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Observations of Sediment Transport in Lake Erie during the Winter of 2004–2005

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ABSTRACT. *Time series measurements of current velocity, wave action, and water transparency were made at two sites—one in 24 m of water and the other in 53 m—in Lake Erie during the fall and winter of 2004–2005. The observations at the shallow site show that bottom resuspension occurred several times during the deployment. Although local resuspension did not occur at the deeper station, several advection episodes were observed. The storms during the observation period were not unusually large, so the processes observed are probably typical of those that occur on a yearly basis. The observations agree reasonably well with previous estimates for both the bottom shear stress during storms, and for the critical shear stress needed to resuspend bottom sediment, but previous estimates of the particle settling velocity are probably too low, while previous estimates of the sediment entrainment rate are too high. The results show that bottom material in the central basin is reworked numerous times before it is finally buried. Deposition in the eastern basin is a more continuous process, but the events observed were not sufficient to match the long-term accumulation rate, so deposition at this site is probably also due in part to larger, more infrequent storms.*

INDEX WORDS: *Lake Erie, sediment resuspension.*

INTRODUCTION

Lake Erie, the smallest and shallowest of the Laurentian Great Lakes, is divided into three basins: a shallow western basin with an average depth of less than 10 m, a large central basin with maximum depth of about 24 m, and the eastern basin, with a maximum depth of about 64 m (Fig. 1). The shallowness of most of the lake makes it very susceptible to the resuspension of bottom sediments by wind-generated waves. The resuspension and transport of this material has long been a concern because of the affinity of anthropogenic pollutants to absorb to the particles and be transported with them, and because high concentrations of suspended sediment may limit the amount of light available to the lower food web. Although these concerns have led to numerous laboratory investigations of the properties of the lake sediments, and to the development of numerical models of sediment resuspension and transport in the lake (Lick *et al*. 1994 and references cited therein), direct observations of sediment resuspension have been lacking. This paper reports the first *in situ* time series observations of sediment resuspension and transport in the lake.

METHODS

Arrays of instruments were deployed at two sites in Lake Erie—one in the central basin (E07) and the other in the eastern basin (E12)—in late September 2004 and retrieved in May 2005 (Fig. 1). Details of the moorings are given in Table 1. The instruments made time series measurements of water temperature, water transparency, sediment flux, current velocity, and water pressure (to measure the surface waves). Although measurements were made throughout the deployment, only the data recorded between 12 October and the formation of ice in the lake (20 January) are reported here. This period includes all of the major resuspension events observed during the deployment.

Current velocities were measured with upward-looking 300 kHz RDI acoustic Doppler current profilers mounted 0.5 meters above the bottom (mab). Fifteen-minute ensemble measurements were made

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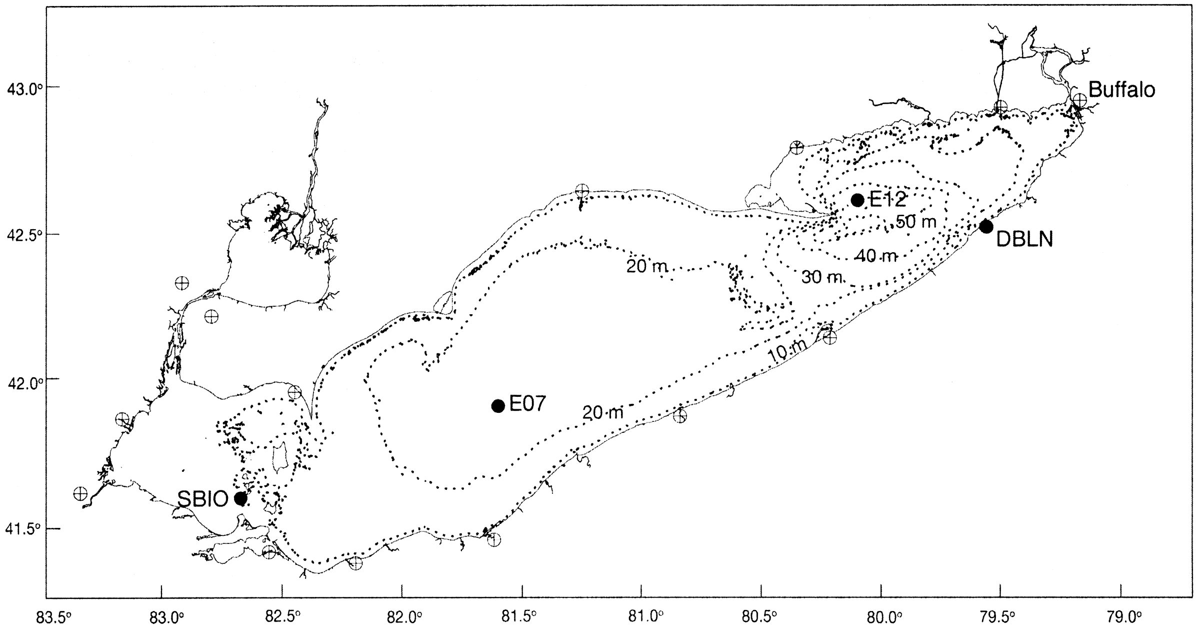

FIG. 1. Locations of the two stations (E07 and E12), and the CMAN stations (SBIO and DBLN) where wind measurements were made. Longitudes and latitudes are given on the x and y axes.

in either 0.5 m bins (E07) or 1 m bins (E12) from approximately 3 mab to close to the water surface. Single point measurements of water temperature were made using Seabird SBE39 temperature loggers. Water transparency was measured with SeaTech transmissometers (either 0.10 or 0.25 m path length) sampled at 0.5 Hz for a minute each hour. The mean values of the observations were converted to beam attenuation coefficient (bac, units are 1/m) using an equation supplied by the manufacturer. Water pressure was measured with Paroscientific Digiquartz pressure sensors. A burst of 2048 measurements made at 2 Hz was recorded hourly and used to calculate the significant wave height and average wave period at the height of the pressure sensor.

TABLE 1. Deployment information.

	E07	E12
Deployed	22 September 2004	21 September 2004
Retrieved	6 May 2005	4 May 2005
Latitude	41°55.78′N	42°34.88′N
Longitude	81°38.88′W	79°54.70′W
Water Depth (m)	24.3	54.5
Particle diameter (mm)	0.010	0.013
Adcp range (mab)	2.75–21.75	3–48
Adcp sample interval	15 min	15 min
Transmissometer heights (mab)	0.9, 5, 10	0.9,5,10
Transmissometer sample interval	30 min	30 min
Temperature heights (mab)	0.9, 5, 10	0.9, 5, 10, 30, 40
Temperature sample interval	15 min	15 min
Pressure sensor height (mab)	1.40	1.42
Pressure sensor sample interval	60 min	60 min
Sediment trap height (mab)	5	5
Sediment trap sample interval	9 days	9 days

The wave parameters and the near-bottom current velocity were used to calculate the bottom stress due to combined waves and currents using the program of Li and Amos (2001), who used the method of Grant and Madsen (1986) to calculate the combined bottom stress. This method uses an iterative technique to determine the bottom friction coefficient, which is a function of both the ratio of the wave and current strengths, and the bottom roughness, which in turn is a function of the particle size and the bottom bed forms present (if any). The friction coefficient, which changes with time, is then used to determine the bottom stress. Further description of the technique can be found in Grant and Madsen (1986) and Li and Amos (2001).

Sediment flux was measured with 0.2 m diameter sequencing sediment traps (Muzzi and Eadie 2002) programmed to collect samples every 9 days. After the collection bottles were removed from the traps, they were allowed to settle overnight before the excess water was siphoned off. The samples were then freeze-dried and weighed to determine the mass flux before being analyzed for chemical composition. Carbonates were removed from sub-samples of approximately 0.2 grams of material by adding several milliliters of 2N HCl and mixing on a shaker table overnight. The samples were then dried for 24 hours at 60°C, reweighed to determine the amount of inorganic carbon removed, and ground with a mortar and pestle before being analyzed for organic carbon and organic nitrogen content using a CE Instruments EA 1110 CHN analyzer. Total carbon was measured on samples which included the carbonate material. The inorganic fraction was determined by subtracting the organic carbon from the total carbon.

Bottom samples at each site were collected for particle size analysis with a box corer and analyzed using sieves for the particles larger than 1 mm and a Malvern 2000 laser particle sizer for the finer particles. Sediments at both sites were primarily silt and clay, with less than 10 % sand-sized material; the mean particle size at each station is given in Table 1. Wind measurements during the deployment were obtained from the NOAA CMAN stations located at Dunkirk, NY (DBLN) and South Bass Island, OH (SBIO). Since the wind speeds were measured approximately 20 m above the surface, they were corrected to the standard 10 m elevation using a power law with an exponent of 1/7 for the wind speed profile (Davenport 1960, Richards *et al.* 1966).

Water samples were collected at various times and locations throughout the lake in 2004 and 2005 to determine the concentration of total suspended solids (TSS). Triplicate samples were collected and filtered through pre-washed, pre-weighed Gelman A/E glass-fiber filters (nominal pore size 1.0 µm). The filters were dried overnight at 40°C and allowed to equilibrate for several hours in the balance room before being weighed. The results were then combined with measurements of beam attenuation made with a transmissometer attached to a vertical profiler to develop an equation relating the beam attenuation to TSS. A linear regression of the observations gives

$$TSS = 1.59*bac - 0.94 \quad (1)$$

where TSS is measured in mg/L. Equation 1 has an r^2 value of 0.81 based on 113 observations.

RESULTS

Observations from E07 and E12 are shown in Figures 2 and 3. Water temperatures (Figs. 2c and 3c) at both stations decreased throughout the deployment until ice formed in late January. The water at E07 was isothermal throughout the period, but the water at E12 was stratified until early November. Maximum wind speeds (Figs. 2a and 3a) at both locations were approximately 20 m/s, and the speeds frequently exceeded 10 m/s. Bottom currents (Figs. 2b and 3b) were usually in the opposite direction from the wind, illustrating the return flow pattern described by Saylor and Miller (1987). Peak near-bottom current speeds reached 0.37 m/s at E07 and 0.28 m/s at E12.

The strong winds produced large waves at both stations during several storms. The wave data shown in Figures 2d and 3d were derived from the pressure measurements made near the bottom by assuming that the surface wave distribution is described by the Donelan *et al.* (1985) spectra. The increased attenuation of the wave energy with increasing depth, and its dependence upon the wave period, are evident in the data from station E12 (Fig. 3d), which show far fewer wave events than at station E7. This does not mean that fewer wave events occurred at this station, but that only those events when the wave period exceeded about 8 s were recorded by the pressure sensor.

Given the orientation of Lake Erie, one might expect that winds from either the southwest or northeast would generate the largest waves. These effects are not too evident at E07, where the fetches are fairly large regardless of wind direction. Although

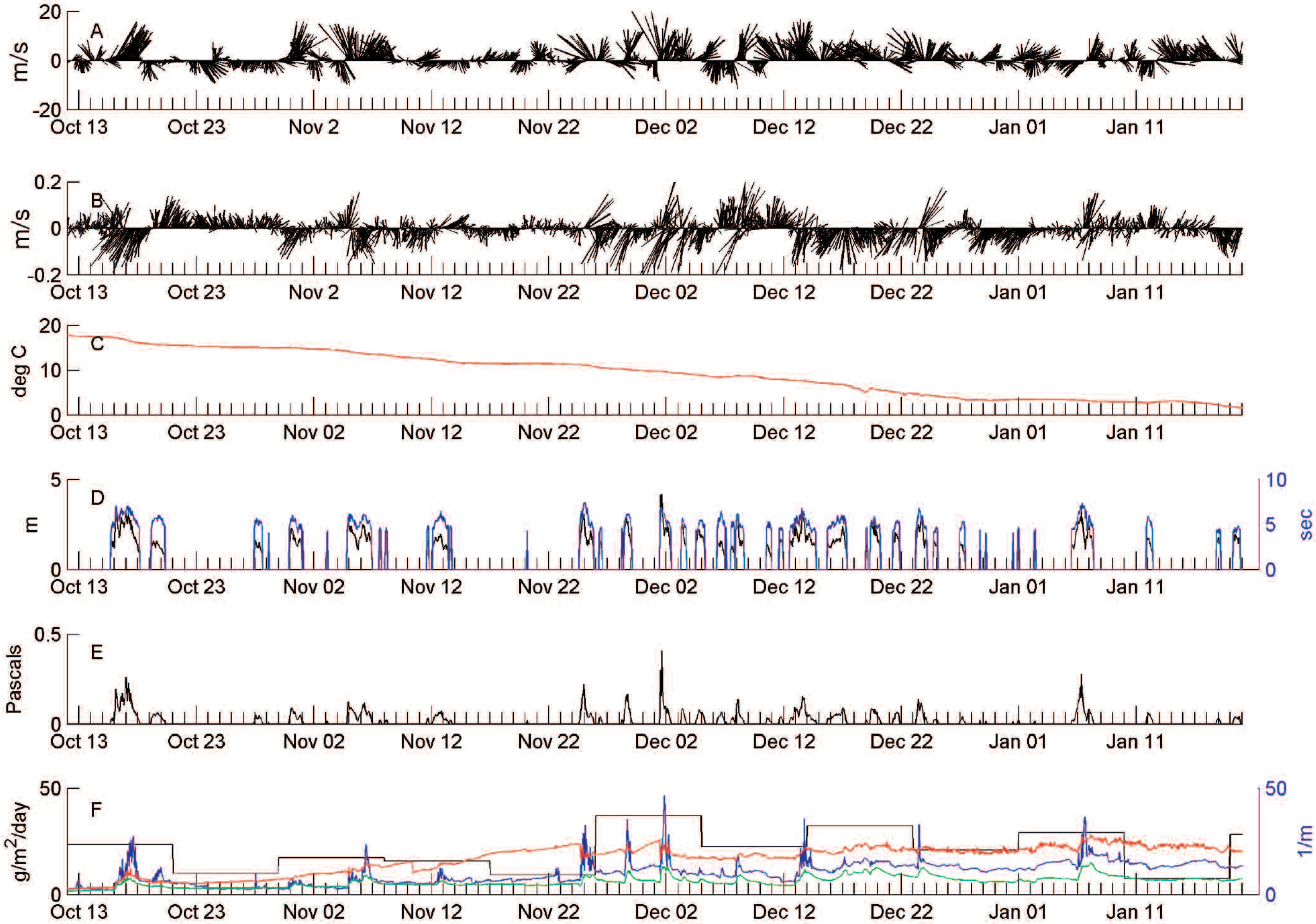

FIG. 2. Observations made at E07. A. Wind velocity at the South Bass Island CMAN station. B. Near-bottom current velocity. C. Water temperatures at 0.9 mab (black), 5 mab (blue), and 10 mab (red). The data from the three elevations are almost identical. D. Surface wave height (black) and period (blue). E. Bottom stress due to combined waves and currents. F. Vertical sediment flux measured 5 mab (black), and beam attenuation at 0.9 mab (blue), 5 mab (red), and 10 mab (green).

strong winds from the southwest (16–18 October) and the northeast (6–7 January) did produce large waves, equally large waves occurred on 24–25 November, when the winds were from the southeast, and the largest waves observed occurred on 2 December, when the winds were from the south. It thus appears that, at least at this station, the size of the waves is more dependent upon the wind speed than on the wind direction. The effect of wind direction is more pronounced at E12, where winds from the southwest have a much larger fetch than from other directions. Although the storm on 1–2 December (when the winds were from the south) still produced the largest waves, the waves on 16–18 October (when the winds were from the southwest) are comparable in size even though the wind speed was slightly less. Although the waves on 7 January are comparable in size to those on 1–2 December, they do not occur until the wind changed direction from northeast to south.

Bottom stresses (Figs. 2e and 3e) due to the combined effects of waves and currents exceeded 0.4 Pascals at E07, but because of the greater water depth (which attenuated the water motions due to surface waves) never exceeded 0.03 Pascals at E12. The beam attenuations at E07 (Fig. 2f) show numerous instances of local sediment resuspension. Although the 5 mab transmissometer became fouled during the deployment, the responses of the other transmissometers during the resuspension events are quite clear. The mass flux measured by the sedi-

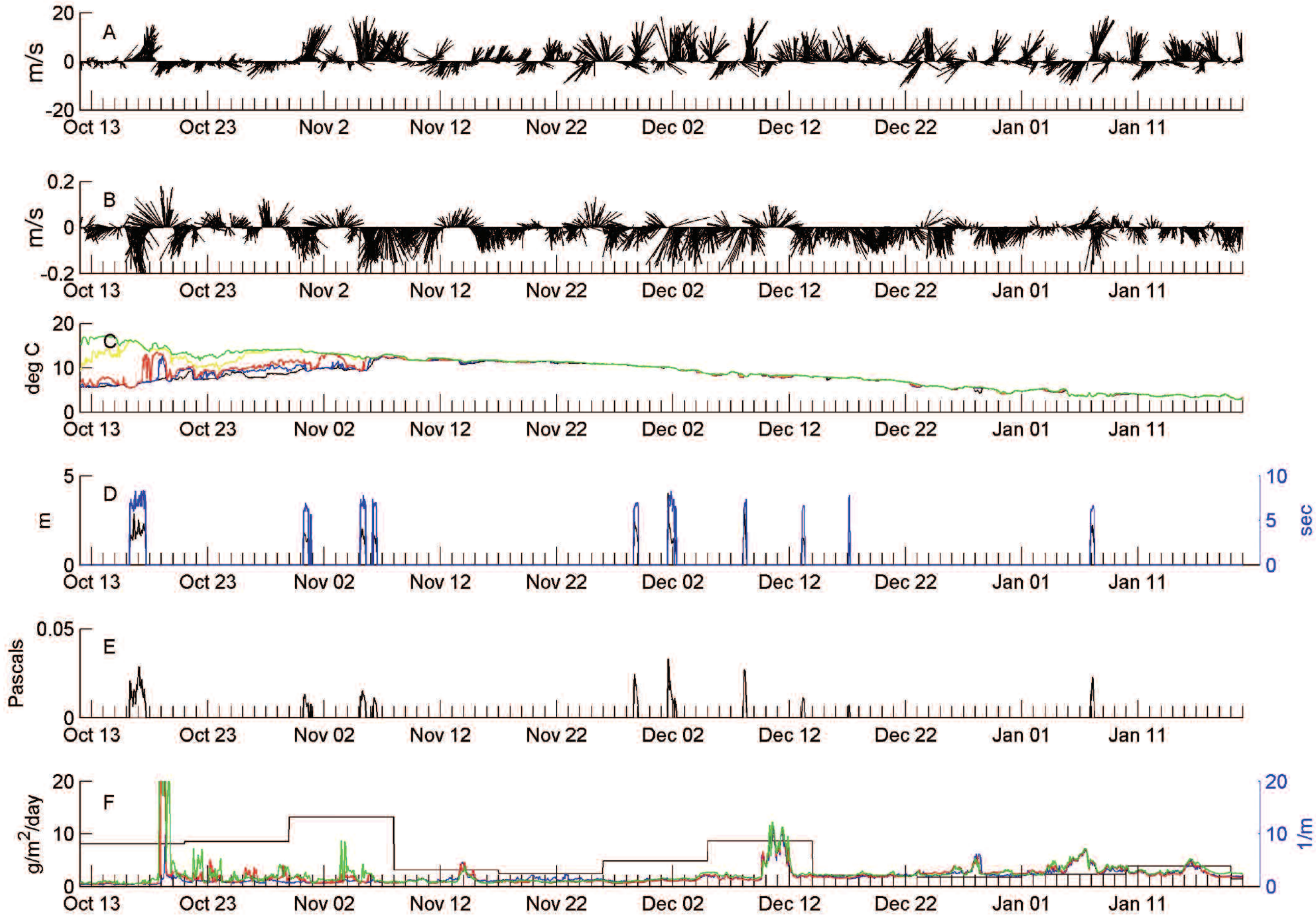

FIG. 3. Observations made at E12. A. Wind velocity at the Dunkirk CMAN station. B. Near-bottom current velocity. C. Water temperatures at 0.9 mab (black), 5 mab (blue), 10 mab (red), 30 mab (yellow), and 40 mab (green). D. Surface wave height (black) and period (blue). E. Bottom stress due to combined waves and currents. F. Vertical sediment flux measured 5 mab (black), and beam attenuation at 0.9 mab (blue), 5 mab (red), and 10 mab (green).

ment traps also reflects the occurrence of the resuspension events.

Thirteen resuspension events can be identified at E07. Table 2 lists both the maximum stress (τ_{max}) and the stress at which resuspension began (τ_{cr}) for each storm. Since the bottom stress frequently increased dramatically at the time resuspension was initiated, the table gives the bottom stress just before and just after resuspension began. The minimum stress required to resuspend bottom material was about 0.03 Pascals on 12 November, but this value was much higher during many of the events. This variation is probably due to differences in the amount of consolidation and bioturbation that the sediments underwent between the different resuspension events. Values of the maximum stress also

TABLE 2. Resuspension events at E07, stresses are in Pascals.

Dates	τ_c at E07	τ_{max} at E07	τ_{max} at E12
16–18 October	0.09–0.20	0.26	0.02
19–20 October	0.05–0.06	0.06	0.01
30–31 October	0.06–0.07	0.09	0.01
4–5 November	0.06–0.12	0.12	0.01
5–6 November	0.04–0.05	0.12	0.01
12–13 November	0.03–0.05	0.07	0.01
24–25 November	0.07–0.08	0.22	0.01
28 November	0.07–0.12	0.18	0.02
1–2 December	0.06–0.30	0.41	0.03
7–8 December	0.08–0.09	0.14	0.03
12–14 December	0.04–0.09	0.15	0.01
23 December	0.05–0.07	0.14	0.01
6–7 January	0.06–0.07	0.28	0.01

varied widely, reflecting the differing intensity of the storms.

The deeper water at E12 caused the bottom stresses to be much less than at E07—they never exceeded 0.03 Pascals (Table 2). This is equal to the minimum stress needed to erode bottom material at E07, but no resuspension was observed. However, there were six intervals (18–19 October, 13–15 November, 9–12 December, 27–28 December, 4–7 January, and 14–17 January) when all three of the transmissometer readings were elevated (Fig. 3f), even though the bottom stresses were negligible. The very high attenuations at 5 and 10 mab on 18 October are probably due (at least in part) to mixing of the water column as the thermocline broke down.

These six episodes are most likely due to lateral advection of suspended sediment to the site. Because of the large amount of cloud cover, few satellite images of the lake during the deployment period are available, but Figure 4 shows the MODIS true color images on 2 days when the cloud cover was minimal. Figure 4a shows the turbidity in the lake on 7 November (at the end of one of the resuspension events at E07), and Figure 4b shows the turbidity on 28 December (during one of the high turbidity events at E12). In both cases large areas of the central basin are highly turbid and there is a plume of suspended sediment extending eastward from Long Point, which is just to the southwest of E12. This plume of sediment, which appears to be caused primarily by local coastal erosion along the north shore of the lake (local resuspension of bottom material in the shallower parts of the basin may also be a source of material), forms a counterclockwise rotating spiral of material in the deeper parts of the eastern basin. It appears that E12 was just out of the high turbidity area on 12 November and just within it on 28 December. This counterclockwise eddy is visible throughout the year in many of the remote sensing images of the eastern basin, so it appears to be a rather ubiquitous feature of the circulation, and may be responsible for much of the sediment transport in the basin.

There is not a good correlation between the resuspension events observed at E07 and the high turbidity episodes observed at E12. Four of the presumed advection events (those on 18–19 October, 13–15 November, 9–12 December, and 4–7 January) occurred immediately after one of the resuspension events identified at E07, and the other two may have been caused by local erosion along the north coast, even though no sediment resuspension was observed at E07. However there is no indication of sediment transport at E12 after most of the largest resuspension events at E07, and the largest advective episode (9–12 December) occurred after the relatively small resuspension event on 8 December. The high attenuations during this event may have been due more to runoff from a rain storm on 9 December than local resuspension.

The trap fluxes at E12 were not as consistent with the transparency measurements as at E07. The flux rates were much lower than at E07, and the highest values occurred at the beginning of the deployment (prior to 7 November) when the water was still stratified. This may be due to mixing of the water column as the thermocline broke down. Only the largest advection event (on 9–12 December) affected the flux measurements.

Results from the chemical analyses of the trap samples (Fig. 5) show some differences in composition between the two stations. The organic carbon content at E07 is only about 3%, so most of the material collected (probably over 90%) is inorganic, but the low (8–10) ratios of organic carbon to organic nitrogen (C:N) at E07 are near the Redfield ratio of 6.6 for pure biogenic material, so most of the organic material appears to be autochthonous material settling directly out of the water column. Although the C:N ratio remained almost constant during the intervals when resuspension occurred, the concentrations of both total carbon and organic carbon decreased, so the additional material collected during these intervals was most likely composed of siliceous bottom sediments. The organic carbon content is even lower at E12 (about 0.5%), indicating that even less of the trap material was biogenic in origin. Since no local resuspension was observed at the station, it seems likely that most of the trap material was either bottom sediment resuspended at shallower depths, or material eroded from the bluffs along the northern shoreline.

DISCUSSION

The responses of the bottom sediment at the two stations to the same wind events are considerably different. Station E07 is shallower, and local resuspension occurred numerous times. Sediment fluxes at the station were high, and the composition of the material collected in the traps indicates that while most of it is inorganic, the organic fraction is only slightly degraded. In contrast, no resuspension was observed at E12, the mass fluxes were much lower, and the material appears to be derived almost exclu-

FIG. 4. Satellite images of surface reflectance. A. 7 November, 2004. B. 28 December, 2004.

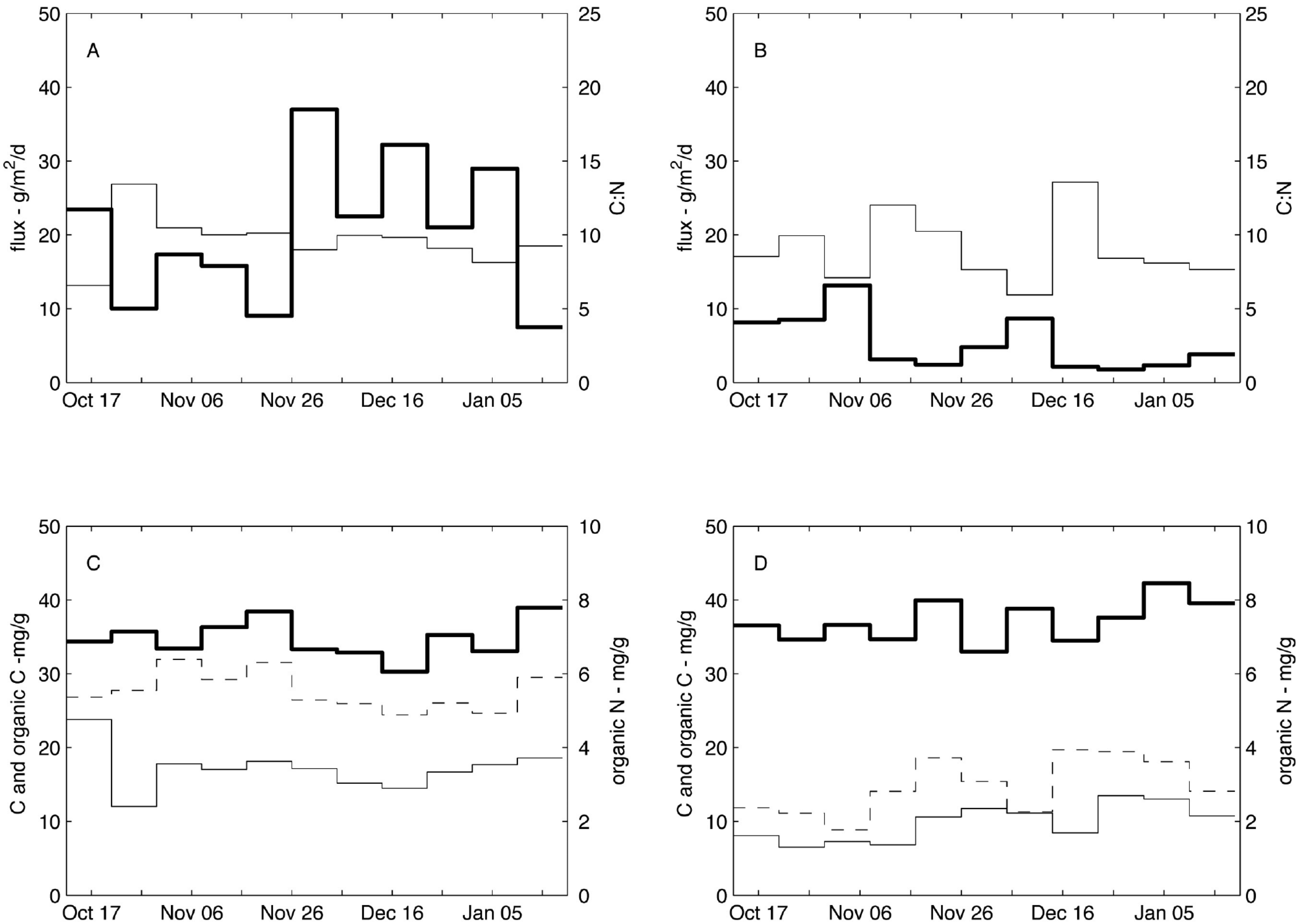

FIG. 5. Vertical flux and chemical composition of the material collected in the sediment traps. A. Mass flux (heavy line) and C:N ratio at station E07. B. Mass flux (heavy line) and C:N ratio at station E12. C. Total carbon (heavy solid line), organic carbon (solid line), and organic nitrogen (dashed line) at E07. D. Total carbon (heavy solid line), organic carbon (solid line), and organic nitrogen (dashed line) at E12.

sively from terrestrial sources. Table 3 compares the average mass fluxes measured by the traps (during both the 100 day observation period and for the year April 2004–April 2005) to several estimates of the long-term sediment accumulation rate at each site. The trap fluxes at both stations show that most of the mass flux during the year occurred during the observation period. Note that the long-term accumulation rate at E12 is greater than at E07 (accumulation rates at this site are among the highest measured in the lake), and that the trap fluxes at E12 are less than the long-term accumulation rates, while at E07 the trap flux is much greater than both the fluxes measured at E12 and the long-term accumulation rates measured at E07. It thus appears that the resuspension events at E07 resuspend and deposit the same material over and over again with little net accumulation or erosion, while at E12 the deposition of advected material is a more continuous process, with little or no resuspension taking

TABLE 3. Trap fluxes and sediment accumulation rates, units are kg/m²/y.

	E07	E12
Mean trap flux (deployment and yearly)	7.6, 4.2	2.1, 1.2
Accumulation (Kemp *et al.* 1977)	0.7	2.7
Accumulation (Robbins *et al.* 1978)	0.8	4.4
Accumulation (Klump *et al.* 2006)	1.37	5.91

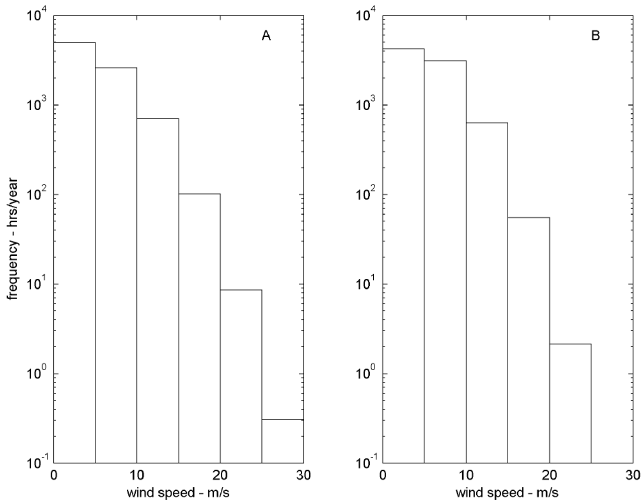

FIG. 6. Yearly occurrence of wind speeds from 1983-2005 at Dunkirk (A), and South Bass Island (B). The data have been normalized to a height of 10 m and grouped in 5 m/s bins.

place. Since the annual mass flux at E12 is only 20–45% of the long-term accumulation rates, processes other than those observed must also contribute to the long-term deposition at this site.

Wind speeds during the resuspension events were usually between 10 and 20 m/s. The speed never exceeded 20 m/s at Dunkirk (maximum speed was 19.8 m/s) and only exceeded 20 m/s for 3 hours at South Bass Island (maximum speed was 24 m/s on 1 December). A compilation of the wind speeds measured at the two stations between 1983 and 2005 (Fig. 6) shows that wind speeds in excess of 20 m/s averaged 2 h/y at South Bass Island, and 9 h/y at Dunkirk. For speeds greater than 15 m/s the numbers are 56 h/y and 90 h/y. When the speed exceeded 15 m/s, the wind directions were evenly divided between southwest, south, and southeast at South Bass Island, and between southwest and south at Dunkirk. Thus the resuspension events observed during the deployment at E07 were not caused by unusually high winds, and are probably characteristic of events that occur each year, while the lack of resuspension at E12 is probably also typical of the normal pattern of events at this site.

Since the storms observed during the deployment appear to be typical of those that occur on an annual basis, the erosion, deposition, and transport of sediment due to these storms can be considered to be the background, or ambient, processes that normally occur in the lake each year at these sites. The high trap fluxes at E07 show that the yearly storms resuspend and rework material deposited during the year numerous times, and that any long-term deposition that occurs is a residual of a large number of episodes of sediment resuspension and deposition. Since the station is located in the deepest part of the central basin, similar processes probably occur throughout the central and western basins of the lake. In contrast, since the mass fluxes at E12 are significantly less than the long-term accumulation rates, processes other than the ambient ones seem to be needed to account for the long-term deposition at this site. It may be that larger, but more infrequent, storms cause much of the deposition at this site.

Lick *et al.* (1994) first suggested this hypothesis and conducted a numerical modeling study to examine the relative importance of small and large storms on sediment movement in the lake. They presented results for a steady southwest wind at 10 m/s. It is difficult to compare the results presented here to those of Lick *et al.* (1994), since they did not present exact values for any particular site, but the bottom stresses reported here are similar in magnitude to (but larger than) their results. The maximum bottom stresses at E07 were less than 0.2 Pascals during most of the storms reported here, although the values reached as high as 0.41 Pascals on one occasion. Since the wind speeds during most of the storms were between 10 and 20 m/s, it is not surprising that the bottom stresses are larger than those reported by Lick *et al.* (1994). The critical stresses required to erode bottom material are also similar to those used by Lick *et al.* (1994). Critical bottom stresses for the events listed in Table 2 range between 0.03–0.1 Pascals, which is similar to the range (0.01–0.1 Pascals) used by Lick *et al.* (1994).

Although the stresses reported here are similar to those used by Lick *et al.* (1994), the settling velocities differ considerably. Based on laboratory measurements (Burban *et al.* 1990), Lick *et al.* (1994) estimated that particle settling velocities were of the order of 0.1 mm/s (or about 8.6 m/day). Examination of the events listed in Table 2 shows that the average time required to clear the water column of suspended sediment (determined as the interval between the time when the bed stress decreased below the critical stress and the time when the suspended sediment concentration returned to ambient levels) was 7 h (with a range of 3–11 h). For a water depth of 24 m, this gives a mean settling velocity of 0.95 mm/s (82 m/day), which is about an order of mag-

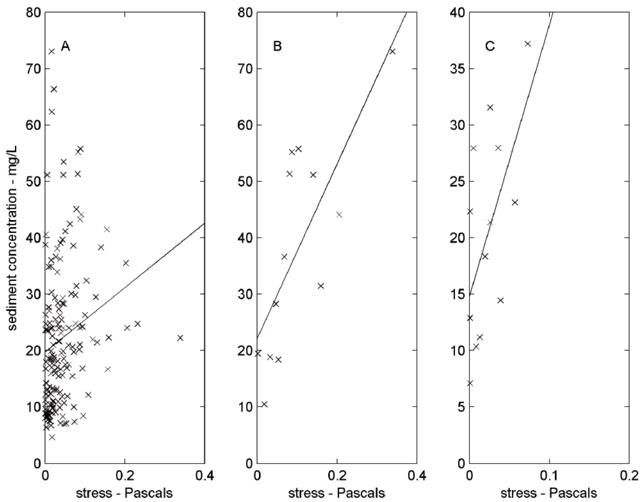

FIG. 7. Relationship at E07 between net bottom stress and total suspended solids at 1 mab. A. All observations during the 13 storms listed in Table 2. The solid line is the best linear fit ($r^2 = 0.04$). B. Mean stress and mean concentrations during the 13 storms. The solid line is the best linear fit ($r^2 = 0.37$). C. Maximum net stress and maximum sediment concentration during the 13 resuspension events at E07. The solid line is the linear regression ($r^2 = 0.59$).

nitude greater than the values used by Lick *et al.* (1994). Since none of the sediments used in the experiments of Burban *et al.* (1990) were collected from near E07, differences in composition may explain the discrepancy, but the observations indicate that particles settle out of the water column far more quickly than Lick *et al.* (1994) calculated. The effect of the higher settling velocity also increases the tendency of the particles to be concentrated near the bottom (compare the attenuations at 1 and 10 mab in Fig. 2). This is contrary to the assumption of vertical homogeneity made by Lick *et al.* (1994).

The greatest difference between the results presented here and those of Lick *et al.* (1994) is in the relationship between bottom stress and the sediment entrainment rate. Based on laboratory experiments (MacIntyre *et al.* 1990 and references cited by them), Lick *et al.* (1994) found that the mass of sediment resuspended is proportional to the cube of the net stress, $(\tau\text{-}\tau_c)^3$. It is difficult to determine entrainment rates from field data because the bottom stress does not usually increase monotonically (as it does during laboratory experiments), and because the peak sediment concentration frequently lags the peak in bottom stress (even near the bottom). Figure 7a shows the relationship between the net stress and the near-bottom sediment concentration (calculated from the 1 mab attenuation measurements and equation 1) during the 13 resuspension events listed in Table 1. There is little or no correlation between the measurements (the r^2 value for the best linear fit is only 0.04), but the data clearly show that a cubic relationship does not exist. The relationship between the mean and peak values during the 13 storms are shown in Figures 7b and 7c. These results show a much better correlation between the parameters, but the relationship is linear, not cubic (r^2 values for the best linear fit are 0.37 for the mean values and 0.59 for the peak values). Although there is considerable scatter in the data, it is evident that the amount of resuspended sediment is not proportional to the cube of the net stress, and that a linear relationship is probably more appropriate.

The relationship between the net stress and the rate of erosion obviously has important implications for the total amount of sediment resuspended and has been widely investigated. Formulas that use a power law (similar to Lick *et al.* 1994) have frequently been used, with exponents ranging between 1.2 and 4.7 (Lavelle *et al.* 1984), while others have used an exponential form (Li and Amos 2001). Many other investigations use a linear relationship (Wiberg *et al.* 1994, Harris and Wiberg 2001). Hawley and Lesht (1992) used a linear relationship to model sediment resuspension in Lake St. Clair and obtained good results. Sanford and Maa (2001) presented an extensive review of this subject and found that a linear relationship between the net stress and the erosion rate could be used for all applications if both the rate of change in the applied stress and the rate of change in the erodability of the sediment were accounted for. They also noted that in their experiments the applied stress and the erodability of the sediment increased simultaneously (as they did in some of the experiments cited by Lick *et al.* 1994), and that this lead to an apparently greater than linear dependence of the erosion rate on the net stress. The exact value of the exponent for the net stress will depend upon both the model being used and the region that is being modeled, so there is no single value that is appropriate for all situations, but the data presented here indicate that a value of 3 is too large for use in Lake Erie and that the correct value is probably close to 1 for the model of Lick *et al.* (1994). The stress in the experiments cited by Lick *et al.* (1994) did not exceed 0.16 Pascals (which is considerably less than many of the peak bottom stresses reported here) and none of the sediments were collected from near E07, so it may not be appropriate to extend their results to the stresses reported here.

It is clear that Lick *et al.*'s (1994) model correctly simulates the main features of the transport and deposition of suspended material in the lake, but the reduction in the value of the stress exponent from 3 to 1 means that the difference in the amount of sediment resuspended during small and large storms will be much less than they calculated, while the increase in the particle settling rates will reduce the distance that suspended material is transported during a storm. Lick *et al.* (1994) concluded that deposition in the eastern basin was almost exclusively due to the transport of suspended material to the basin during very large but infrequent storms, but the results presented here show that normal, yearly events provide a substantial proportion (up to 45%) of the material needed to maintain the long-term accumulation rate. It may be that the principal effect of large storms is to rework material already transported to the site, rather than transporting and depositing large quantities of additional material (although at least some such transport is also required). Although erosion occurs in the central basin more frequently than the results of Lick *et al.* (1994) suggest, the distance that the resuspended material is transported is probably less than that calculated by them, and it appears that relatively little of this material is transported to and deposited in the eastern basin during normal storms.

It is difficult to determine the thickness of the sediment deposited from the mass rates given in Table 3, but Klump *et al.* (2006) reported that the dry weight of sediment in the top 60 mm of a core taken near E07 was 1–2 mg/mm^2 and 2.5–4 mg/mm^2 in the top 60 mm of a core taken near E12. The difference in these values is consistent with the idea that sediment at E07 is frequently reworked, while sedimentation occurs more continuously at E12, thus allowing the sediment to consolidate. If these values are used, then the yearly trap fluxes give a depth of 21–42 mm of material deposited at E07 and 3.0–4.8 mm at E12. Similar calculations using the long-term depositional rates given by Klump *et al.* (2006) give depths of 6.9–13.7 mm at E07, and 14.8–23.6 mm at E12, while erosion depths at E07 (calculated from the amount of material suspended during the storms listed in Table 2) vary between 1 and 5 mm. These depths show that the top 20–40 mm of sediment at E07 is subject to erosion and deposition on an annual basis, while at E12 the long-term burial rate is on the order of tens of mm/y.

CONCLUSIONS

The observations reported here are the first *in situ* time series observations of sediment resuspension and transport made in the lake. They show that during the fall and early winter of 2004–2005 sediment resuspension occurred frequently in the central basin (station E07, water depth 24 m), but these resuspension events had only a small effect on the deposition of sediment in the deeper parts of the eastern basin (station E12, water depth 54 m). Deposition there is due mainly to the transport of material eroded from either along the northern shore of the lake or from shallower parts of the basin, and then transported to the site. Since the storms reported here are not unusually large, they provide a background level of sediment resuspension and transport against which the effects of more severe storms can be measured.

The observations reported here are similar to previous estimates of both the bottom stress that occurs during storms, and the critical stress required for sediment resuspension, but do not agree with earlier estimates of the particle settling rates, or the amount of sediment resuspended as a function of bottom stress. Thus the idea that a few severe storms account for almost all of the sediment transport and deposition in the eastern basin may not be correct. At least 20–40% of the deposition is caused by rather ordinary "background" events that occur several times each year, and the bulk of the material is probably supplied by coastal erosion from the north shore of the lake. It seems likely that previous numerical simulations (Lick *et al.* 1994) underestimate the amount of material resuspended in the central basin during moderate storms, but overestimate the distance that sediment is transported during these events. Lick *et al.* (1994) cautioned that many of their model parameters should be considered only as first approximations. The results presented here should allow more realistic values to be used for both particle settling velocities and sediment entrainment rates in future modeling efforts.

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