Circulation during winter and northerly storm events in southern Lake Michigan

Y. R. Rao
National Water Research Institute, Burlington, Ontario, Canada

M. J. McCormick
Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan, USA

C. R. Murthy
National Water Research Institute, Burlington, Ontario, Canada

Received 9 May 2003; revised 3 September 2003; accepted 27 October 2003; published 6 January 2004.

[1] Moored observations of winds, currents, and temperature made off the southeastern Lake Michigan shore during 1998 to 2000 winter-spring periods are studied to describe the mean winter circulation and episodic circulation during northerly storms in Lake Michigan. Late winter-spring sediment plumes in southeastern Lake Michigan were attributed to these episodic circulation features. The winter-spring currents in southeastern Lake Michigan are quite depth independent, and the mean currents flow predominantly alongshore and toward the north. The observed currents show the signature of a forced two-gyre circulation in the southeastern basin. The interannual variability of mean and fluctuating currents is mainly due to the variability of prevailing wind-forcing. The intermittent episodic circulation influenced by northerly storms causes significant asymmetry to the mean circulation. During northerly storm episodes, the mean current speeds increased significantly, and the currents within 10 km of shore followed the surface wind stress, while farther offshore the circulation was oppositely directed. During these episodes it is also observed that the combination of directly wind-forced currents and northward propagating vorticity wave generates significant offshore transport in this region. *INDEX TERMS:* 4512 Oceanography: Physical: Currents; 4558 Oceanography: Physical: Sediment transport; 4223 Oceanography: General: Descriptive and regional oceanography; 1845 Hydrology: Limnology; *KEYWORDS:* Lake Michigan, circulation, episodic events

Citation: Rao, Y. R., M. J. McCormick, and C. R. Murthy (2004), Circulation during winter and northerly storm events in southern Lake Michigan, *J. Geophys. Res.*, *109*, C01010, doi:10.1029/2003JC001955.

1. Introduction

[2] In the Great Lakes, the gradients of many biogeochemically important materials (BIMs) are considerably higher in the offshore direction than in the longshore direction [*Brink et al.*, 1992]. In the presence of these large gradients, cross-isobath circulation is a primary mechanism for the exchange of material between nearshore and offshore waters. Understanding the frequency, magnitude, and causes of offshore transport is one of the most important goals of several ongoing coastal research programs. Although phenomena like coastal upwelling and topographic steering in both coastal oceans and the Great Lakes have been studied for many years, the recent observations of plume-like offshore transport in southern Lake Michigan have prompted a new set of experiments.

[3] The southern basin of Lake Michigan is subjected to recurrent episodes of sediment resuspension caused by storm-induced waves and currents [*Mortimer*, 1988]. These resuspension events are suggested as the main mechanism for reintroducing nutrients and contaminants stored in sediments into the water column [*Eadie et al.*, 1996]. Satellite imagery from early 1996 captured the initiation, development, and decay of a recurrent coastal plume in southern Lake Michigan. A 10-km-wide plume of resuspended material extending over 100 km along half of southern Lake Michigan coincided with the disappearance of the ice in the southern basin in late March. The plume was initiated by a major storm with strong northerly winds generating large waves in the southern basin. Subsequently, the plume appeared along the entire southern coastline of the lake. It occasionally veered offshore along the eastern shore of the lake, coincidentally near the areas of maximum observed long-term sediment accumulation of the lake. *Eadie et al.* [1996] estimated that the 1996 plume moved over one million tons of material.

[4] In the Great Lakes, both the alongshore and cross-shore current components exhibit strong episodic behavior due to wind-forcing. In order to understand the cross-shore

0148-0227/04/2003JC001955$09.00

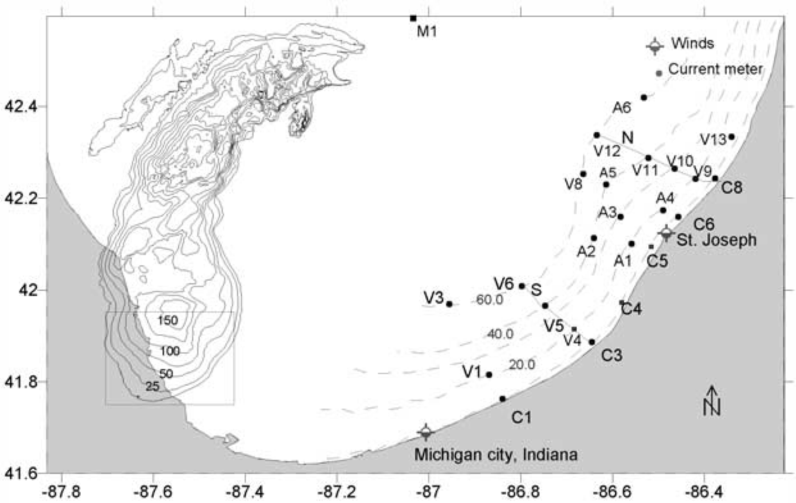

Figure 1. Geometry and bathymetry of southern Lake Michigan showing meteorological stations and current meter stations (A: ADCP; V: VACM, C: SACM).

transport during certain episodic conditions and quantify the physical processes that are responsible for the nearshore-offshore mass exchange, a multidisciplinary research program, Episodic Events Great Lakes Experiment (EEGLE) has been initiated by the National Oceanic and Atmospheric Administration and the National Science Foundation in Lake Michigan. The EEGLE program was designed as an integrated observational and numerical modeling program to quantify and develop prediction tools for winter-spring resuspension events and to assess the impact of such events on lake ecology due to the transport and transformation of BIMs.

[5] Circulation in the lakes is driven primarily by wind, but the effects of the Earth's rotation, basin topography, and vertical density structure are also important. During the unstratified season, the higher wind speeds and the absence of the thermocline allow the effects of wind action to penetrate deeper into the water column [*Boyce et al.*, 1989]. Circulation in Lake Michigan is also highly episodic, with the most energetic currents and waves occurring during storms. In the shallow waters of the southern basin of Lake Michigan, the entire water mass moves in the direction of the wind, while return flow occurs in the deeper parts of the lake with a relatively uniform over-lake wind field. This forms two counter-rotating closed gyres, a cyclonic gyre to the right of the wind, and an anticyclonic gyre to the left [*Saylor et al.*, 1980; *Schwab*, 1983]. The simple two-gyre circulation pattern can be modified to a single gyre cyclonic circulation by lake stratification or vorticity in the wind field [*Beletsky and Schwab*, 2001]. These rotary motions have been suggested as one of the important mechanisms for nearshore-offshore transport in the Great Lakes. *Schwab et al.* [2000] simulated the generation of a two-gyre circulation pattern during the March 1998 northerly wind event in their numerical experiments. Besides the two-gyre circulation, the cross-shore transport could also be due to Ekman veering of currents in the bottom boundary layer [*Saylor and Miller*, 1988], and topographic steering of storm-induced currents due to a bathymetric protrusion along the east coast of southern Lake Michigan.

[6] The purpose of this paper is to provide a description of the spatial and temporal characteristics of coastal circulation in southern Lake Michigan, including net circulation during the winter season and the lake's response to episodic events. An overview of the EEGLE experiment is provided first, followed by a brief description of prevailing wind-forcing, currents, and temperatures during the three EEGLE field years. In the last section, an intercomparison of circulation during three northerly storm episodes is provided.

2. An Overview of the EEGLE

[7] Lake Michigan is one of the Laurentian Great Lakes, and the sixth largest lake in the world. The southern Lake Michigan is characterized by simple bottom topography. The significant feature is a bathymetric protrusion off St. Joseph (Figure 1). Water depth to the south of the instrumented array gradually increases to 60 m over a wider shelf (28 km). To the north of S-line the shelf width (60 m) decreases to about 18 km, and then gradually widens to 25 km to the north of St. Joseph. The EEGLE measurements for obtaining currents, winds, and temperatures consisted of Eulerian measurements for three field years in the region from 1997 to 2000. As part of the field program, current meters were deployed at several cross-sections of the lake. During the 1997–1998 field year a relatively small-scale experiment was conducted with a few vector-averaging current meters (VACM) and acoustic Doppler current profilers (ADCP). No nearshore observations were available during this period. The vertical resolution was achieved by putting one VACM within 10–12 m below the surface and another close to the bottom. Four bottom-mounted ADCPs provided vertical profiles of horizontal currents during this period. Water temperature was observed on VACM current meters and near the ADCP instrument location at the bottom. Winds from routine meteorological stations around the lake were available during this period.

[8] During the fall of 1998, these instruments were recovered and re-deployed at the same locations. For the

Table 1. Description of Current Meters and Meteorological Stations That Returned Good Quality Winter-Spring Data During EEGLE Experiment[a]

Station (Type of Current Meter)	Depth, m (Inst. Depth/Water Depth)	1997–1998 (1 January to 29 April 1998)	1998–1999 (1 January to 29 April 1999)	1999–2000
C1 (SACM)	11/12	not deployed	P	F
C2	11/12	not deployed	no data	no data
C3	11/12	not deployed	no data	F
C4	11/12	not deployed	no data	no data
C5	11/12	not deployed	F	no data
C6	11/12	not deployed	F	F
C8	11/12	not deployed	no data	F
V1 (VACM)	12,19/20	12 and 19(F)	19 (F)	F
V3	12,59/60	12 and 59 (F)	12 and 59 (F)	F
V4	19/20	19 (F)	19 (F)	no data
V5	12,39/40	no data	12 and 39 (F)	F
V6	12,59/60	12 (P), 59 (P)	59 (P)	F
V7	59/60	no data	59 (P)	59 (P)
V8	10,57/58	no data	10 (P)	10 (P)
V9	11,18/19	12 & 19 (F)	18 (F)	F
V10	11,28/29	no data	11,28 (F)	F
V11	11,38/39	no data	11,38 (F)	F
V12	12,59/60	12 & 59 (F)	59 (P)	F
V13	20/21	no data	no data	F
CM1 (VACM/ADCP 300 kHz)	5 depths/154 24-4 m bins	20,55,115,152 (F)	12,22,57,117,154 (F)	F
A1-300 kHz	14-1m-bins/20.5	F	F	F
A2-300 kHz	31-1m-bins/40.3	P	no data	F
A3-600 kHz	24-1m-bins/28.7	no data	F	F
A4-1200 kHz	15-1m-bins/20	P	F	F
A5-300 kHz	32-1m-bins/38	F	F	F
A6-300 kHz	24-2m-bins/60	not deployed	not deployed	F
St. Joseph (wind)	+10 m	F	F	F
Michigan City (wind)	+10 m	no data	F	F

[a]Here the data availability is denoted by F for full coverage and P for partial coverage of time periods.

next field season (1998–1999) the horizontal extent of the array was expanded with six smart acoustic current meter (SACM) moorings in the shallow region. These instruments were obtained from the National Water Research Institute (NWRI). A total of 24 current meter moorings and two shore-based meteorological towers on piers at Michigan City, Indiana, and St. Joseph, Michigan, were deployed during this period. The data return from this year is reasonably good (Table 1). In the last field year (1999–2000), 17 moorings of ADCPs and VACMs were deployed from the 20-m to 60-m-depth contours by the NOAA Great Lakes Environmental Research Laboratory (NOAA-GLERL). As a part of the program, NWRI deployed additional instrumentation consisting of seven SACMs and two ADCPs in shallow waters at a depth of 12 m along with two coastal meteorological stations installed at Michigan City and St. Joseph. During the 2000 winter season, several of these moorings returned high-quality data, and provided extensive coverage of coastal lake region (Table 1 and Figure 1). In addition to moored instruments, the EEGLE physical limnology experiment also obtained currents from Lagrangian drifters [*McCormick et al.*, 2002]. However, in this paper we have used only data obtained from moored instruments due to their extensive spatial and temporal coverage in the EEGLE area.

3. Wind Stress Field

[9] The coastal currents in Lake Michigan are largely determined by the prevailing winds over the lake. Two shore-based stations at St. Joseph and Michigan City provided wind speeds and directions during 1998 to 2000. In addition, routine observations were available from several coastal meteorological stations around the lake in all the

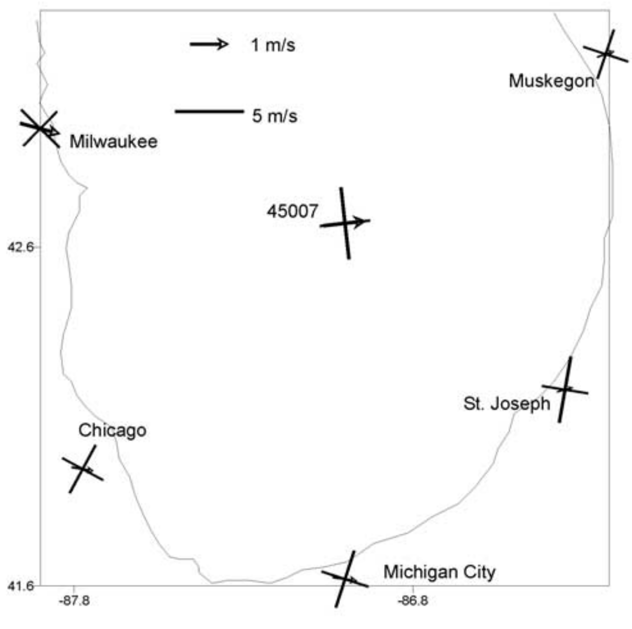

Figure 2. Standard deviations of the wind stress along principal axes and mean vector wind stress during 2000 winter season.

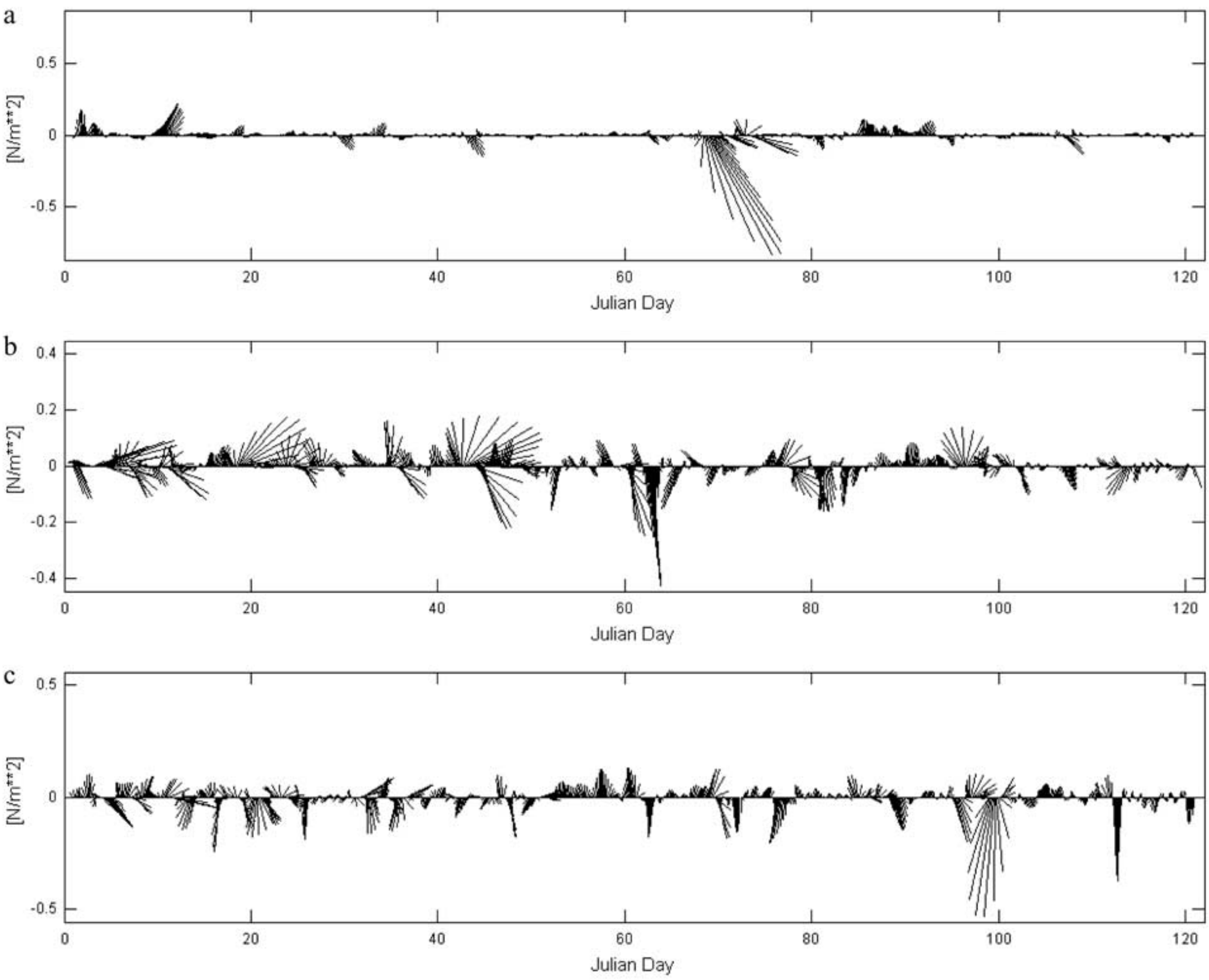

Figure 3. Time series of wind stress estimated from wind measurements at St. Joseph during the winters of three EEGLE field years.

three field years. Wind data from a mid-lake meteorological buoy (45007) were also available during the early spring. The fluctuating wind field is often quite complex over the lake. However, the mean monthly wind speeds and directions at these stations showed a uniform wind-forcing over southern Lake Michigan. For example, Figure 2 shows the time average and principal axes of hourly averaged wind speed and direction from Julian Day (JD) 1 to JD 121 at these coastal stations and the mid-lake buoy. The data from the meteorological buoy are available only from 14 March 2000 (JD 73). The mean wind-forcing is directed generally eastward with a slight cyclonic turning. The orientation of principal axes show more or less non-directed wind fluctuations over the EEGLE area. Along the east coast it appears that the winds are slightly polarized in the alongshore direction. It was also observed from the time series of wind speed and direction that the winds at St. Joseph and Michigan City were highly coherent for the major part of the season. Hence the winds at St. Joseph station have been taken as representative of meteorological forcing due to its proximity to the current meter locations and the relatively straight-line topography of this area. The vector wind stress was obtained from the quadratic law given as $\tau = \rho_a C_d\, |W|\, W$, where ρ_a = 1.2 kg m^{-3} is air density and W is wind velocity. In general, the drag coefficient C_d increases with wind speed and is estimated as $C_d = (0.8 + 0.065\, W) \times 10^{-3}$ for $W > 1$ m/s [*Wu*, 1980].

[10] Time series of wind stress at St. Joseph for the three winter field seasons are depicted in Figure 3 to illustrate the general characteristics and interannual variability of winds over the experimental region. The winds were generally moderate and fluctuated between north and south with a typical period of 3–4 days. During the winter season the mean wind stress is southeastward to southwestward. During 1998 a major northwesterly storm with wind stress reaching a maximum of 0.80 N/m^2 was observed from JD 68 to JD 70, with winds shifting to southerly for a brief period, and then again to weak to moderate northerlies that persisted for a few more days. Although during 1999 several moderate northerly southerly events were observed, the major northerly storm with a wind stress reaching 0.41 N/m^2 occurred from JD 60 to JD 64. During this period, the winds are mainly northerly with a brief reversal on JD 61. During the early part of the 2000 winter season, winds rotated between northerly and southerly with a periodicity of about 3 days. After JD 46, winds were generally oriented

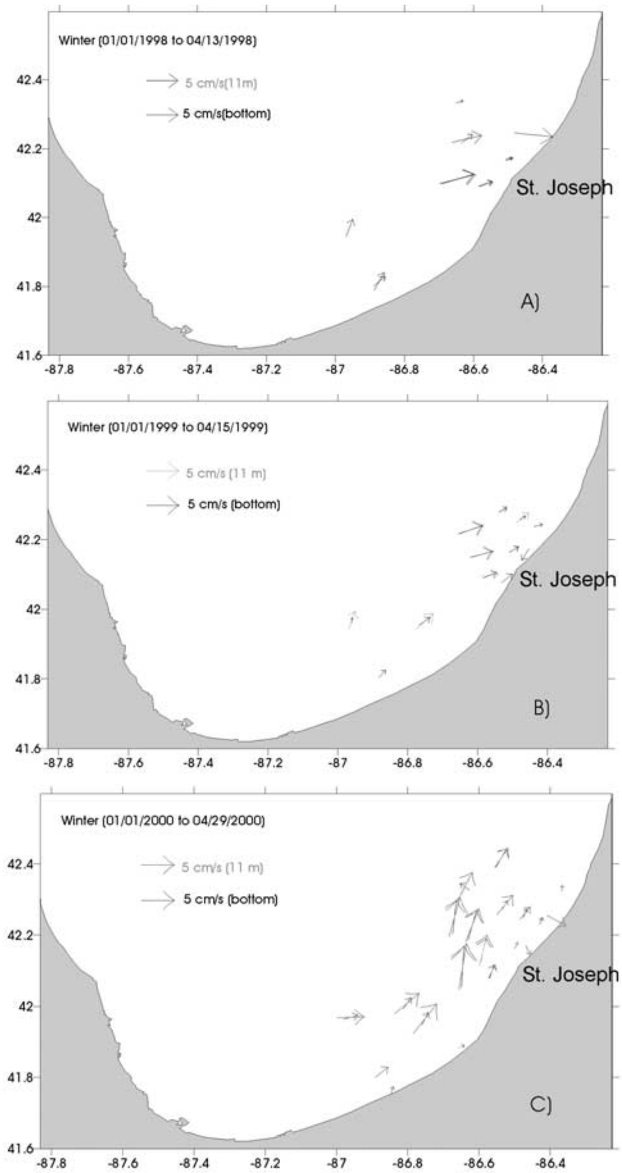

Figure 4. Vector averaged surface and bottom currents observed in southern Lake Michigan during the winters of three EEGLE field years.

toward the north, with several northerly wind events and a strong northerly storm with wind stress exceeding 0.5 N/m^2 from JD 99 to JD 102.

4. Characteristics of Winter Currents

4.1. Mean Flows

[11] The mooring array coverage was not extensive enough to obtain mean flows in the entire basin of southern Lake Michigan; however, it was extensive enough to obtain mean winter currents in the coastal region off St. Joseph. The currents observed during the three winter seasons are shown in Figure 4. The mean currents are generally directed in a northward direction except very near the coast, where the mean currents flowed sometimes toward the shore and southward. During both 1998 and 1999 winters, the mean currents are directed toward the northeast, whereas during the 2000 season the mean flows are generally toward the north. The northward currents at all levels in southeastern Lake Michigan are consistent with the observed mean cyclonic circulation in Lake Michigan [*Beletsky et al.*, 1999]. Several mechanisms were proposed for mean cyclonic circulation during homogeneous conditions. *Rao and Murty* [1970] attributed it to mean curl of the wind stress. Note the slight cyclonic turning in the present wind measurements (Figure 2). There are also indications that nonlinear interactions of topographic waves can contribute to the mean cyclonic circulation [*Simons*, 1985].

[12] The mean winter currents near the surface (10–12 m) varied from 0.5 cm/s to 6 cm/s in 1998, 0.8 to 4.6 cm/s in 1999, and 0.85 to 8 cm/s in 2000. Recently, *Beletsky and Schwab* [2001] computed the winter circulation with current speeds in the range of 1.5 to 7.5 cm/s in the coastal regions of southern Lake Michigan. This is somewhat comparable

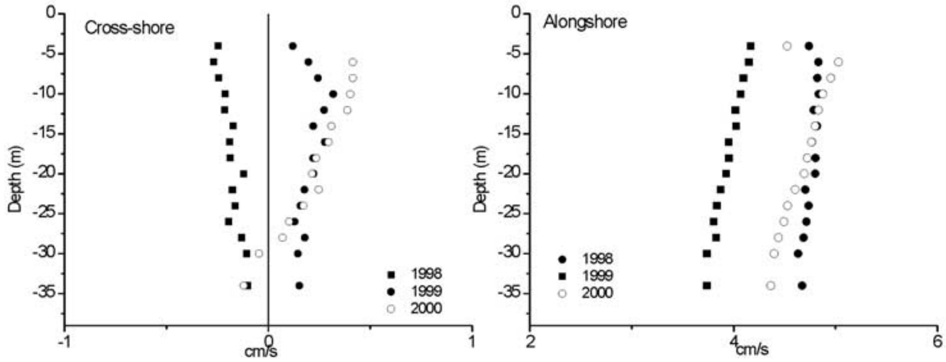

Figure 5. Vertical structures of mean cross-shore (positive values represent onshore) and alongshore (positive values represent northeastward) currents at A5 during the winters of three EEGLE field years.

to the observations reported here. In general, surface currents were slightly stronger than bottom currents. Reductions in net speed of near-bottom currents could be due to bottom friction. The mean alongshore currents at both cross-sections (N and S lines in Figure 1) increased offshore, whereas cross-shore currents exhibited onshore flow in the coastal region, with much stronger offshore flow occurring at the mid-depth stations.

[13] The vertical structure of mean currents at station A5 is shown in Figure 5. The interannual variability of mean offshore flows is clearly visible from this figure. The cross-shore currents during 1998 were dominated by net offshore flow (−0.2 cm/s), whereas in 1999 they were directed onshore (+0.2 cm/s) in the entire water column. During 2000, mean cross-shore currents show a zero crossing at a depth of 28 m, indicating a net offshore flow in the lower 10–12 m of the water column. The alongshore component of currents shows a nearly barotropic nature of currents during this period. This can also be observed in the time series of low-pass filtered vertical structure of temperature data shown in Figure 6. For most of the winter the temperatures at both surface and bottom everywhere were below 4°C. However, on several occasions it is observed that bottom temperature fluctuations show higher temperatures. The largest observed change in temperatures occurred during the winter-spring transition, with stratification starting from JD 107.

[14] The horizontal structure of surface and bottom current variability at two transects (N and S lines in Figure 1) is illustrated in Figure 7 by plotting the standard deviation (u_{sd}, v_{sd}) of currents during the winter of 2000. These are obtained as the root-mean square values of the deviations of currents from the time-means. It is evident from Figure 7 that the fluctuation field is non-isotropic. Along the N line, both surface and bottom cross-shore current fluctuations (u_{sd}) decreased in the shallow region (<20 m), while farther offshore they increased. The surface alongshore current fluctuations (v_{sd}) on this transect reached a maximum value at the 20-m isobath, and farther offshore they decreased. However, near-bottom values of v_{sd} decreased uniformly in the offshore direction. Along the S line, v_{sd} at the surface shows similar structure to that observed at the N line. Near the bottom, standard deviations in alongshore currents show a decreasing trend within 5 km from the shore, and it increases in the offshore direction. The cross-shore values (u_{sd}) exhibit different characteristics than those observed at

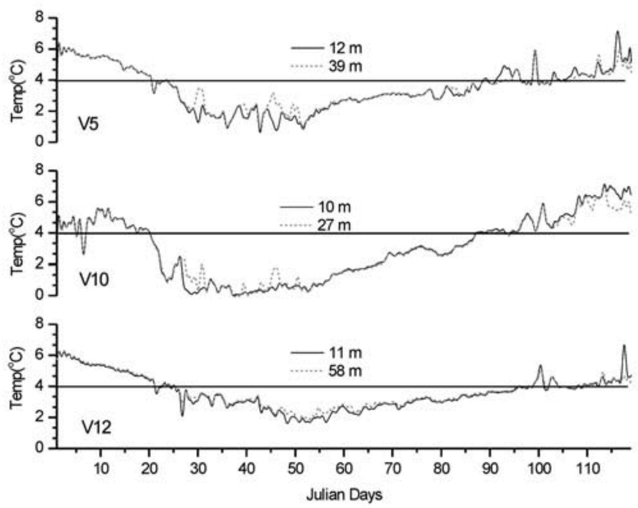

Figure 6. Time series of low-pass filtered temperature at surface and bottom depths at selected stations during the winter-spring transition period of 2000. See color version of this figure in the HTML.

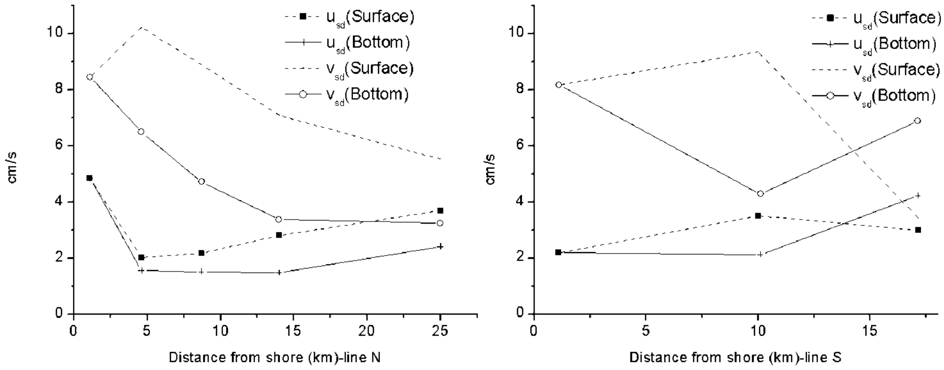

Figure 7. Standard deviations of alongshore (v_{sd}) and cross-shore (u_{sd}) components of currents at surface and bottom at line N and line S identified in Figure 1.

the N line both near the surface and at the bottom. However, within 5 km from the shore the flow is comparatively larger than that observed along the N line. This could be due to the width of the shelf region at the S line, which is smaller than the width at the N line.

[15] The cross-shore flow may also be associated with the Ekman veering of bottom boundary layer currents. Off the southeastern shore of Lake Michigan the observed net northward alongshore currents can produce an offshore component flow near the bottom. During the EEGLE field years the placement of current meters are not intended for resolving the bottom boundary layer characteristics. However, a crude estimation of veering angle is possible from the currents at the bottom-most bins and at 10 m above bottom (mab) from ADCP stations. Veering angles are also obtained at each VACM moorings from the current meters at 1 m above the bottom and the one at 11 m below the surface. The average angular displacement between two low-pass filtered vector series is obtained by calculating the phase angle and complex correlation coefficient between the two vector series [*Kundu*, 1976]. The very large magnitude of correlation suggests a uniform phase difference through the time record. The veering of the velocity vector in an anti-clockwise direction was observed at several stations (Table 2). The veering angle varied from 1.8° to 12.8° in 1999 and 4° to 15° in 2000, an evidence of Ekman layer flow near the bottom of southeastern Lake Michigan. This angle is somewhat comparable to the earlier observations in Lake Michigan [*Saylor and Miller*, 1988].

4.2. Spectral Characteristics

[16] To help describe the structure of currents, we have calculated the rotary spectra of horizontal currents at several moorings. The rotary spectra and cross-spectra were computed by the lagged covariance method with a maximum lag of 12 days; i.e., one tenth of the total record length of 120 days. Spectral estimates are smoothed with a Hanning filter [*Emery and Thomson*, 1997]. Figure 8 shows an example of clockwise (CW) and anti-clockwise (ACW) rotary components at two selected stations, one in the coastal region (V9) and another in mid-lake (CM1). The nearshore current meter is located at 11 m depth in a water depth of 20 m, and the mid-lake current meter (M1) is at 22 m and 20 m below the surface in 1999 and 2000 in a water depth of 156 m, respectively. The energy spectra of the currents show that the currents favor clockwise rotation in the coastal region yet are anti-clockwise at the mid-lake station with a peak at 3- to 5-day period.

[17] As observed in the mean currents, the variance levels of currents observed during the two years differ significantly. For example, the clockwise spectra show that in the 3- to 4-day period band the variance at CM1 shows almost an order of magnitude difference between 1999 and 2000. However, the variance in the anti-clockwise motions shows minor differences between the two years. These differences could be due to the differences observed in wind stresses from 1999 to 2000. Although earlier observations have recognized a 4-day vortex mode in the lake, those studies were mainly confined to summer and fall periods [*Saylor et al.*, 1980]. The present observations during winters of 1999 and 2000 also clearly indicate that the observed low-frequency oscillatory phenomenon in southern Lake Michigan has a 4-day periodicity with clockwise rotation in the coastal areas and anti-clockwise rotation in the mid-lake. The rotary spectra also show that the nearshore current fluctuations have similar magnitudes between clockwise and anti-clockwise components, indicating a rectilinear flow in this zone.

[18] The phase speed of wave propagation may be estimated from the cross-spectral estimates of coherence and phases of currents for selected station pairs in alongshore moorings (Table 3). The cross-spectral estimates of currents in the 3- to 4-day period band at the 20-m isobath shows that the oscillations propagate northward at an average

Table 2. Observations of Ekman Veering of Low-Frequency Currents Averaged Over the Winter Period During 2000 and 1999[a]

Station	Upper/Lower Current Meters	Correlation Coefficient	Phase
A1	10/15	0.961 (0.95)	7.4 (4.9)
A3	10/22	0.98 (0.989)	6.9 (3.6)
A4	10/17	0.97 (0.96)	5.5 (3.2)
A5	10/34	0.99 (0.975)	4.5 (1.8)
V10	10/28	0.98 (0.97)	16 (14.2)
V11	10/38	0.99 (0.90)	8 (7.4)
V5	10/39	0.96 (0.96)	15 (12.7)
V3	12/61	0.91 (0.94)	9.1 (2.85)

[a]Values in the brackets indicate 1999 values.

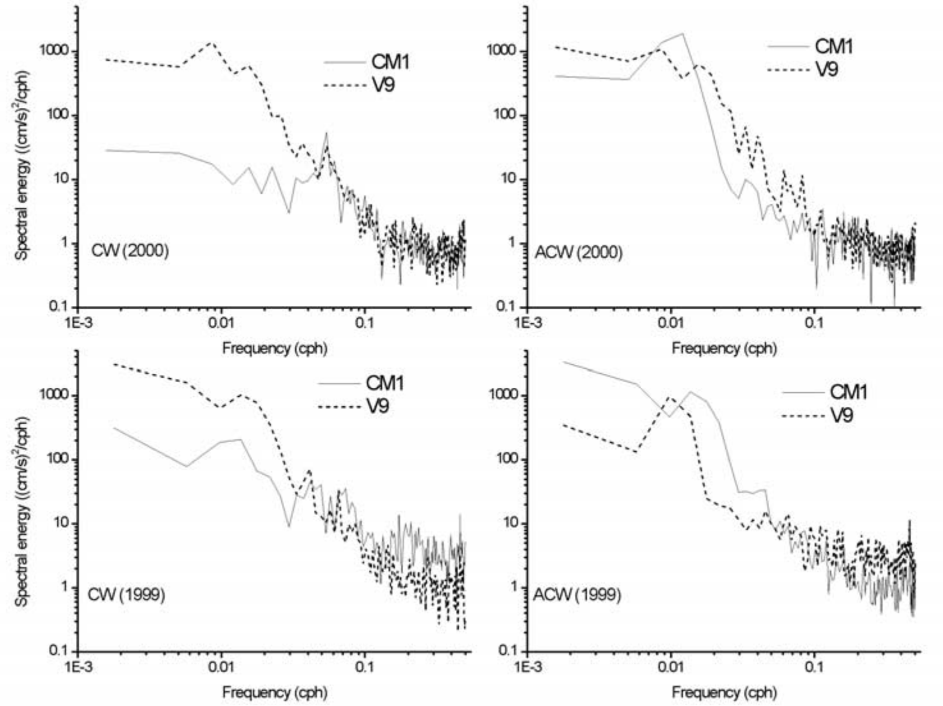

Figure 8. Rotary spectra showing the clockwise and anti-clockwise components of currents at two stations during the years 1999 and 2000.

speed of 0.62 m/s in 1999 and 0.7 m/s in 2000. During summer conditions, *Saylor et al.* [1980] observed northward propagating waves with similar phase speeds. Excitation of the 4-day oscillation is related to meteorological forcing initiated by southward-directed wind impulses. In order to analyze the relationship between wind stress and currents along the east coast of Lake Michigan, cross-spectral analyses between alongshore components of wind stress and currents in alongshore and cross-shore moorings were calculated. Significant coherence is observed in the low-frequency band (2–5 days). The phase differences between alongshore wind stress and currents showed that winds lead currents at coastal stations, and lagged at deeper stations indicating topographic response due to the influence of bottom friction [*Simons*, 1983].

4.3. Depth-Averaged Currents

[19] The mean currents presented above describe a uniform vertical structure, and except for the cross-shore currents in 2000, the currents are rarely found to reverse with depth. A simple vertical averaging may thus provide meaningful estimates of low-frequency fluctuating currents,

$$\langle u \rangle, \langle v \rangle = \sum_{n=1}^{N} h_n(u, v)$$

where N is the number of instruments in each mooring and h_n is a weight representing the range of depth represented by *n*th current meter [*Winant et al.*, 1987]. In these calculations, only those current meters that have returned a significant amount of data are included. In the following examples, four stations illustrated in Figures 9–11 are representative of currents from the southernmost array (V1) to the northern array (A4 and V9). Further ADCP stations (A2 in 1998 and 2000 and A5 in 1999) depict characteristics in the offshore region.

[20] To illustrate the temporal structure of currents, the time series currents are resolved into shore parallel and shore perpendicular components by rotating the east and north components to align with the local shore line. *Rao et al.* [2002] observed that the low-frequency currents in southern Lake Michigan are highly correlated with the alongshore component of the wind stress. Positive alongshore values of currents and wind stress are defined as those components directed toward the north and positive cross-shore values as those directed toward onshore. Figures 9 to 11 show the time series of low-pass filtered (>24 hour) wind stress at St. Joseph and the depth-averaged currents during the three winter seasons. The alongshore currents are dominant at all the stations, and cross-shore velocities account for less than 30–40% of the current flow. The alongshore currents are dominated by 3- to 5-day oscillations. It appears that the current fluctuations are primarily

Table 3. Cross-Spectral Estimates of Coherence and Phase at 3- to 4-Day Periodicity for Moorings Deployed Along the 20-m Depth Contour During 2000 and 1999 Winter Periods[a]

	East-West Component		North-South Component	
Station Pair	Coherence	Phase	Coherence	Phase
V1-A1	0.809 (0.839)	51 (81)	0.940 (0.841)	74 (62)
A1-A4	0.978 (0.878)	17 (24)	0.970 (0.950)	13 (15.6)
A4-V9	0.969 (0.980)	17 (15.1)	0.980 (0.990)	7.2 (9.2)
V9-V13	0.950	15.8	0.910	7.6

[a]Values in the brackets indicate 1999 values.

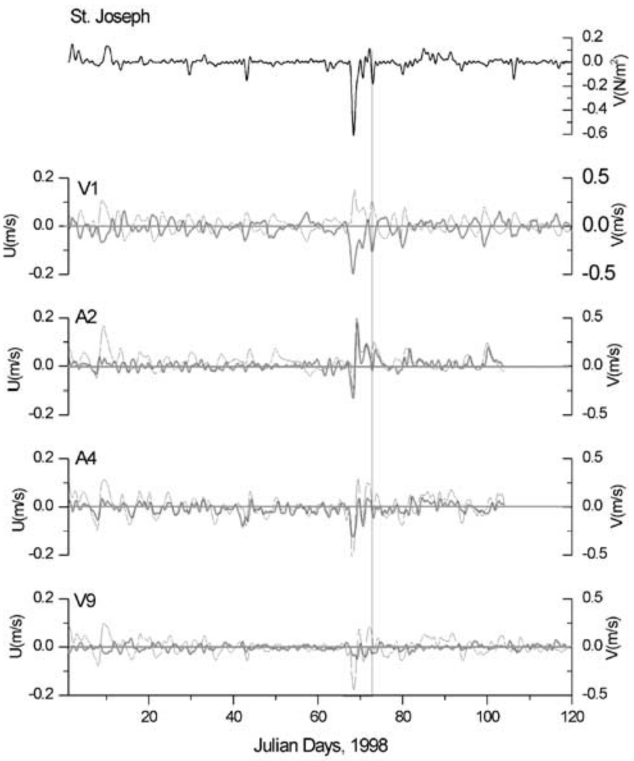

Figure 9. Time series of low-pass filtered alongshore wind stress at St. Joseph and alongshore (thin curve) and cross-shore (thick curve) components of currents at selected stations during the winter-spring of 1998.

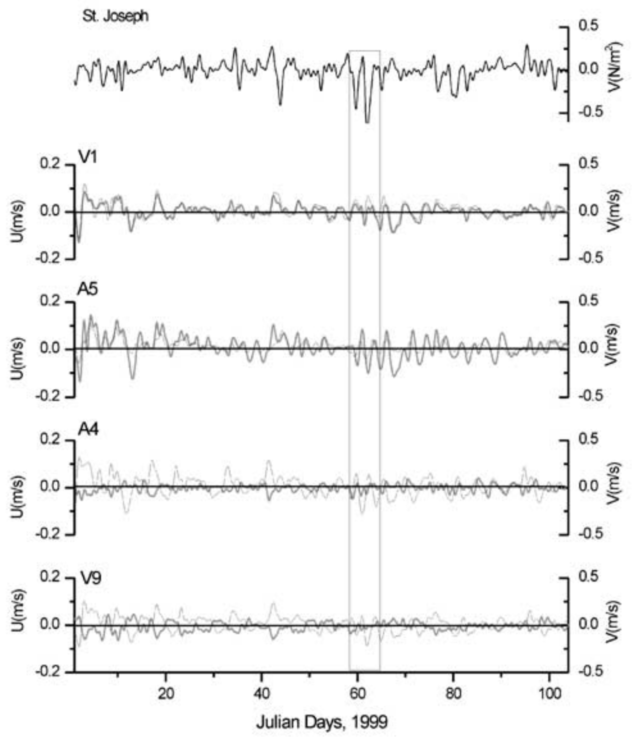

Figure 10. Same as in Figure 9 except for winter-spring of 1999.

caused by local wind impulses. The secondary effects are due to the relaxation of two-gyre circulation as northward propagating vorticity waves (see Table 3). The interannual variability of currents seems to have arisen due to the variability in wind stresses. The periods identified by vertical lines in Figures 9 to 11 are typical of the response of water column to strong northerly wind stress. The characteristics of circulation during these episodes will be discussed in detail in later sections.

[21] The depth-and-time integrated transports per unit width at the ADCP array during two winter seasons (1999 and 2000) have been presented in Table 4. These years were chosen because of the high quality of data at four stations in 1999, and at all six stations in 2000. Positive values represent onshore or northward transports. In general, the depth-integrated transports are oriented toward the north-west direction. It is apparent that the mean transport during the 2000 winter season is marginally higher than during the 1999 winter season, which is also evident from vector plots (see Figures 4a and 4b). The net transport is mainly oriented toward northward and offshore. The region near stations A3 and A5 is characterized with dominant offshore transport resulting from topographic steering.

5. Episodic Events

[22] The time series of vertically integrated currents showed that the circulation in southern Lake Michigan is episodic during the winter and early spring since it is largely driven by the wind. Several episodic events, mostly northerly storms, dominated the winter-spring meteorological conditions. In this analysis we have identified three such storms for further analysis. The first storm with northerly winds up to 18 m/s on 9 March 1998 (JD 68) caused a large

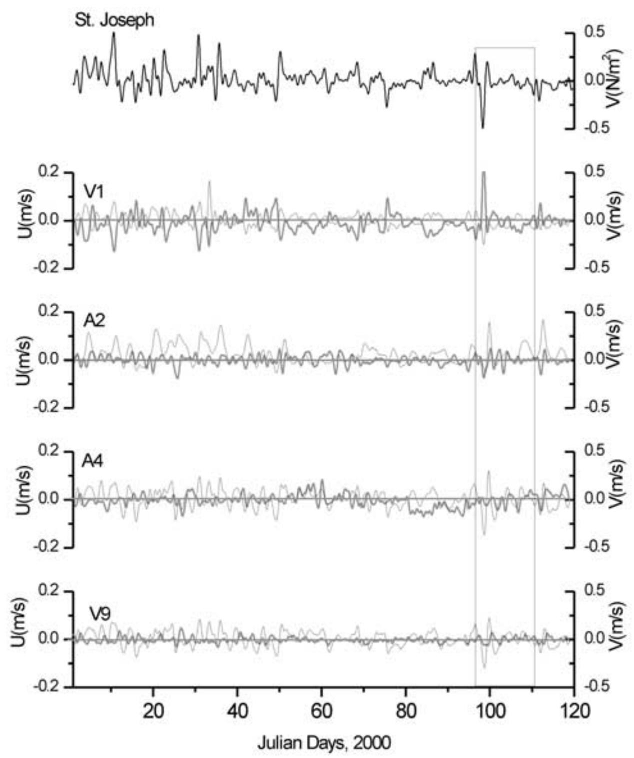

Figure 11. Same as in Figure 9 except for winter-spring of 2000.

Table 4. Depth-and-Time Integrated Transports (m^2/s) During 2000 and 1999 Winter Seasons at ADCP Stations

	Winter (2000)		Winter (1999)	
Stations	Cross-Shore	Alongshore	Cross-Shore	Alongshore
A1	0.019	0.26	−0.0054	0.52
A2	−0.03	2.55	NA	NA
A3	−0.41	1.01	−0.32	0.97
A4	−0.05	0.24	−0.048	0.36
A5	−1.01	1.62	−0.20	1.52
A6	0.13	1.74	NA	NA

Table 5. Depth-and-Time Integrated Transports (m^2/s) During Northerly Storm Events During 1999 and 2000 at ADCP Stations

	Storm Event (2000)		Storm Event (1999)	
Stations	Cross-Shore	Alongshore	Cross-Shore	Alongshore
A1	−0.20	−2.10	−0.65	−0.25
A2	−0.52	1.790	NA	NA
A3	−1.01	−0.77	−0.40	−0.85
A4	−0.14	−1.70	−0.15	−1.12
A5	−1.30	1.570	−0.64	−0.29
A6	−1.38	0.79	NA	NA

suspended sediment plume in southern Lake Michigan [*Schwab et al.*, 2000]. The winds from 9 March started blowing from the north/northwest with peak wind stress reaching around 0.80 N/m^2 (Figure 3a). The response in circulation is clearly visible immediately at all current meters, with coastal currents responding immediately to the storm-forced winds than offshore stations. The alongshore currents flowed in a southward direction (Figure 9). However, at V1 we observe that the cross-shore response is significant with a clear depth-averaged offshore transport. At mid-depths and farther offshore as the winds weakened, the currents relaxed with 3- to 4-day oscillations, which is typical of the propagation of topographic vorticity waves. The mean depth-averaged circulation during the event shows that the alongshore southward currents flowed in an offshore direction off St. Joseph, indicating that the mean circulation during the event is due to a two-gyre circulation, with anti-clockwise motion in the south and clockwise motion in the north (Figure 12a). In a recent modeling study, *Beletsky et al.* [2003] simulated the circulation during the March 1998 storm event in Lake Michigan. As observed here, the model results also showed that the wind caused strong alongshore southerly currents on 9 March that converged initially south of the station V1 and caused significant offshore flow. However, the model results at other stations (for example, at A2, A5, and V12) differ from observations. When the wind relaxed, model results also showed a cyclonic rotation of two-gyre pattern with a period of 4 days.

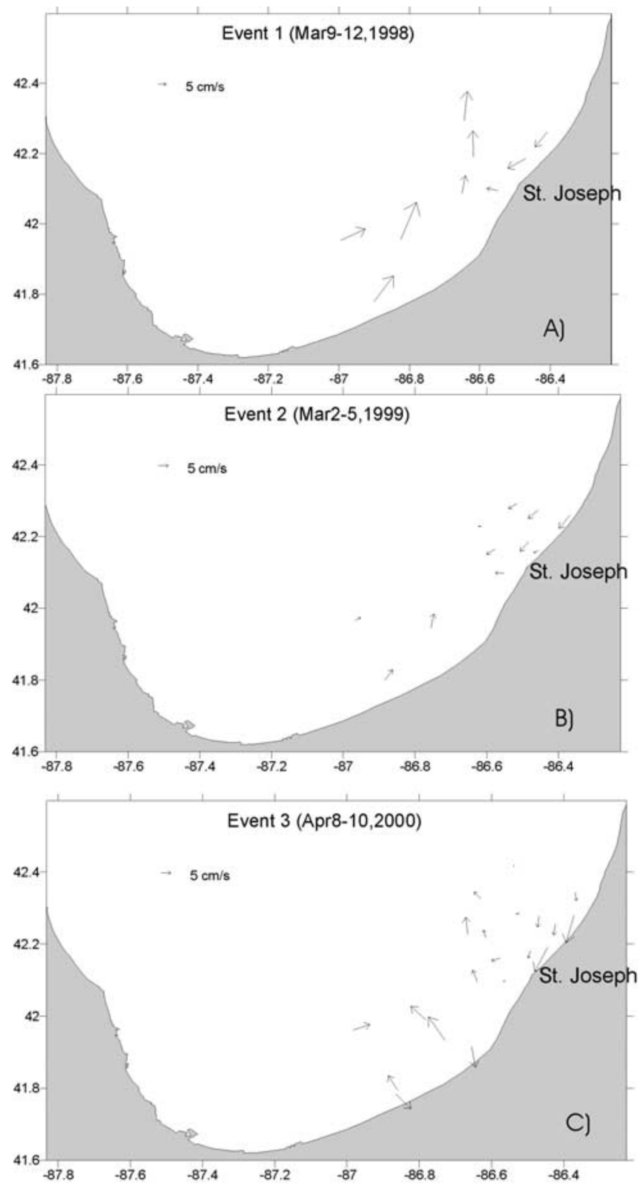

Figure 12. Vector averaged depth-averaged currents observed in southern Lake Michigan during the three episodic events (time intervals as shown in each figure).

[23] During a northerly storm from 2 to 5 March 1999 (JD 61 to JD 64), the winds initially blew from the north for a day with a brief reversal on 3 March (JD 62). However, later on that day the winds shifted again to northerlies with a maximum wind stress reaching to 0.45 N/m^2. This northerly storm is relatively weaker than the March 1998 storm. The depth-averaged currents show more or less immediate response in the shallow region with currents reversing to flow toward the south. The observed currents during this episode are significantly weaker than the currents during the March 1998 event. At both V1 and A5 the offshore transport coincided with southward flowing currents. Figure 12b shows that the net depth-averaged flow averaged from 2 to 5 March appeared as a two-gyre pattern, with offshore transport to the south of St. Joseph.

[24] In Figure 11, alongshore and cross-shore components of wind stress at St. Joseph and depth-averaged currents during a northerly storm episode from 8 to 11 April 2000 (JD 99 to JD 102) were marked by vertical bars. The strong northerly winds (13–14 m/s) on 9 April (JD 100) reversed the currents in the shallow region. The cross-shore currents exhibited short-period oscillations. The currents to the south of the northern transect (N line in Figure 1) show significant offshore transport associated with storm-forced winds (see Table 5). Once the storm has withdrawn, the currents tend to flow as an oscillation of nearly 3- to 4-days period. In Figure 12c we have also shown the mean values of depth-

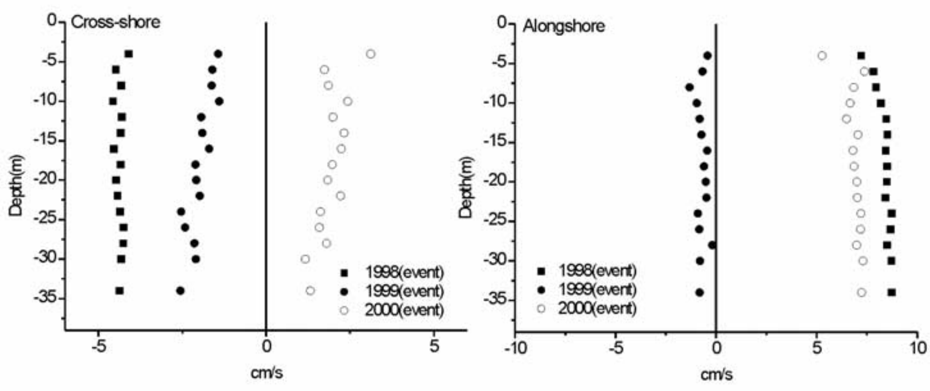

Figure 13. Vertical structures of mean cross-shore (positive values represent onshore) and alongshore (positive values represent northeastward) currents at A5 during the three episodic events.

averaged currents during 8 to 11 April 2000. The alongshore currents reversed in the opposite direction under the influence of prevailing winds within 10–12 km from the shore at N line. During this episode the offshore transport increased marginally at the mid-depth stations, whereas in the nearshore region the offshore transport remained high. However, along the southern transect (S line) the offshore transport significantly increased at the mid-depth stations. The nearshore alongshore currents under the influence of local winds flowed southward in a narrow band of a few kilometers, and the currents in the mid-depth region flowed in the opposite direction.

[25] The vertical structure of currents during these events has been depicted in Figure 13 as mean cross-shore and alongshore components of currents at A5. During both the March 1998 storm event and the March 1999 storm event, the offshore flow is significant, and more or less uniform in the water column. In contrast, the April 2000 event shows that the cross-shore currents are directed onshore, and the magnitude decreases slightly toward the bottom. The alongshore currents show slightly different pictures from one event to another. Although the vertical structure shows that the currents are uniform from top to bottom, the currents during the March 1999 event flowed southward, whereas during the other events the flow is oriented toward the north. These differences from one event to another could be due to the variability of the magnitude and direction of the wind-forcing.

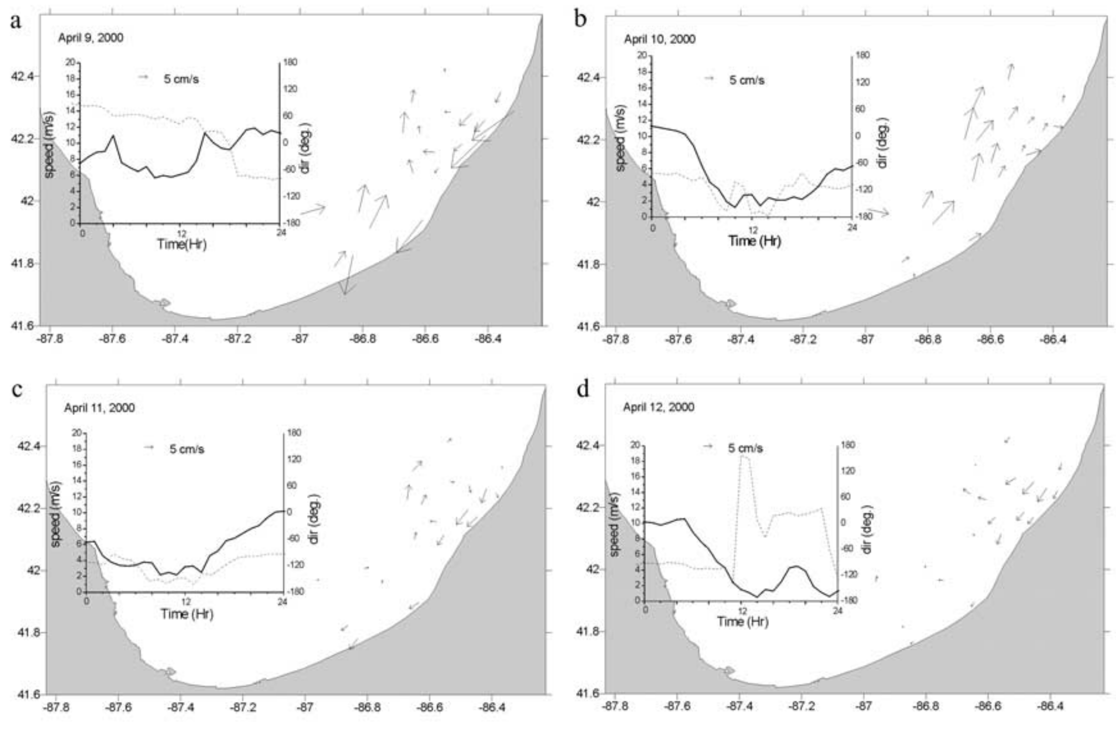

Figure 14. Daily snapshots of currents at surface (10–12 m) and the time series of wind speed (solid curve) and direction (dashed curve) of the day during the northerly storm episode from 9 to 12 April, 2000.

[26] In order to examine the response of surface currents during the storm events, we focus on observations from the April 2000 event because of the extensive mooring array in place. Figures 14a–14d show the daily averages of surface currents and the time series of wind speed and direction inserted in each figure. On April 9, significant winds were initially blowing toward the northeast, which were reversed due to the northerly storm by the evening. The nearshore currents responded significantly to this forcing, whereas offshore surface currents still continued to flow toward the north. Off St. Joseph where the shelf is wider, the southward flowing currents encountered northward flowing currents, and because of this, significant offshore transport was generated. By the next day the northerly winds weakened and in response the surface circulation reversed with northward currents in the entire EEGLE region. On April 11, the winds were still northerly, but by the evening the wind speed increased to 10 m/s. This has resulted in similar circulation albeit with lesser strength than that was observed on April 9. A weak anticyclonic gyre formed on the wider shelf, and to the south of it, a weak cyclonic gyre appeared. By April 12, the northerly wind pulse subsided, and weak southerlies started blowing. However, the effects of the southerlies were not visible on the circulation, as the currents in the entire EEGLE area were more or less directed toward the south with some offshore transport in the deeper region off St. Joseph. This suggests that the response of coastal currents along the southeast coast of Lake Michigan may be attributed to a combination of direct wind-forced currents in the shallow region and to the formation and relaxation of two-gyre circulation in the offshore waters.

6. Conclusions

[27] This study summarizes the mean and fluctuating coastal currents in southeastern Lake Michigan during the winter and early spring during three EEGLE field years. The winter-spring currents in this region are quite depth independent, and the vortex mode identified earlier in offshore waters is also evident in the data from these coastal waters. The net seasonal currents during the winter season flow predominantly alongshore and toward the north. Time-varying alongshore circulation is more closely tied to the alongshore component of the wind. The net offshore transport appears to be a result of the combination of wind-forced two-gyre circulation, Ekman veering of bottom boundary layer currents, and the topographic steering. However, the interannual variability of current speeds and magnitudes seem to be caused mainly because of the variability of surface wind-forcing.

[28] The intermittent episodic circulation influenced by northerly storms causes significant asymmetry to the mean circulation. During northerly storm episodes the mean current speeds increased significantly, and the currents within 10 km of shore followed the surface wind stress, while farther offshore the circulation was oppositely directed. Significant variability of circulation is noticed from one storm to another. As hypothesized before the field program, it appears that the alongshore currents are initially driven by strong northerly wind pulses, but subsequently reverse direction as the forcing stops. The two-gyre circulation seems to be an important mechanism for the relaxation of currents as well as the offshore transport in the southern Lake Michigan. The directly wind-forced offshore transport is observed in the region close to the southernmost array. Furthermore, these observations also suggest that the topographically steered coastal currents in combination with the counter-clockwise veering of bottom boundary layer currents are other important mechanisms for quantifying the offshore transport.

[29] **Acknowledgments.** The authors thank G. Miller and J. Saylor at GLERL and F. Chiocchio at NWRI for their contributions to the physical oceanographic measurements program. The staff at NWRI Engineering Services and Technical Operations provided considerable effort and resources to implement the EEGLE field program. We also thank Rich Garvine and two anonymous reviewers whose constructive suggestions improved this paper.

References

Beletsky, D., and D. J. Schwab (2001), Modeling circulation and thermal structure in Lake Michigan: Annual cycle and interannual variability, *J. Geophys. Res.*, *106*(C9), 19,745–19,771.

Beletsky, D., J. H. Saylor, and D. J. Schwab (1999), Mean circulation in the Great Lakes, *J. Great Lakes. Res.*, *25*, 78–93.

Beletsky, D., D. J. Schwab, P. J. Roebber, M. J. McCormick, G. S. Miller, and J. H. Saylor (2003), Modeling wind-driven circulation during the March 1998 sediment resuspension event in Lake Michigan, *J. Geophys. Res.*, *108*(C2), 3038, doi:10.1029/2001JC001159.

Boyce, F. M., M. A. Donelan, P. F. Hamblin, C. R. Murthy, and T. J. Simons (1989), Thermal structure and circulation in the Great Lakes, *Atmos. Ocean*, *27*(4), 607–642.

Brink, K. H., et al. (1992), Coastal ocean processes: A science prospectus, report, Woods Hole Oceanogr. Inst., Woods Hole, Mass.

Eadie, B. J., et al. (1996), Anatomy of a recurrent episodic event: A winter-spring plume in southern Lake Michigan, *Eos Trans. AGU*, *77*, 337–338.

Emery, W. J., and R. E. Thomson (1997), *Data Analysis Methods in Physical Oceanography*, 634 pp., Pergamon, New York.

Kundu, P. K. (1976), Ekman veering observed near the ocean bottom, *J. Phys. Oceanogr.*, *6*, 238–242.

McCormick, M. J., G. S. Miller, C. R. Murthy, Y. R. Rao, and J. H. Saylor (2002), Tracking coastal flow with surface drifters during the episodic events Great Lakes experiment, *Verh. Int. Verein. Limnol.*, *28*, 365–369.

Mortimer, C. H. (1988), Discoveries and testable hypothesis arising from Coastal Zone Color Scanner imagery of southern Lake Michigan, *Limnol. Oceanogr.*, *33*, 203–226.

Rao, D. B., and T. S. Murty (1970), Calculation of the steady-state wind driven circulation in Lake Ontario, *Arch. Meteorol. Geophys. Bioklimatol., Ser. A*, *19*, 195–210.

Rao, Y. R., C. R. Murthy, M. J. McCormick, G. S. Miller, and J. H. Saylor (2002), Observations of circulation and coastal exchange characteristics in southern Lake Michigan during 2000 winter season, *Geophys. Res. Lett.*, *29*(13), 1631, doi:10.1029/2002GL014895.

Saylor, J. H., and G. S. Miller (1988), Observation of Ekman veering at the bottom boundary of Lake Michigan, *J. Great Lakes Res.*, *14*, 94–100.

Saylor, J. H., J. C. K. Huang, and R. O. Reid (1980), Vortex modes in Lake Michigan, *J. Phys. Oceanogr.*, *10*, 1814–1823.

Schwab, D. J. (1983), Numerical simulation of low-frequency current fluctuations in Lake Michigan, *J. Phys. Oceanogr.*, *13*, 2213–2224.

Schwab, D. J., D. Beletsky, and J. Lou (2000), The 1998 coastal turbidity plume in Lake Michigan, *Estuarine Coastal Shelf Sci.*, *50*, 49–58.

Simons, T. J. (1983), Resonant topographic response of nearshore currents to wind forcing, *J. Phys. Oceanogr.*, *13*, 512–523.

Simons, T. J. (1985), Reliability of circulation models, *J. Phys. Oceanogr.*, *15*, 1191–1204.

Winant, C. D., R. C. Beardsley, and R. E. Davis (1987), Moored wind, temperature and current observations made during Coastal Ocean Dynamics Experiments 1 and 2 over the northern California shelf upper slope, *J. Geophys. Res.*, *92*(C2), 1569–1604.

Wu, J. (1980), Wind-stress coefficients over sea surface near neutral conditions: A revisit, *J. Phys. Oceanogr.*, *10*, 727–740.

M. J. McCormick, Great Lakes Environmental Research Laboratory, Ann Arbor, MI 48105, USA. (mccormick@glerl.noaa.gov)

C. R. Murthy and Y. R. Rao, National Water Research Institute, 867 Lakeshore Road, Burlington, Ontario L7R4A6, Canada. (raj.murthy@ec.gc.ca; ram.yerubandi@ec.gc.ca)