J. Great Lakes Res. 32:50–62
Internat. Assoc. Great Lakes Res., 2006

Climatology of Large Sediment Resuspension Events in Southern Lake Michigan

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ABSTRACT. *Lake Michigan, particularly the southern basin, is subject to recurrent episodes of massive sediment resuspension by storm-induced waves and currents. The purpose of this paper is to investigate the climatology of these events for Lake Michigan, including an analysis of associated meteorological conditions. This paper begins by examining turbidity records from two water treatment plants (Chicago, IL and St. Joseph, MI) for which long-term records are available. The turbidity records from the two plants show significant differences indicating that turbidity measurements from a single location would probably not be representative of a basin-wide climatology. A one-dimensional sediment resuspension and deposition model for fine-grained sediments is then developed and calibrated with data from the water treatment plants. The one-dimensional model is applied at 15 points around the southern basin for a 45-year period for which Lake Michigan wave climatology is available and the results are averaged to obtain a basin-wide turbidity index (Southern Lake Michigan Turbidity Index, SLMTI). A frequency distribution of the turbidity index is presented and meteorological conditions associated with the largest events are examined. Our analysis indicates that significant resuspension events in southern Lake Michigan are usually caused by a strong cyclone passing to the east of the lake. The most likely time of the year for this to occur is October to April. There is an average of 1 event per year with SLMTI above 25 mg/L and each event typically lasts about 3 days. Our analysis indicates that events have occurred more frequently since the late 1980s as the number of winter storms has increased and ice cover has decreased.*

INDEX WORDS: *Lake Michigan, turbidity, sediments, climatology.*

INTRODUCTION

Lake Michigan, particularly the southern basin, is subject to recurrent episodes of massive sediment resuspension caused by storm-induced waves and currents (Mortimer 1988, Eadie *et al.* 1996). These resuspension events are the primary mechanism for reintroducing large inventories of nutrients and contaminants stored in sediments back into the water column. During the episodic process of resuspension and transport, pelagic biota can be exposed to constituents delivered to the lake years to decades earlier (Eadie and Robbins 1987, Eadie *et al.* 1984, Eadie *et al.* 1989, Eadie *et al.* 2002). While sediment resuspension and transport are produced at various time and space scales by a wide spectrum of waves and currents, we are specifically focusing on large energetic events that remobilize sediments from temporary deposits in deeper water and appear to impact the lake on a *basin-wide* scale. The total amount of material resuspended during one of these large events has been estimated to be comparable to the total annual load (erosion, atmospheric deposition, and tributary input) of fine-grained material to the entire basin (Colman and Foster 1994, Eadie *et al.* 2002, Lou *et al.* 2000). Resuspension events are evident in satellite imagery as well as turbidity records from municipal water treatment plants

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around the lake. Spring and fall storms can create a nearshore zone of turbid water up to 10 km wide that sometimes encompasses the entire southern basin of the lake. Much of the resuspended material consists of fine-grained silty clay that can remain in suspension for several weeks after a storm. There is a considerable amount of variability in the exact location and extent of these events, but they all appear to contribute to the gradual transport of fine-grained material from near shore to offshore regions.

The purpose of this paper is to develop a climatology of these large events for Lake Michigan, including an analysis of the type of meteorological conditions that can trigger an event. The two main data sources available for developing such a climatology, water intake turbidity records and satellite imagery, each have some limitations that restrict their usefulness for such a purpose. Intake turbidity records from water treatment facilities around the basin cover a fairly long period, but they each represent turbidity measurements from only a single point in the lake and may not be indicative of large-scale events. Satellite imagery can provide excellent spatial coverage, but has only become readily available in recent years and is often severely restricted by cloud cover. For these reasons, we chose to develop a surrogate measure of large-scale turbidity that is based on a 45-year climatology of wind waves in the lake. Since resuspension in Lake Michigan is primarily wave driven, we believe this approach will provide a more representative estimate of the frequency, intensity, and duration of sediment resuspension events than either water intake measurements or satellite imagery.

We first examine the turbidity records from two water treatment plants (Chicago, IL and St. Joseph, MI) for which long-term records are available. We then develop a one-dimensional sediment resuspension and deposition model for fine-grained sediments and apply it to the 45-year wave climatology period. The model is calibrated with data from the water treatment plants. The one-dimensional model is applied at 15 points around the southern basin and the results are averaged to obtain a basin-wide turbidity index. The index is compared to estimates of basin-wide turbidity derived from calibrated satellite imagery. A frequency distribution of the turbidity index is presented and meteorological conditions associated with the largest events are examined.

Water Treatment Plant Data

Daily averaged turbidity measurements from municipal water treatment plants in Chicago, IL and St. Joseph, MI (Fig. 1) were obtained from plant operators. Turbidity at both plants was measured using a Hach Nephelometric Turbidimeter which is calibrated daily against formazin standards (Method 2130B; American Public Health Association, 1998). The Chicago water intake crib is in 10 m of water and the St. Joseph crib in 7 m. Records were obtained for the period 1 Jan. 1971–31 Dec. 2000 for Chicago and 1 Jan. 1961–31 Dec. 2000 for St. Joseph. The readings were provided in Nephelometric Turbidity Units (NTU) and were taken at 3-hour intervals. Because turbidity units are not generally used in studies of suspended sediment, we converted the turbidity readings in NTU to an estimate of suspended sediment concentration in mg/L using a conversion factor of 1 mg/L = 0.88 NTU[1]. We will continue to use the term "turbidity" in this paper to distinguish the water intake data from other measurements of sediment concentration.

The upper panels of Figure 2 show all of the average daily turbidity readings for the 30-year record at the Chicago plant (left panel) and the 40-year record at the St. Joseph plant (right panel) as well as the median reading for each day of the year (solid line). The lower panels show the average exceedance frequency of turbidity levels at the two locations. At Chicago, peak median daily values of 4–5 mg/L occur in March and are accompanied by the largest variability. Mid-summer median turbidities are 1–2 mg/L. A second peak in turbidity occurs in December, with peak median daily values of 3–4 mg/L. On average, there are about 4 days per year when the daily turbidity exceeds 25 mg/L. At the St. Joseph plant, median values peak at 10–12 mg/L in March and April as well as December. Median summer values are 2–3 mg/L. At St. Joseph, there are about 12 days per year with average turbidities greater than 25 mg/L. Differences in turbidity levels between Chicago and St. Joseph most

[1] This conversion is based on a long history of transmissometer calibration measurements in the Great Lakes presented by Hawley and Zyren (1990) and a comparison of simultaneous transmissometer and water intake turbidity measurements by Lee and Hawley (1998). Hawley and Zyren (1990) developed a linear relation between the beam attenuation coefficient (BAC) from the transmissometer measurements and suspended sediment concentration, C (in mg/L) as BAC = 0.5 + 0.53 C. Lee and Hawley estimated the relation between BAC and water intake turbidity (W) as BAC = 0.5 + 0.466 W. Combining these calibrations yields C = 0.88 W.

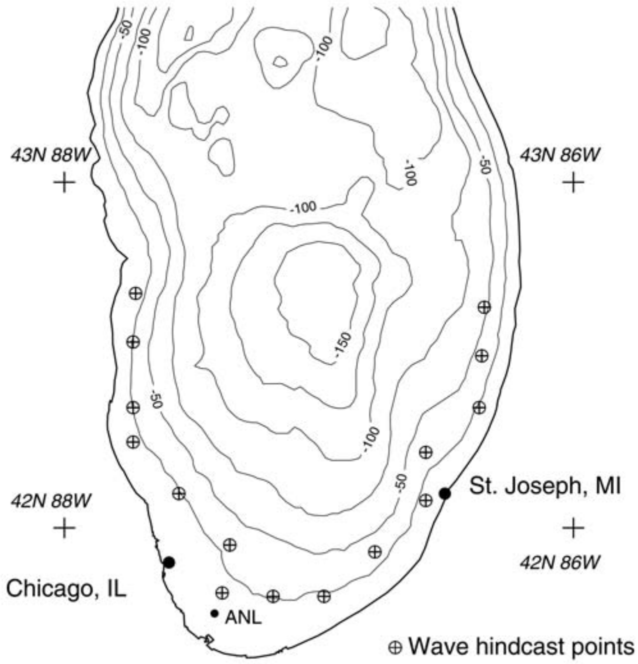

FIG. 1. Location map showing Chicago, IL and St. Joseph, MI water treatment plant intakes and 15 wave hindcast points from U.S. Army Corps of Engineers Wave Information Study. Depth contours are in meters.

likely are due to the locations of the intakes and differences in local sediment characteristics. The St. Joseph intake is located in shallower water and exhibits consistently higher turbidity levels than Chicago. In general, the sediments near the Chicago intake have larger grain size (Cahill 1981, Eadie and Lozano 1999), thus requiring more energy for resuspension.

From 1979–80, Lesht (1989) measured the frequency of sediment transport events at a 10-m-deep station southeast of the Chicago water intake (ANL in Fig. 1). A moored near-bottom camera was used and events were characterized as periods when ripple marks in the sandy bottom moved or when the bottom was obscured by cloudy water. Few of the more energetic events were observed in two summer deployments. However in a longer fall deployment (1 Oct.–10 Nov. 1980) cloudy water was recorded about 23% of the time. Lesht was able to simulate the measurements using a model driven by wave orbital velocity. During periods of video measurements, the largest signals observed by the Chicago intake were from 3–6 Oct. 1980 with an average of 2.5 mg/L and a maximum of 3.3.

Southern Lake Michigan Turbidity Index (SLMTI)

Turbidity in southern Lake Michigan has been modeled previously with relatively sophisticated numerical sediment dynamics models (Lou *et al.* 2000, Schwab *et al.* 2000). The complexity of these models restricts their application to individual cases of limited duration (days to weeks). A simpler approach was used by Lesht and Hawley (1987) to explain 4 weeks of continuous observations of total suspended material in 28 m of water in southern Lake Michigan. They included the effects of mean currents and waves in a one-dimensional sediment reuspension and deposition model and were able to reproduce many of the principal features of the observed suspended sediment concentration record. As reported by Lesht (1989), wave orbital velocity plays a dominant role in episodic sediment resuspension in studies of southern Lake Michigan. Because wave-induced resuspension is dominant, we felt that it would be possible to analyze the climatology of resuspension events by using information about the climatology of waves in the lake.

In order to develop a more representative measure of average turbidity in the southern basin of Lake Michigan than either the Chicago or St. Joseph water treatment plant records could provide, we obtained the results of a 42-year (1956–1997) hindcast of wave conditions on Lake Michigan carried out by the U.S. Army Corps of Engineers (Great Lakes Wave Information Study, WIS—Hubertz *et al.* 1991). A numerical wave prediction model was used in conjunction with wind observations from standard National Weather Service surface observation stations around to estimate wave conditions at 70 points in the lake. We obtained 3-hourly time series of wave height and period at the 15 points in southern Lake Michigan shown in Figure 1 to serve as a basis for developing an index of basin wide turbidity conditions. We also supplemented the 42-year Corps of Engineers hindcast with 3 more years (1998–2000) of wave model calculations which were carried out as part of the EEGLE program (Eadie *et al.* 2002). These hindcasts used a denser network of meteorological observations than the Corps of Engineers WIS, but otherwise were comparable.

The 45-year records of wave data from the 15 points were used as input to a simple one-dimensional mass conservation model of sediment resuspension and deposition

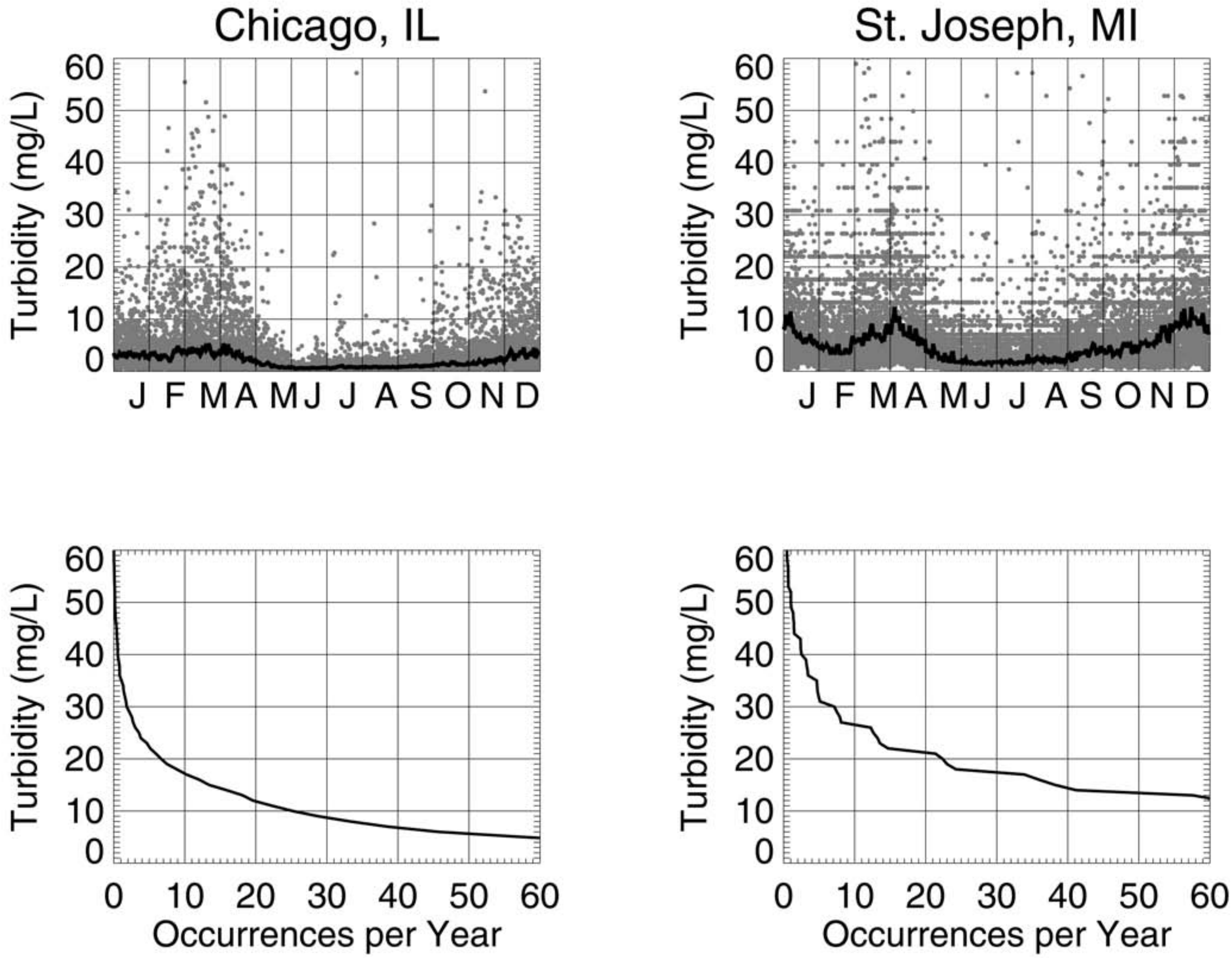

FIG. 2. Daily turbidity readings (grey circles) at the Chicago, IL (left, years 1971–2000) and St. Joseph, MI (right, years 1961–2000) water treatment plants along with the daily median value (solid line). Lower panels show the average exceedance frequency of turbidity levels.

$$h\frac{dC}{dt} = S(t) \qquad (1)$$

where h is water depth, C is the vertically averaged suspended sediment concentration, t is time, and *S(t)* represents the time dependent sources and sinks of sedimentary material from and to the bottom. We chose to use the vertically integrated concentration in the resuspension model because empirical evidence obtained during the EEGLE experiment generally shows very uniform vertical distributions of turbidity during the several days following significant resuspension events. Incorporating vertical variation of concentration in the model would not yield significantly different results. Various forms of the source term *S(t)* for resuspension and settling have been reported in the literature. Blom and Aalderink (1998) compared three of the most popular forms and found all were able to provide a reasonable simulation of laboratory and in situ data with an appropriate choice of adjustable coefficients. In this paper we use a combination of formulations suggested by Partheniades (1965) and Lick (1982). In our model, the source term is specified as:

$$S(t) = \begin{cases} -w_s C & \text{for } \tau < \tau_c \\ \varepsilon\left(\dfrac{\tau}{\tau_c} - 1\right) - w_s C\left(\dfrac{\tau}{\tau_c} - 1\right)^n & \text{for } \tau \geq \tau_c \end{cases} \qquad (2)$$

where w_s is a characteristic settling velocity, ε is an adjustable resuspension parameter, τ is bottom shear stress, τ_c is the critical shear stress, and n is between 0 and 1. This model assumes that the source term for sediment resuspension is proportional to the amount of wave-induced bottom shear stress in excess of a specified critical shear stress (Partheniades 1965). When the bottom stress is less than the critical shear stress, deposition occurs at a rate proportional to a specified settling velocity times the ambient water column concentration (Lick 1982). It also assumes that deposition occurs simultaneously with resuspension at a rate proportional to water column concentration times a fixed power of excess shear stress between 0 and 1. If a settling term is not included during resuspension, the water column concentration will increase indefinitely in the case of a continuously applied excess shear stress and an unlimited source of bottom material. Some models of resuspension limit the water column concentration for this case by increasing the critical shear stress with erosion depth, but they must ultimately rely on an empirical description of sediment erosion potential with depth. If n = 0, the equilibrium concentration for a constant excess shear stress increases linearly with excess shear stress. If n = 1, the equilibrium concentration is independent of excess shear stress. Since we do not have data for any long periods of constant excess shear stress in Lake Michigan and we felt that neither of these extremes was entirely realistic, we chose n = 0.6 as a reasonable intermediate value. We found that model results were very similar for values of n between 0.5 and 0.75. Bottom shear stress is calculated from linear wave theory as

$$\tau = \frac{\rho v^{1/2} H (2\pi / T)^{3/2}}{2 \sinh kh} \tag{3}$$

where H is significant waveheight, T is peak energy wave period, k is wavenumber, ρ is water density, and ν is viscosity. We used constant values for density (1 g/cm^3) and viscosity (1cp). Variation of viscosity with water temperature could change τ by as much as 20% from summer to winter (higher in winter), but we did not include this effect in our model.

During many winters, Lake Michigan experiences significant ice cover. To account for the effect of the ice cover on resuspension, we obtained data on ice cover percentage at the Chicago and St. Joseph water intakes as well as each of the 15 WIS stations. The ice cover percentage was derived from daily digital ice maps compiled (Assel and Norton 2001) for the ice years 1973–2000. For years prior to 1973, the cumulative freezing degree-day history for Milwaukee for that year was compared to the cumulative freezing degree-day history for each year from 1973–2000. We then used the daily percentage ice cover data from the closest matching year as a substitute for that year. As a test of this procedure, we selected several years from the post-1973 group and determined the closest matching cumulative freezing degree day year from the same group. The percent ice cover for the paired years was generally found to be quite similar, so we feel confident that the matching procedure for the years before 1973 provides a reasonable estimation of ice cover. To incorporate ice cover into the sediment resuspension model described above, we reduced the WIS wave height in the model at each station by the percentage ice cover for that day before calculating bottom shear stress. We have no specific data to validate our assumption that wave height decreases linearly with percentage ice cover, but the main impact of any formulation for ice cover should be that waves are eliminated under total ice cover and waves are not affected with no ice cover. Our simple formulation attains this result.

The remaining adjustable parameters in the model are the resuspension parameter, ε, the settling velocity, w_s, the critical shear stress, τ_c, and the settling exponent, n. In order to test and calibrate the turbidity index model, we estimated a representative settling velocity for the fine-grained sediments in Lake Michigan using the water treatment plant records from Chicago and St. Joseph. We first calculated the ratio (C/C_0) between consecutive daily readings for cases when the readings were decreasing. We assume this condition generally occurs when $\tau < \tau_c$ so that (from equations 1 and 2)

$$\frac{dC}{dt} = -\frac{w_s}{h} C \tag{4}$$

The solution to (4) is

$$\frac{C}{C_0} = e^{-w_s t / h} \tag{5}$$

Solving for w_s yields

$$w_s = -\frac{h}{t} \ln\left(\frac{C}{C_0}\right) \tag{6}$$

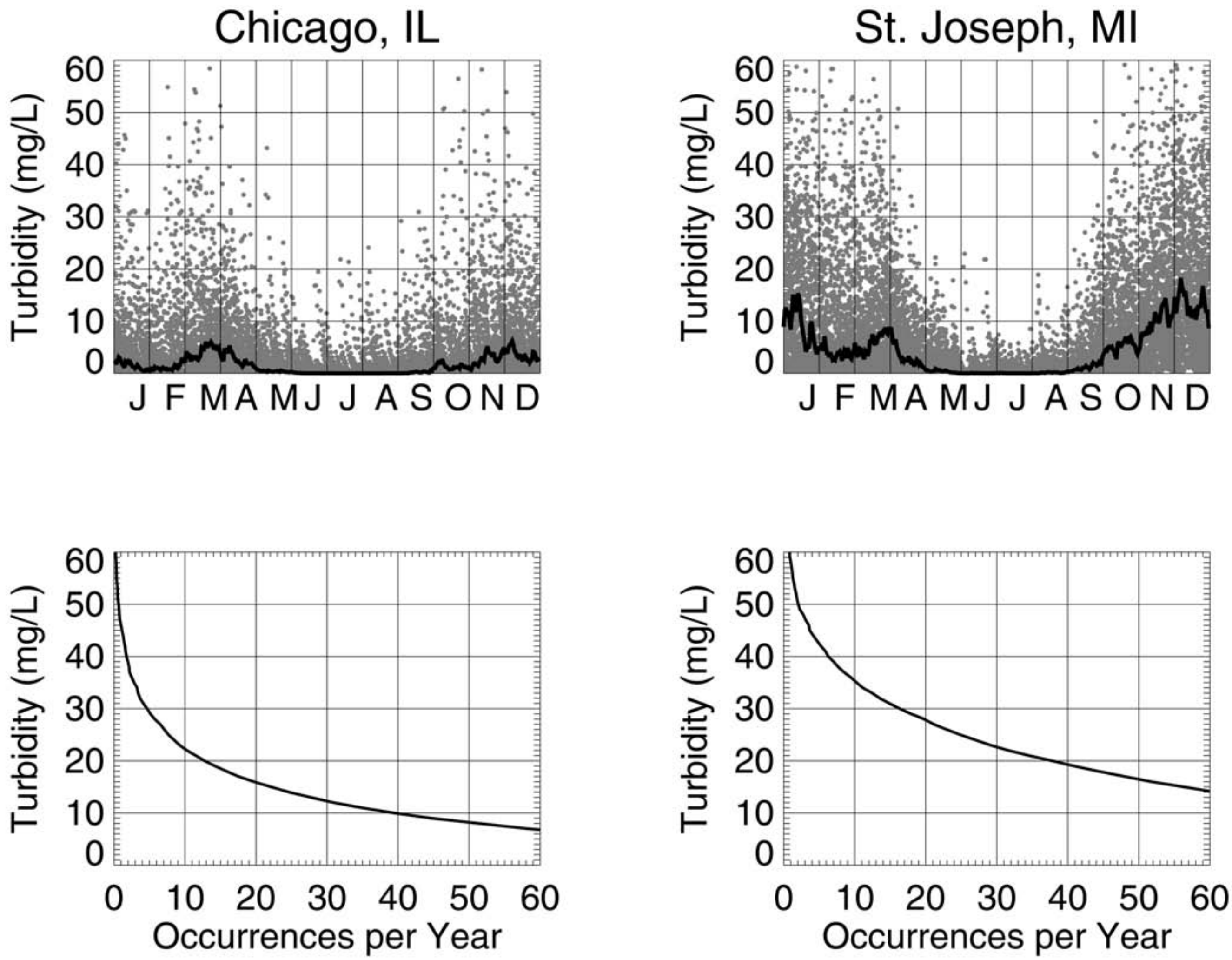

FIG. 3. Average modeled daily turbidity at Chicago, IL (left) and St. Joseph, MI (right) water treatment plants along with the daily median value (solid line). Lower panels show the average exceedance frequency of turbidity levels.

We plotted histograms of w_s calculated this way (with t = 24 hr) and found clear peaks at $w_s = 3.0 \times 10^{-5}$ m/s for Chicago and $w_s = 2.4 \times 10^{-5}$ m/s for St. Joseph. These values were then used in the model to find optimal values of the resuspension parameter, ε, and the critical shear stress, τ_c. The criteria used to optimize these choices were 1) maximize the correlation between calculated and observed daily turbidity values, 2) minimize the root mean square error and mean difference between calculated and observed turbidity values, and 3) produce a frequency distribution of calculated turbidity that closely resembles the frequency distribution of observed values. We found that not all of these conditions can be obtained simultaneously, so we experimentally adjusted the parameters to obtain a reasonable compromise. The resulting parameter values were $\varepsilon = 2.0 \times 10^{-6}$ kg/m^{2}sec and $\tau_c = 0.4$ N/m^2 for Chicago and $\varepsilon = 1.5 \times 10^{-6}$ kg/m^{2}sec and $\tau_c = 0.65$ N/m^2 for St. Joseph. These parameters resulted in correlation coefficients of 0.55 and 0.40 for Chicago and St. Joseph respectively. The root mean square differences were 4.2 and 7.7 mg/L and mean differences were 0.5 and 1.5 mg/L.

The frequency distributions of model results for Chicago and St. Joseph are shown in Figure 3. The Chicago results are very similar to the observed frequency distribution for the Chicago water treatment plant in Figure 2. The St. Joseph results are also similar to the observed distribution at the St. Joseph

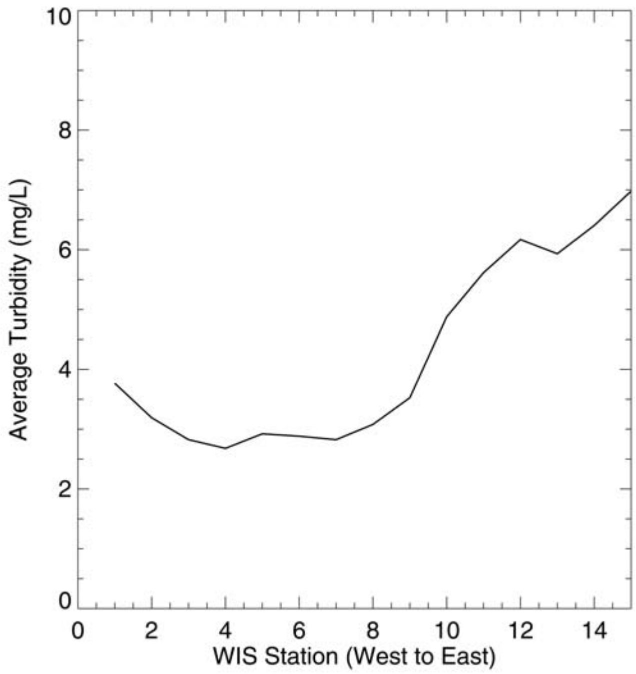

FIG. 4. Average modeled turbidity at each of 15 WIS stations shown in Figure 1. Station 1 is the northernmost station on the western shore and station 15 is the northernmost station on the eastern shore.

plant in Figure 2, particularly in the winter. There is a somewhat lower peak in the springtime model results than in the observed values and the observations show a higher background level of turbidity throughout the summer than the model results.

Since the calibration parameters for Chicago and St. Joseph were somewhat different, we arbitrarily chose to use the parameters from the Chicago calibration ($w_s = 3.0 \times 10^{-5}$ m/s, $\varepsilon = 2.0 \times 10^{-6}$ kg/m^{2}sec, and $\tau_c = 0.4$ N/m^2) for the 15 station turbidity index calculation. Similar results could have been obtained using the parameters from the St. Joseph calibration. Using the Chicago parameters, we ran the model for 45 years for each of the 15 WIS points resulting in 15 time series of turbidity values. As an indication of the spatial variability of resuspension in southern Lake Michigan, the average value of modeled turbidity at each of the 15 WIS locations is shown in Figure 4. The average turbidity is a maximum at the northernmost WIS point along the eastern shore. It drops to a minimum in the Chicago area and increases again going northward along the western shore. This pattern is a reflection of the wave climate created by the combined effects of the shape of the lake and the directional distribution of the prevailing winds. The Southern Lake Michigan Turbidity Index (SLMTI) is calculated as the average value of suspended sediment concentration at the 15 points. The results are shown in Figure 5 as daily average values of the SLMTI. The episodic nature of resuspension is evident as is the increased likelihood of events in winter and spring. There also appears to be a marked increase in the frequency of events after the mid 1980s. In the 45-year period of record, the SLMTI exceeded a value of 25 mg/L on 113 days. These days were aggregated into 43 episodes of consecutive days for the purpose of examining the meteorological conditions associated with each episode. The 43 episodes are indicated by triangles in Figure 5 and listed chronologically in Table 1. The frequency distributions of SLMTI are shown in Figure 6. The distributions are similar to the Chicago and St. Joseph water treatment plant records with distinct peaks in the annual distribution in March and December and a similar frequency of occurrence curve.

The purpose of the SLMTI is to provide an indication of large-scale resuspension events in southern Lake Michigan. In order to test its ability to indicate such events, we examined remote sensing reflectance data from the SeaWIFS satellite from March and April of 1998, 1999, and 2000. High-resolution images from the 555 nm reflectance band were processed for geolocation, atmospheric correction, and cloud masking and then converted to estimates of water column sediment concentration using the calibration curve developed by Lesht (personal communication). The spatially averaged water column concentrations from 50 different images with less than 20% cloud cover in Lake Michigan's southern basin were compared to the SLMTI for that day. The results are plotted in Figure 7. The satellite-derived average concentration values range from a minimum background level of about 1 mg/L to a maximum of about 4 mg/L. The SLMTI values are much higher because they were computed for 10 m water depth where turbidity values are generally much greater than the basin-wide average, particularly during a turbidity event. The overall agreement between basin wide average concentration derived from satellite imagery and SLMTI is excellent with correlation coefficient of 0.84.

Relation to Weather Conditions

A sea level pressure analysis was generated from the National Centers for Environmental Prediction

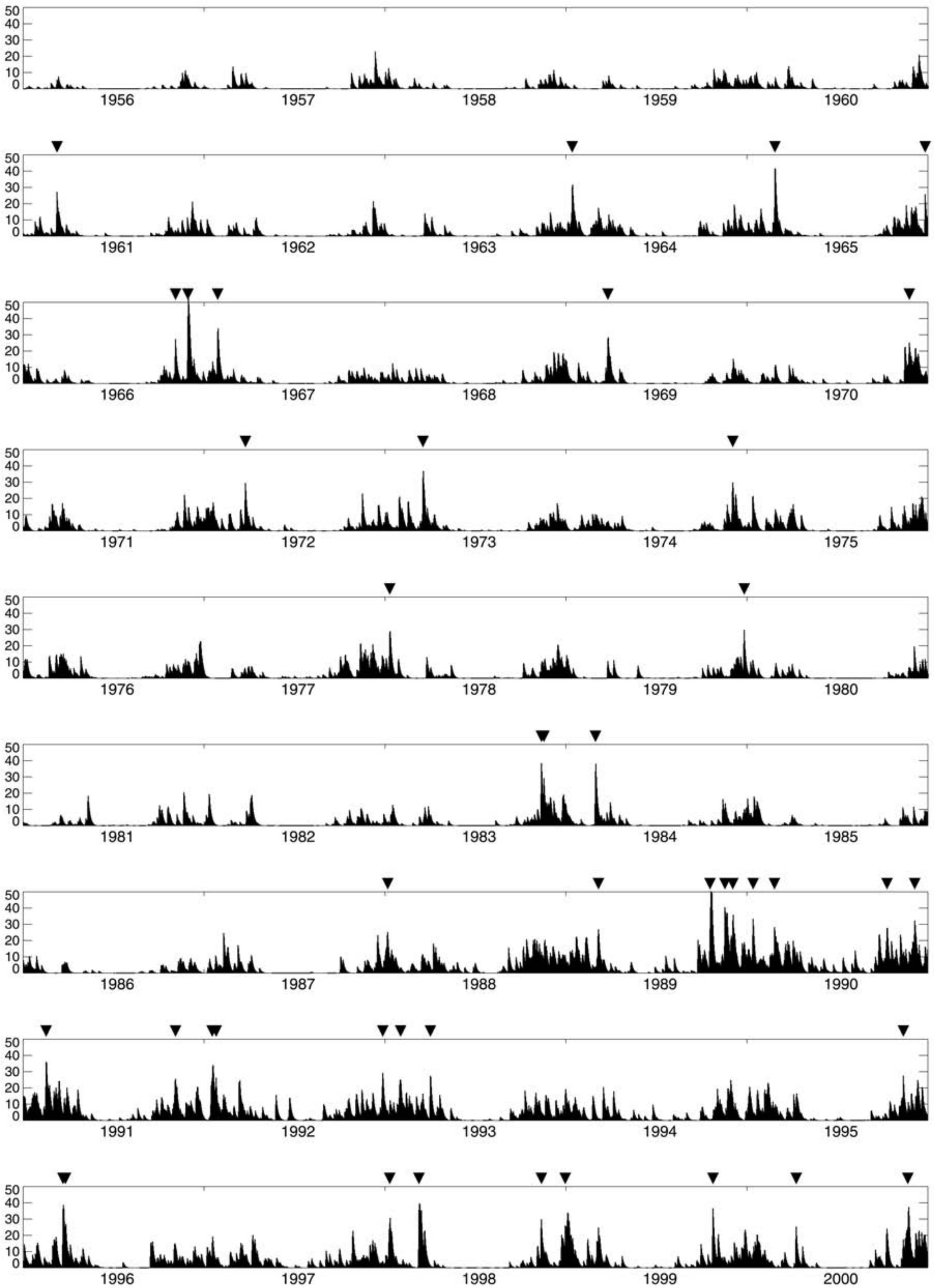

FIG. 5. Southern Lake Michigan Turbidity Index (SLMTI) for 1956–2000. Triangles indicate episodes with SLMTI > 25.

TABLE 1. Chronological list of high turbidity events in southern Lake Michigan for the years 1956–2000. A high turbidity event is defined as one or more days when the Southern Lake Michigan Turbidity Index (SLMTI) exceeds 25 mg/L.

Year	Month	Day	SLMTI	Duration	Direction
1961	3	10	27.3	1	E
1964	1	13	29.0	3	S
1965	2	26	35.3	4	E
1965	12	26	25.9	1	E
1966	11	4	27.4	1	E
1966	11	29	41.8	6	E
1967	1	28	31.0	3	E
1969	3	26	28.0	2	E
1970	11	24	25.2	1	N
1972	3	24	29.5	1	E
1973	3	18	31.1	4	E
1974	12	3	28.1	2	S
1978	1	10	28.6	2	E
1979	12	26	29.8	1	N
1983	11	12	32.5	3	E
1983	11	17	29.3	1	E
1984	2	29	33.9	3	E
1988	1	6	25.3	1	N
1989	3	7	26.9	1	S
1989	10	18	40.8	7	S
1989	11	17	35.2	7	E
1989	12	3	32.1	3	N
1990	1	13	31.3	2	N
1990	2	25	27.3	2	E
1990	10	10	27.7	2	S
1990	12	5	31.0	2	S
1991	2	16	33.3	3	E
1991	11	4	25.6	1	N
1992	1	17	30.7	4	E
1992	1	25	26.3	1	E
1992	12	26	27.5	2	N
1993	2	1	25.2	1	N
1993	4	2	27.0	2	S
1995	11	12	27.6	1	E
1996	3	21	35.0	4	E
1996	3	26	26.1	2	N
1998	1	10	29.1	2	S
1998	3	10	35.3	7	E
1998	11	12	29.9	1	W
1998	12	30	28.5	9	E
1999	10	24	34.0	2	E
2000	4	9	25.4	1	E
2000	11	20	32.3	4	E

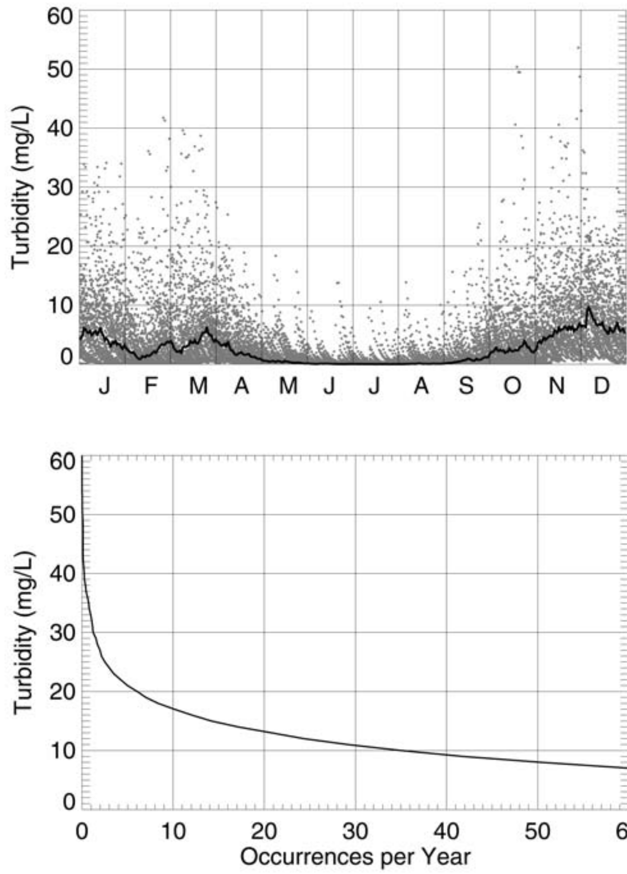

FIG. 6. Daily SLMTI (Southern Lake Michigan Turbidity Index) (upper panel, gray circles) and median daily values (upper panel, thick line) as well as the average exceedence frequency of turbidity levels (lower panel) for the years 1956–2000.

(NCEP) reanalysis dataset Kalnay (1996) for each of the 43 large turbidity events in southern Lake Michigan listed in Table 1. Since each high turbidity event was associated with the passage of a cyclone through the region, each map was subjectively classified according to the position of the cyclone relative to Lake Michigan. This decision led to four classes: cyclone east (strong west-east pressure gradient and northerly geostrophic wind, Fig. 8a; 25 cases); cyclone south (strong north-south pressure gradient and easterly geostrophic wind, Fig. 8b; 8 cases); cyclone north (strong south-north pressure gradient and westerly geostrophic wind, Fig. 8c; 9 cases); cyclone west (strong east-west pressure gradient and southerly geostrophic wind, Fig. 8d; 1 case). The class assigned to each episode is listed in Table 1.

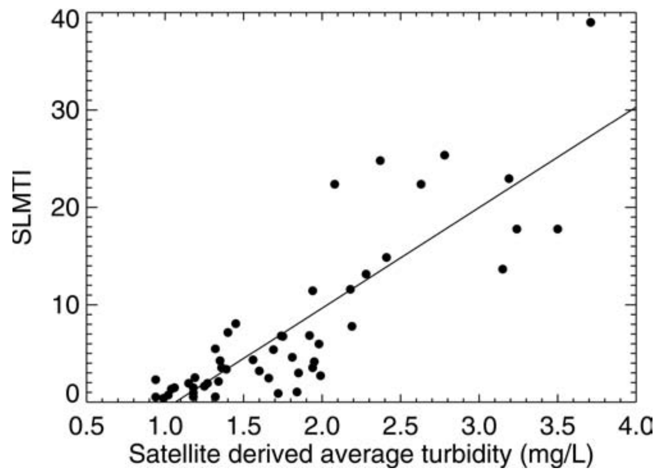

FIG. 7. Comparison of SLMTI to average turbidity in southern Lake Michigan calculated from satellite imagery. Correlation coefficient is 0.84.

An important question is whether it is possible to recognize a likely resuspension event based only on the meteorology. This requires a search for meteorologically similar cases (hereafter, analogs) to the events listed in Table 1. Daily sea-level pressure maps in the region 30–60°N, 110–70°W for each of the 43 events of Table 1 were compared to maps from all dates in the period 1956–2002 to find other periods with similar meteorological conditions. Note that the maps are snapshots of atmospheric pressure at 00Z so that there may be some uncertainty associated fast moving low pressure systems. For 14 of the 43 events of Table 1, at least one analog could be found in the period 1956–2002. Of these 14 events, two had at least one analog that produced an event with SLMTI greater than 25, while 10 had at least one analog that produced elevated SLMTI (greater than or equal to 10).

It is important to recognize, however, that many analogs did not produce elevated SLMTI. Clearly, large events are sensitive to the details of the cyclone structure pertaining to the pressure gradient force and consequently, the winds. From a forecast perspective, this is an important point, since such details can be volatile even at short forecast ranges (0–48 hours). To quantify this effect, for all analogs, sea-level pressure deviations from the event in question were composited. These composites were stratified according to two classes: those analogs with elevated SLMTI and those analogs without elevated SLMTI. The elevated SLMTI analogs exhibit an increase in the west-to-east oriented pressure gradient force across southern Lake Michigan of 8.7 hPa per 500 km, representing an additional 14.7 m s^{-1} of geostrophic northerlies in those cases. This indicates that the meteorological conditions necessary to trigger a large resuspension event have to include a sufficiently strong west-to-east geostrophic pressure gradient in addition to the general cyclone pattern.

DISCUSSION AND CONCLUSIONS

From an examination of water intake turbidity records we found that differences in readings between the stations and the limited number of locations available around southern Lake Michigan restricted the usefulness of these records for a basin wide climatology of large turbidity events. The numerical sediment resuspension model based on the WIS wave climatology appears to provide a more robust basis for this purpose. Model parameters could be adjusted so that model results were statistically similar to water intake turbidity records at Chicago and St. Joseph. The main model parameters (settling velocity, resuspension potential, and critical shear stress) were consistent with previous laboratory and field-based estimates for fine-grained sediments (Miller *et al.* 1977, Eadie *et al.* 1989, Lou *et al.* 2000). Model-derived estimates of basin-wide turbidity also agreed quite well with satellite-derived estimates.

The observations (Lesht 1989) of sediment transport under relatively low energy conditions (the maximum SLMTI Index for the nearest wave hindcast point was 3.6) are consistent with the concept that sediment transport occurs across a wide spectrum of scales. In this analysis, we are interested in the upper end of the energy scale, events that appear to have lake-scale sediment transport implications. Figure 9 summarizes the climatology of resuspension events in southern Lake Michigan. It shows a monthly histogram of SLMTI over the 45-year study period for exceedance values of 10 and 25 mg/L. High turbidity events are much more likely to occur between October and April than during the rest of the year. There is a slightly lower probability of a turbidity event in February than in January or March. This may be due to the increased probability of more extensive ice cover in February. December had the highest number of days with SLMTI exceeding 10 mg/L, but the days for which SLMTI exceeded 25 mg/L were more uniformly

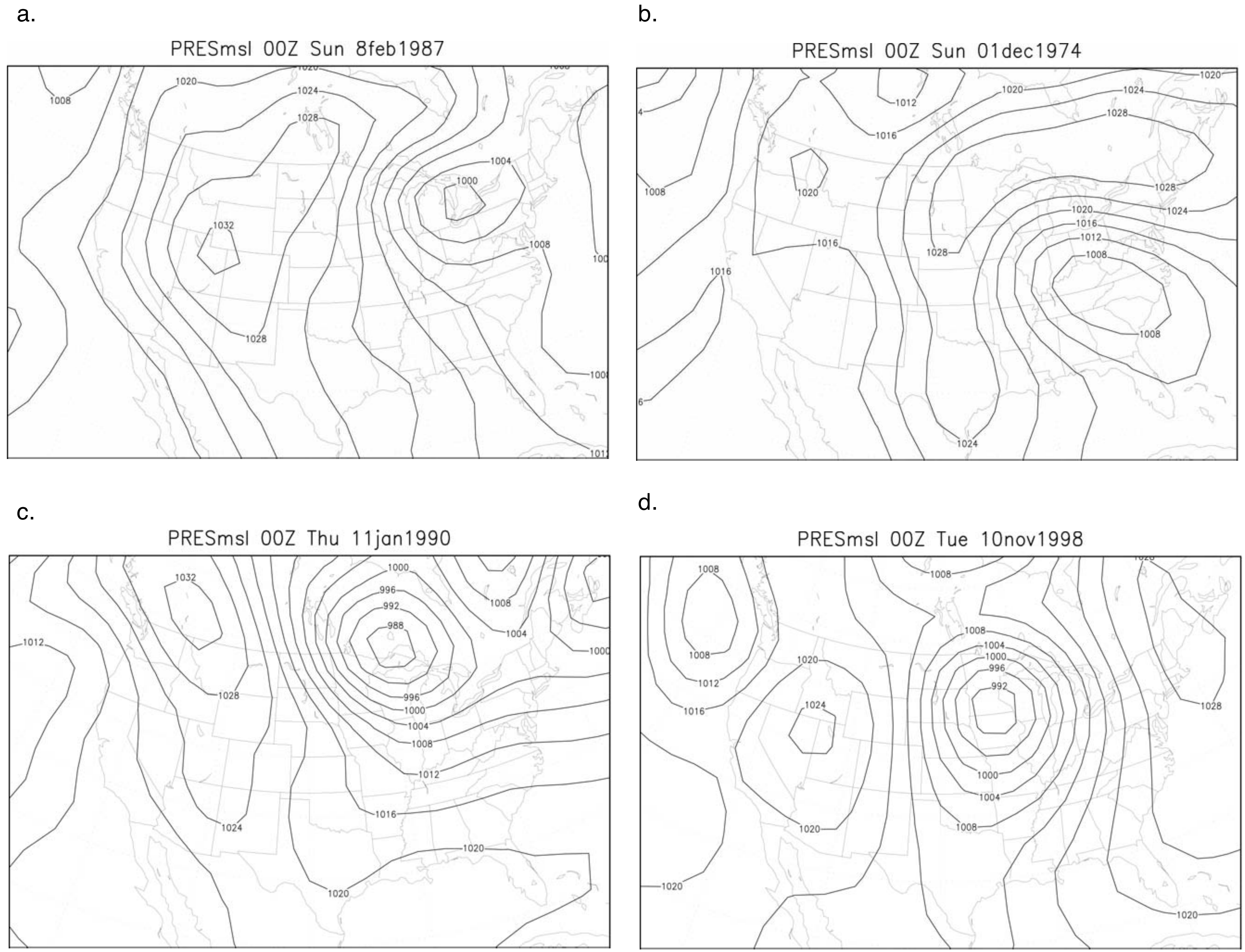

FIG. 8. Representative sea level pressure maps for high turbidity events where a cyclone passes (a) east, (b) south, (c) north, and (d) west of Lake Michigan.

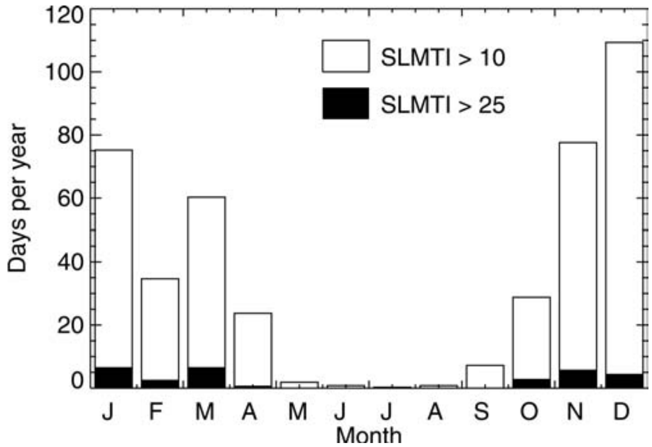

FIG. 9. Monthly histogram of Southern Lake Michigan Turbidity Index (SLMTI) for exceedance values of 10 and 25 mg/L for the years 1956–2000.

distributed between January, March, November, and December.

It is apparent from Figure 5 and Table 1 that the frequency of occurrence of high turbidity events showed a marked increase in the late 1980s. The most obvious cause for the increase would be an increase in wave energy. Figure 10 shows the average annual wave height from the 15 WIS stations and the average annual SLMTI both with and without the reduction of wave height due to ice cover. In order to separate the data into winter seasons (ice years), the averaging period is from July of the previous year to June of the current year. From Figure 10 it is clear that the increase in the turbidity index is correlated with an increase in average wave height (correlation coefficient 0.92 with ice, 0.88 without) which is not unexpected since wave height and ice cover are both used in the forcing function for the model from which SLMTI is derived. The third panel in Figure 10 shows the total number of storms that were either associated with a large turbidity event or identified as an analog. The total number of storms also exhibits a noticeable increase in the late 1980s. The lower panel in Figure 10 provides an indication of the mildness or severity of the winter season by plotting the average amount of open water (100 minus average ice cover) for each winter season. It is clear from Figure 10 that the increase in wave energy and SLMTI in the late 1980s occurs at the same time as an increase in the number of storms and a decrease in ice cover. The correlation between the number of storms and the percent open water is 0.32. It appears that winters with a higher number of storms and the lowest ice cover are associated with higher waves, whether ice cover is included in the calculations or not.

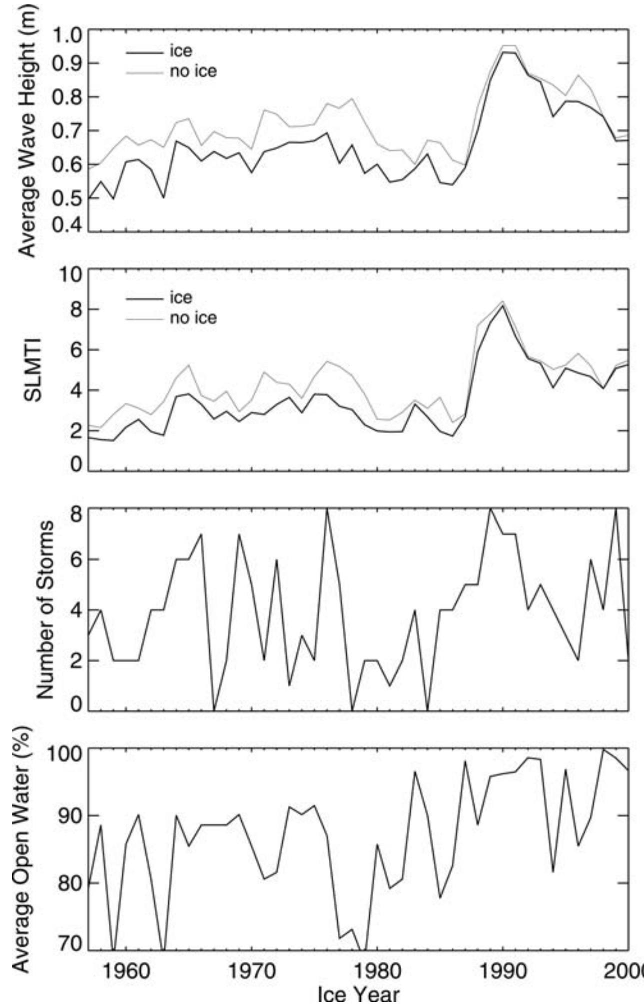

FIG. 10. Annual average (July-June) WIS wave height (top panel), SLMTI (center panel), and amount of open water (lower panel) for ice years 1957–2000. (Ice year starts in December of the previous year.)

In summary, our analysis indicates that large resuspension events in southern Lake Michigan are usually caused by a strong cyclone passing to the east of the lake. The most likely time of the year for this to occur is October to April. On average, there is one event per year with SLMTI above 25 mg/L and turbidity levels remain above 25 mg/L for about 3 days during each event. There is also some indication that events have occurred more frequently since the late 1980s as the number of winter storms has increased and there has been less ice cover.

ACKNOWLEDGMENTS

The authors wish to thank the operators of the Chicago and St. Joseph water treatment plants for providing intake turbidity records. Thanks also to Nathan Hawley for helpful discussions about critical shear and other boundary layer concerns and to two anonymous reviewers for helpful comments. This is GLERL contribution number 1378.

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Submitted: 22 June 2004
Accepted: 1 November 2005
Editorial handling: Barry M. Lesht