspended Sediment Concentration Associated with the Mean Flow

Changes in the concentration of total suspended material measured at a fixed location just above the sediment-water interface may result from a combination of many processes, among them resuspension of bottom sediments, horizontal advection of either turbid or clear water, settling, and *in situ* production or destruction (coagulation) of particles. Although it is possible to make direct measurements relevant to all of these processes, it is hardly practical to do so, especially over long time periods. It is important to note, therefore, that the results presented here are based on a limited set of direct measurements that have been used to make inferences about the processes responsible for those measurements. For example, we infer that the initial increase in TSM that occurs on 4 October when current speeds are relatively low is associated with advection of warm turbid water from southwest of the tripod (Fig. 5). This increase in TSM in the (assumed) absence of an upward flux of bottom sediments (i.e., resuspension) would require a horizontal gradient in TSM. Although we have no direct measure of such a gradient, one can be inferred on the basis of the concentration and velocity record. The similar forms of the temperature and TSM signals for this event add support to this inference.

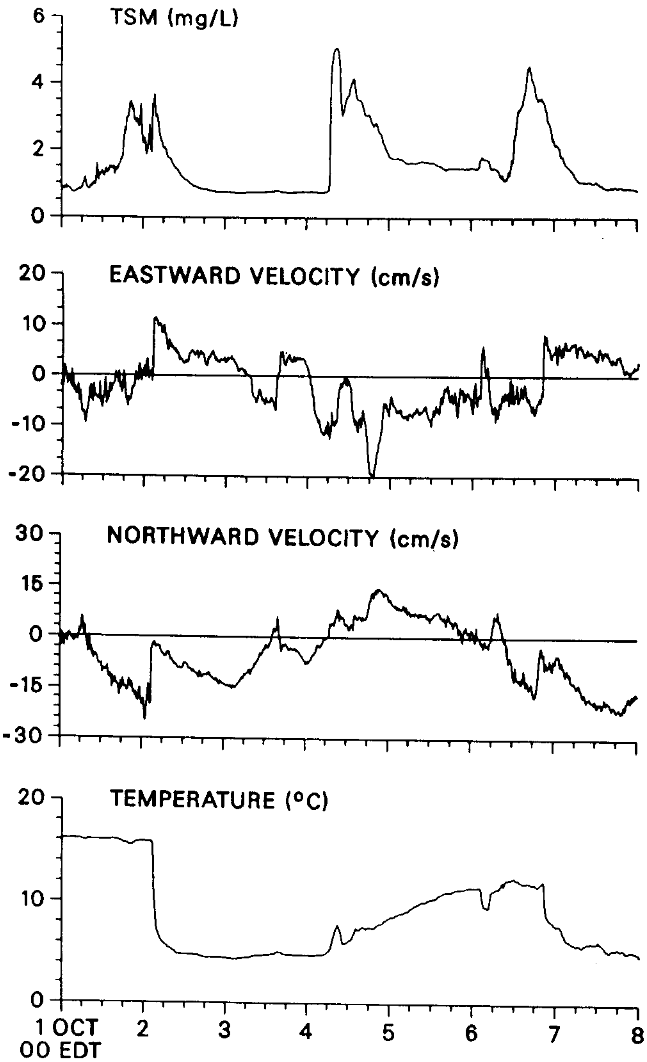

FIG. 5. Time series of total suspended material (TSM), horizontal velocity components, and temperature during 1 October - 8 October 1981.

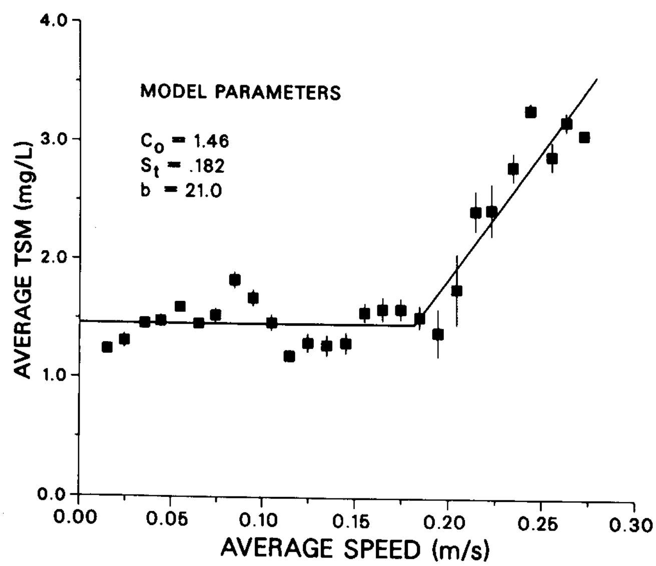

FIG. 6. Average TSM binned by flow speed, error bars are ± one standard error. Bin width is 1 cm/s, model parameters fit to Eq. (1).

Since one of our goals is to estimate threshold criteria for prediction of resuspension and since we do not measure the upward flux of bottom sediments directly, it is necessary for us to determine which of the observed increases in TSM are due primarily to local resuspension. Although it may be possible to distinguish between changes in TSM due to local resuspension and those due to advection of turbid water using the variability of the TSM signal (Chriss and Pak 1977), this would require sampling and recording at a higher frequency than was conducted as part of this experiment. We instead used a simple statistical technique to try to identify local resuspension events associated with increases in the mean flow. This technique is based on the assumptions that 1) advection of turbid water and local resuspension are the predominant processes affecting local TSM concentration, and 2) that advection of turbid water may occur at any flow speed, while local resuspension will only occur at high flow speeds. Accordingly, averages of TSM binned by flow speed should be low at low average speeds and high at high average speeds (Lesht *et al.* 1980, Baker and Milborn 1983). The results of this analysis are shown in Figure 6.

The relationship between TSM and mean flow speed shown in Figure 6 can be thought of as a first approximation to a prediction function for resuspension of the sediments and concentration of TSM at this location. It may be written

$$\begin{aligned} C &= C_o \text{ when } S < S_t \\ C &= C_o + b\,(S - S_t) \text{ when } S >= S_2 \end{aligned} \qquad (1)$$

in which C is the TSM concentration, C_o is an ambient concentration in the absence of resuspension, S is mean current speed, S_t is a threshold value of speed at which resuspension will occur, and b is the average rate at which TSM concentration increases with increasing current speed. Note that b may be an underestimate of the local resuspension rate, since some advection of low TSM water can be expected to occur at high flow speeds resulting in a lower average TSM value in the high speed bins than would be the case if there were no advection of low TSM water. Similarly, the estimate of the ambient concentration C_o may be higher than otherwise expected because of high TSM water advected at low speeds.

Fitting our data to a function of this form using the technique presented by Hudson (1966), we estimate that local resuspension occurs when mean flow speeds (measured 0.7 m above the bottom) exceed 0.18 m/s. Above this threshold we estimate that near-bottom TSM concentration (measured at a point 0.9 m above the bottom) increases at a rate of 21 mg/L/m/s from an ambient level of 1.46 mg/L. The calculated resuspension threshold speed value is slightly lower than that determined by Wimbush and Lesht (1979) for medium sands (0.21 m/s at 0.7 m above the bottom) using time-lapse photography. The apparent rate of TSM increase is approximately 20% of that estimated for similar sediments on the Atlantic continental shelf (Lesht *et al.* 1980). However, since the parameterization for the Atlantic sediments was based on wave orbital velocity and not on mean speed they may not be directly comparable.

Application of Eq. 1 to the observed time series of current speed results in a predicted TSM time series (Fig. 7). This predicted TSM time series, however, does not adequately explain the observed TSM. The model fails to predict some observed instances of apparent resuspension (i.e., 6 October, 16 October) and it predicts an increase in TSM when none is observed (7 October). Clearly, this simple model based on mean flow speed only partly describes the situation. In the remainder of this paper we explore other processes that account for the residual variation in the observed TSM concentration.

Effect of Surface Waves

Surface wave height and period measured at NDBO buoy 45007 were used to estimate what wave orbital speeds would be 1 m above the bottom in water 28 m deep during the experiment period. These estimates were made using linear wave theory (Le Mehaute 1969) and are plotted in Figure 8 along with wave height at buoy 45007 and TSM measured at the tripod, averaged to correspond to the hourly samples recorded at the buoy. Although 30 m is commonly considered a limiting depth for wave-induced resuspension in the Great Lakes where wave growth is often fetch-limited, the correlation between the observed TSM and the estimated wave orbital speed is striking, and suggests that surface waves may account for much of the observed variability of the TSM signal at the edge of the coastal shelf (28 m). In our analysis we have assumed that the action of surface waves at the tripod location results in resuspension (i.e., upward sediment flux). It is also possible that the observed increases in TSM correlated with surface waves are the result of wave-induced resuspension in shallower waters and subsequent advection past the tripod, but the direction of the bottom flows associated with the northerly winds that result in the high wave conditions (as well as the upwelling) is usually along-shore following the bottom contours and not from shallower water.

One can think of several ways to incorporate the effect of surface waves into a diagnostic model for TSM. A problem we have here, however, is that we have no direct measurement of wave conditions at the tripod, only the estimate of wave conditions made from the data collected at buoy 45007 some 75 km away. Therefore, we were unable to apply the existing models for combined wave and currents (e.g., Smith 1977, Grant and Madsen 1979) which require detailed information about the local wave conditions, and were forced to use a more qualitative technique to examine the effect of waves on our observations of resuspension. Thus the wave orbital speed estimate used in this analysis must be considered to be a relative, or diagnostic, variable only.

We experimented with several simple models similar to Eq. 1 in which TSM concentration was assumed to be a threshold-linear function of mean currents and waves. Models were tested in which wave and currents were allowed to act independently and also in which additive and multiplicative interaction was allowed. The following model resulted in the lowest residual sum of squares (coefficient of determination equal to 0.87)

$$\begin{aligned} C &= C_o \text{ when } S < S_t \text{ and } W < W_t \\ C &= C_o + b\,(S-S_t) \text{ when } S >= S_t \text{ and } W < W_t \\ C &= C_o + c\,(W-W_t) \text{ when } W >= W_t \text{ and } S < S_t \\ C &= C_o + d\,[(S-S_t)+(W-W_t)] \text{ when } S,W >= S_t,W_t \end{aligned} \tag{2}$$

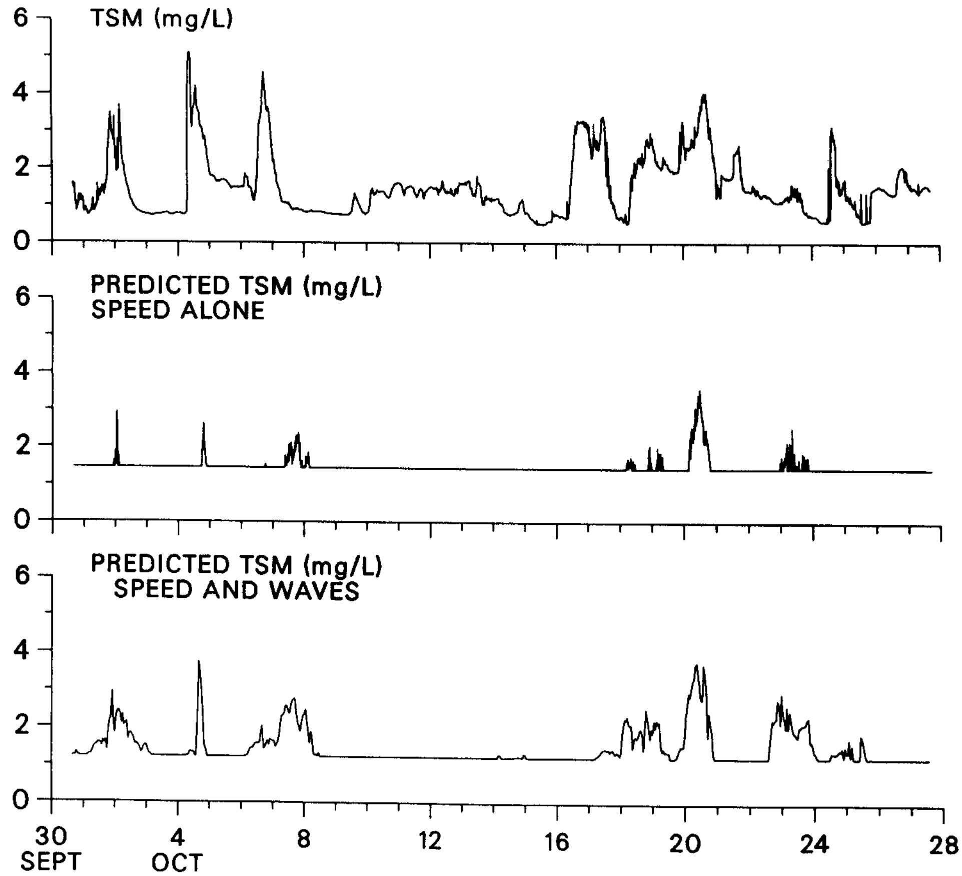

FIG. 7. Observed TSM time series with TSM time series predicted using Eq. (1) and Eq. (2).

in which C, C_o, S, S_t, and b are defined as in Eq. (1), and W is the estimated wave orbital speed, W_t is a threshold value for wave orbital speed, c is the rate at which TSM concentration increases with increasing wave orbital speed, and d is the rate of TSM increase with the sum of excess wave orbital speed and mean current speed. The TSM time series predicted by this model (Fig. 7) more closely resembles the observations than the prediction based on mean speed alone, qualitatively accounting for the major increases in TSM except for the increase that occurred on 16 October.

Effects of Advection

The remaining major anomalies in predicted TSM are probably due to advection of water masses with varying suspended loads past the tripod. High-speed flows of relatively clear water follow the occurrence of the two major upwelling events, reducing observed TSM. On at least one occasion (4 October) a brief influx of turbid water preceded what we have interpreted as a local resuspension event. We interpret the large increase in TSM that occurred on 16 October as an advection event as well, both because of the lack of correlation with either current speed or estimated wave speed and because flow direction and temperature are consistent with offshore movement of the Grand River plume.

Sinking and offshore movement of the Oswego River plume in Lake Ontario was observed by Bell (1978) to occur when river temperature dropped below the lake surface temperature during the late autumn. Although we have no measurements of Grand River temperature at the mouth, measurements of temperature made near the mouth of the Muskegon River (U.S. Geological Survey 1982), located approximately 15 km north of the mouth

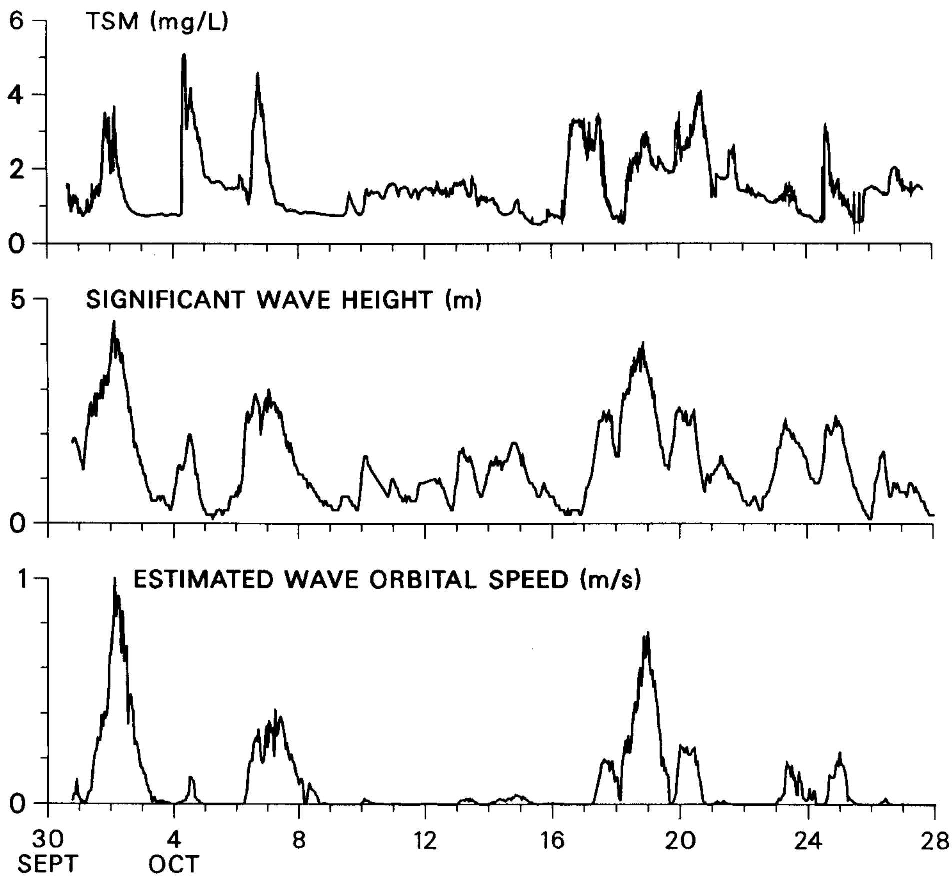

FIG. 8. Time series of significant wave height observed at NDBO buoy 45007 with time series of calculated wave orbital velocity and hour averaged TSM.

of the Grand River, show that the Muskegon River dropped in temperature steadily through the period of observation, and was probably cooler than ambient lake surface water during much of the month. The temperature of the Grand River at the gauging station at Eastman, Michigan, also dropped steadily during the month.

A detailed view of flow velocity and TSM for the period 16-19 October (Fig. 9) shows that the increase in TSM occurred as the flow direction moved from southward to westward. Current speed during this time was at or below 0.10 m/s and estimated wave activity was low. Variations in the TSM were correlated with variations in flow direction as well. TSM dropped below 1 mg/L when the bottom flow direction changed to northwestward, presumably moving the plume back toward the north away from the tripod. The influence of the plume on the remainder of the record is suggested by the increase in ambient TSM levels observed between 16 October and 25 October. This may be due to the deposition of easily erodable material during the plume passage and subsequent resuspension by currents and waves.

Horizontal Sediment Flux

Simultaneous observations of horizontal current velocity and TSM provide all of the information necessary to calculate horizontal sediment flux, simply defined as the product of TSM concentration and velocity. In this calculation we assume that fluctuations in both concentration and velocity with time scales shorter than our 15-min averaging period are unimportant. If fluctuations with short time scales are significant and correlated, then our estimates will be in error. However, it is impossible for us to estimate either the direction or the magnitude of this error from these data.

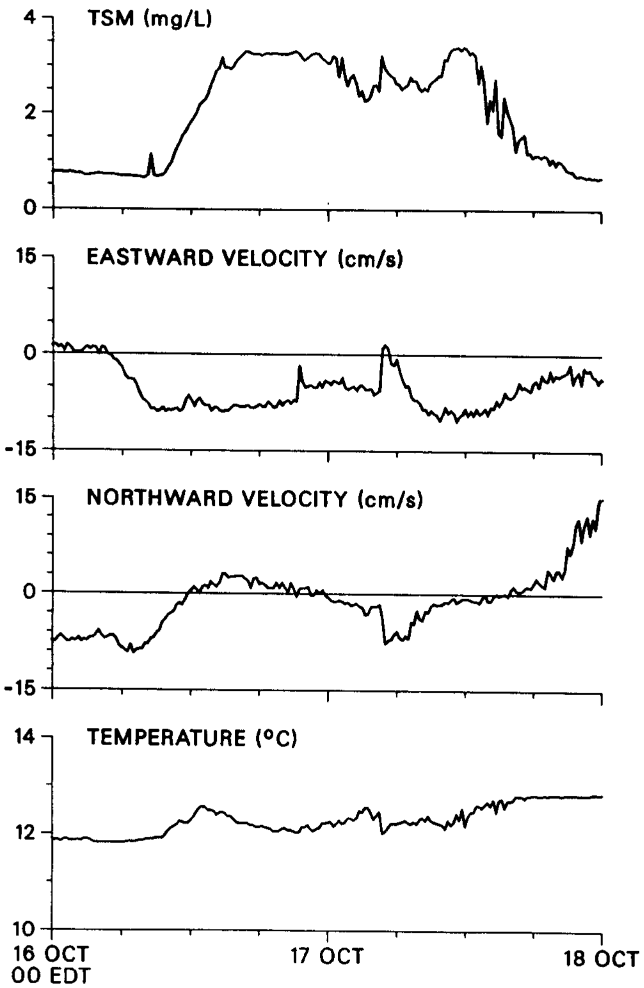

FIG. 9. Time series of TSM, components of flow velocity, and temperature for the period 15-17 October 1981.

The time series of horizontal flux vectors are plotted in Figure 10. Although the major sediment flux events had large northward components reflecting the dominance of alongshore flows (which are oriented nearly north-south at this location), we find that the vector average flux, calculated by summing the individual flux samples for each component, was toward the west-southwest (westward average is 4.3 kg/m^2/day; southward average is 0.1 kg/m^2/day) which is almost directly offshore across the shelf. These horizontal fluxes may be compared with the estimates of vertical mass flux in this region (roughly 5 g/m^2/day) obtained from sediment traps (Eadie *et al.* 1984).

Similarly, we can estimate the onshore particle flux due to upwelling by integrating the observed flux during the upwelling periods when the flow is predominantly eastward. Assuming that all of the sediment mass transport is confined to the bottom meter of the water column and that upwelling occurs along a representative 28 km length of coast (Bell and Eadie 1983), we find that the total particle mass moved onshore during a typical upwelling event is at least 4 x 10^5 kg. This agrees very well with Bell and Eadie's (1983) estimate of 8.4 x 10^5 kg per event for the same region.

CONCLUSIONS

A relatively simple set of measurements has been used to infer that bottom sediments at the edge of the coastal shelf (28 m depth) in southeastern Lake Michigan are resuspended in response to surface waves and bottom currents. Active sediment resuspension occurred approximately 20 percent of the time during October 1981. Much of the observed variation in near-bottom TSM concentration, except that assumed to be associated with advection of turbid water, could be accounted for with a simple diagnostic model in which near-bottom sediment concentration was considered to be a function of the observed mean current speed and an estimated wave orbital speed. The coefficients of the model, which include local threshold criteria and a concentration change rate, were determined empirically from the *in situ* measurements. However, because the local wave orbital speed had to be estimated from observations made some distance from the experiment location, and because of the complicating effects of advection, the diagnostic model cannot be employed for general prediction of near-bottom suspended sediment concentration. Coastal upwelling does appear to move sediment onshore but the net mass flux at this location during the observation period was offshore, principally the result of cross-shelf advection of the Grand River plume.

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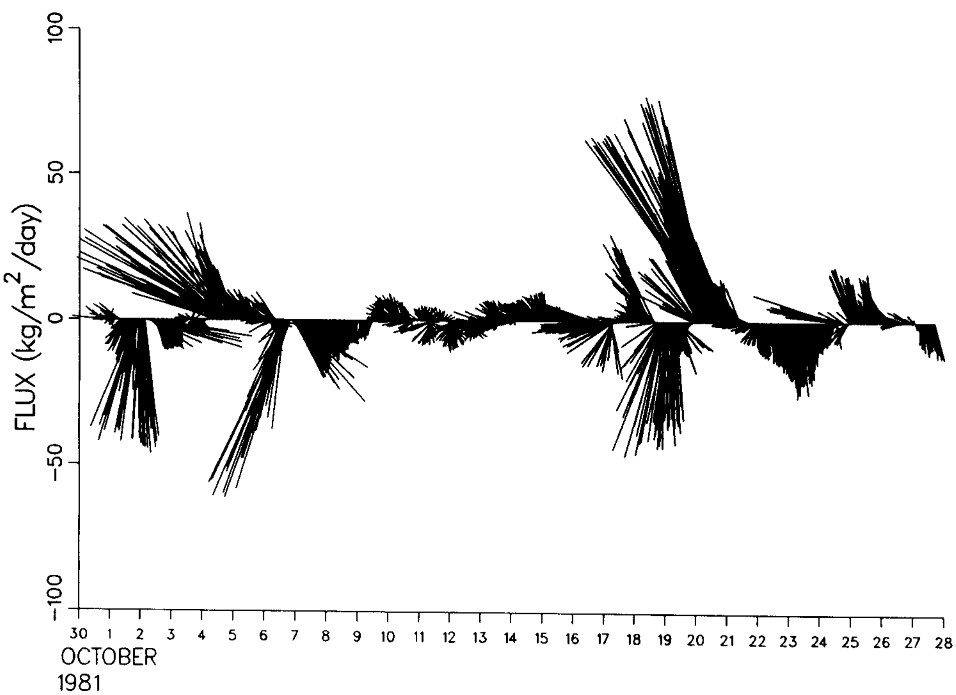

FIG. 10. Time series of horizontal sediment flux observed at tripod location, 30 September - 28 October 1981.

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