Observations of circulation and coastal exchange characteristics in southern Lake Michigan during 2000 winter season

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[1] Intermittent satellite images collected over in the last few years have revealed episodic late winter-spring plumes coinciding with northerly storms in southern Lake Michigan. A major inter-disciplinary observational program was initiated to study the importance of these episodic events on nearshore-offshore transport and the subsequent ecological consequences. In this paper, high density observations of winds and currents made during the winter of 2000 are analyzed to study the variability of the coastal circulation and the physical mechanisms resulting in the alongshore and cross-shore transport in the lake. The measurements of currents show the signature of forced two-gyre circulation in the southern basin. During northerly storm episodes the combination of directly wind forced currents and northward propagating vorticity wave generate significant offshore transport in this region. *INDEX TERMS:* 4223 Oceanography: General: Descriptive and regional oceanography; 4239 Oceanography: General: Limnology; 4512 Oceanography: Physical: Currents; 4599 Oceanography: Physical: General or miscellaneous

1. Introduction

[2] In the Great Lakes, as well as in the coastal oceans, 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, topographic steering in both coastal oceans and the Great Lakes have been studied for several years, the recent discovery of plume-like offshore transport in southern Lake Michigan [*Eadie et al.*, 1996] has prompted a new set of experiments. 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 transport during certain episodic conditions and to quantify the physical processes that are responsible for the nearshore-offshore mass exchange, a multidisciplinary research program, EEGLE (Episodic Events Great Lakes Experiment) was initiated by National Oceanic and Atmospheric Administration and National Science Foundation in Lake Michigan.

[3] 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 the southeastern shore of 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 that generated large waves in the southern Lake Michigan. Subsequently the plume appears along the entire southern coastline of the lake. It occasionally veers offshore along the eastern shore of the lake, coincidentally near the areas of highest measured long-term sediment accumulation of the lake. A conservative estimate is that the 1996 plume moved over one million tons of material [*Eadie et al.*, 1996].

[4] Circulation in the lakes is driven by wind, but the effects of the earth's rotation, basin topography, and vertical density structure are also important. During the unstratified season, higher wind speeds and the absence of a thermocline allow the effects of wind action to penetrate deeper into the water column than during the stratified season [*Boyce et al.*, 1989]. Under a relatively uniform over-lake wind field the entire water mass moves in the direction of the wind in shallow water, while return flow occurs in the deeper parts of the lake. This forms two counter-rotating closed gyres, a cyclonic gyre to the right of the wind and an anticyclonic gyre to the left [*Rao and Murty*, 1970; *Saylor et al.*, 1980]. These rotary motions or vorticity waves have been suggested as one of the important mechanisms for nearshore-offshore transport in the Great Lakes. *Schwab et al.* [2000] observed the presence of this two-gyre circulation pattern during March 1998 northerly wind event in their numerical experiments. In this paper, the data from field measurements during 2000 winter season are used to investigate the influence of a northerly storm in generating the offshore transport in southern Lake Michigan.

2. Experimental Data

[5] The observational strategy for obtaining the cross-shore and alongshore currents, physical environment, and temperature consisted of three components: (a) Eulerian measurements (b) Lagrangian measurements and (c) shipboard surveys. In the Eulerian measurements (moored instrumentation) time series of currents, winds, and temperature data were obtained for the field years of 1997 to 2000.

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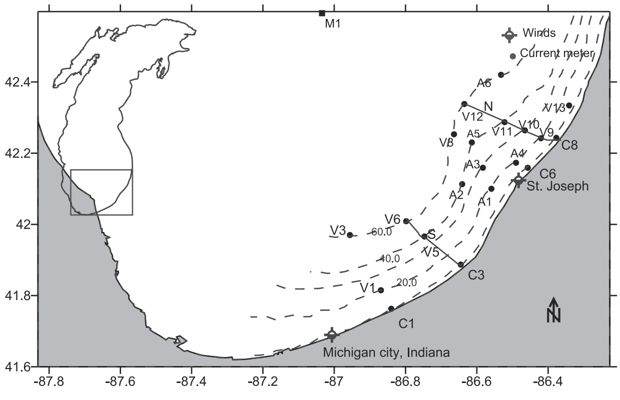

Figure 1. Geometry and bathymetry of southern Lake Michigan showing meteorological and current meter stations (A: ADCP; V: VACM, C: SACM).

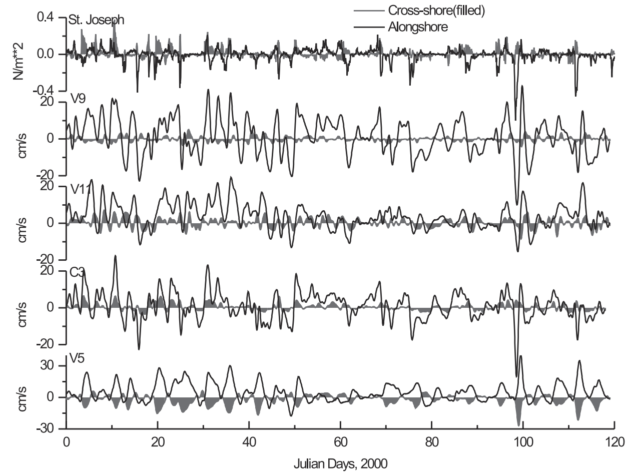

Figure 2. Time series of wind stress (St. Joseph) and low-pass filtered currents at 11 m below surface. Positive values represent northward, and onshore currents.

A maximum of 17 moorings of Acoustic Doppler Current Profilers (ADCP) and Vector Averaging Current Meters (VACM) were deployed from the 20 m to 60 m depth contours by the NOAA Great Lakes Environmental Research Laboratory. As a part of the program National Water Research Institute deployed additional instrumentation consisting of seven Smart Acoustic Current meters (SACM), and two ADCPs in shallow waters at a depth of 12 m along with two coastal meteorological stations installed on piers at Michigan City, Indiana and St. Joseph, Michigan. The complete details of the observational network are reported in EEGLE website (http:\\www.glerl.noaa.gov\eegle\). During the 2000 winter season several of these moorings returned high quality data, and provided extensive coverage of coastal lake region (Figure 1). In this paper, we study the circulation, alongshore and cross-shore exchanges during 2000 winter season, and the variability due to the influence of a northerly storm by using the data from moored instrumentation.

3. Characteristics of Near-Shore Currents

[6] The variability of coastal currents is determined by the prevailing winds over Lake Michigan. Two shore based stations at St. Joseph and Michigan City provided wind speeds and directions during the experimental period. The winds at these stations have been taken as representative of meteorological forcing during this period. 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^{-1} [*Wu*, 1980]. The time series of winds and currents are resolved into shore parallel and shore perpendicular components by rotating the east and north components to align with the local shore line. Here the direction of wind stress points toward the reference. Figure 2 shows the time series of wind stress at St. Joseph and low-pass filtered (>24 h) currents at four selected stations along the northern and southern transects in Figure 1. The alongshore currents are dominant at all the stations, and cross-shore velocities account for less than 30–40% of all sub-surface (10–11m) current flow except at V5. At V5 the magnitude of offshore currents is comparable to alongshore currents. The alongshore currents are dominated by 3–5 day oscillations and are primarily induced by the alongshore component of wind. Table 1 shows the mean winter (January 1 to April 28, 2000), and northerly storm (April 8 to April 11, 2000) values of vertically integrated currents or transports per unit width at five ADCP stations. Positive values represent onshore or northward transports. The net transport is mainly oriented towards northward and offshore. The region near stations A3 and A5 is characterized with dominant offshore transport resulting from topographic steering.

[7] In order to 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 by Hanning [*Emery and Thomson*, 1997]. Figure 3 show the clockwise (CW) and anti-clockwise (ACW) rotary components at three selected stations. The near-shore current meters are located at 11 m depth and mid-lake current meter (M1) is at 33 m below the surface. The energy spectra of the currents show that the currents favor clockwise rotation in the coastal region yet are strongly anti-clockwise at the mid-lake station with a peak at 3–5 day period. Although the earlier observations recognize 4-day vortex mode in the lake, those studies were mainly confined to summer and fall periods [*Saylor et al. 1980*, *Schwab*, 1983]. Our observations during winter 2000 also clearly indicate that the observed low frequency oscillatory phenomenon in southern Lake Michigan is the 4-day gravest vortex mode in the lake basin. The rotary spectra also shows that the nearshore (<20 m) current

Table 1. Depth-and-Time Integrated Transports (m^2/s) During Mean Winter, and a Northerly Storm Episode at ADCP Stations

Stations	Winter		Storm Event	
	Cross-shore	Along-shore	Cross-shore	Along-shore
A1	0.019	0.26	−0.20	−2.1
A2	−0.03	2.55	−0.52	1.79
A3	−0.41	1.01	−1.01	−.77
A4	−0.05	0.24	−0.14	−1.7
A5	−1.01	1.62	−1.30	1.57

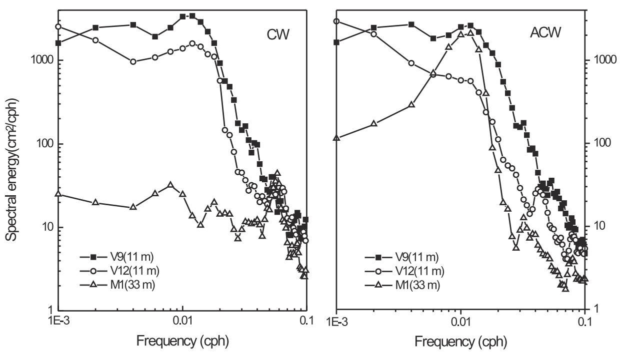

Figure 3. Rotary spectra showing clockwise (CW) and anti-clockwise (ACW) components of current velocities at three stations.

oscillations are essentially rectilinear and oriented along the depth contours.

[8] 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. The alongshore components of currents at 4-day period in the mid-depth (20–60 m) region shows that the oscillations propagate northwards at variable speeds from one station pair to another (0.5–2.5 m/s) with an average speed of 0.7 m/s. During summer conditions *Saylor et al.* [1980] observed northward propagating waves with similar phase speeds. This kind of variation might be expected due to the propagation of shelf waves affected by bottom friction. Excitation of the 4-day oscillation is related to meteorological forcing initiated by southward directed wind impulses. In order to analyze the relation 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 (figures not shown). 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

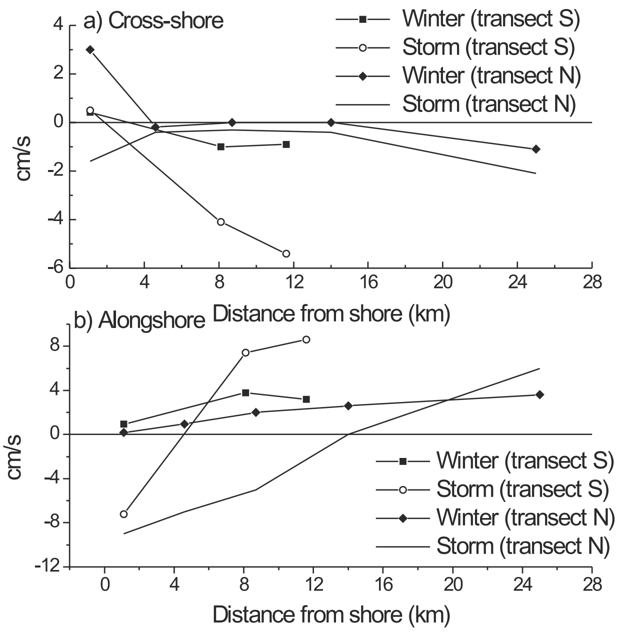

Figure 4. The net depth-averaged alongshore and cross-shore components of currents at two cross-sections. Positive values represent northward and onshore currents.

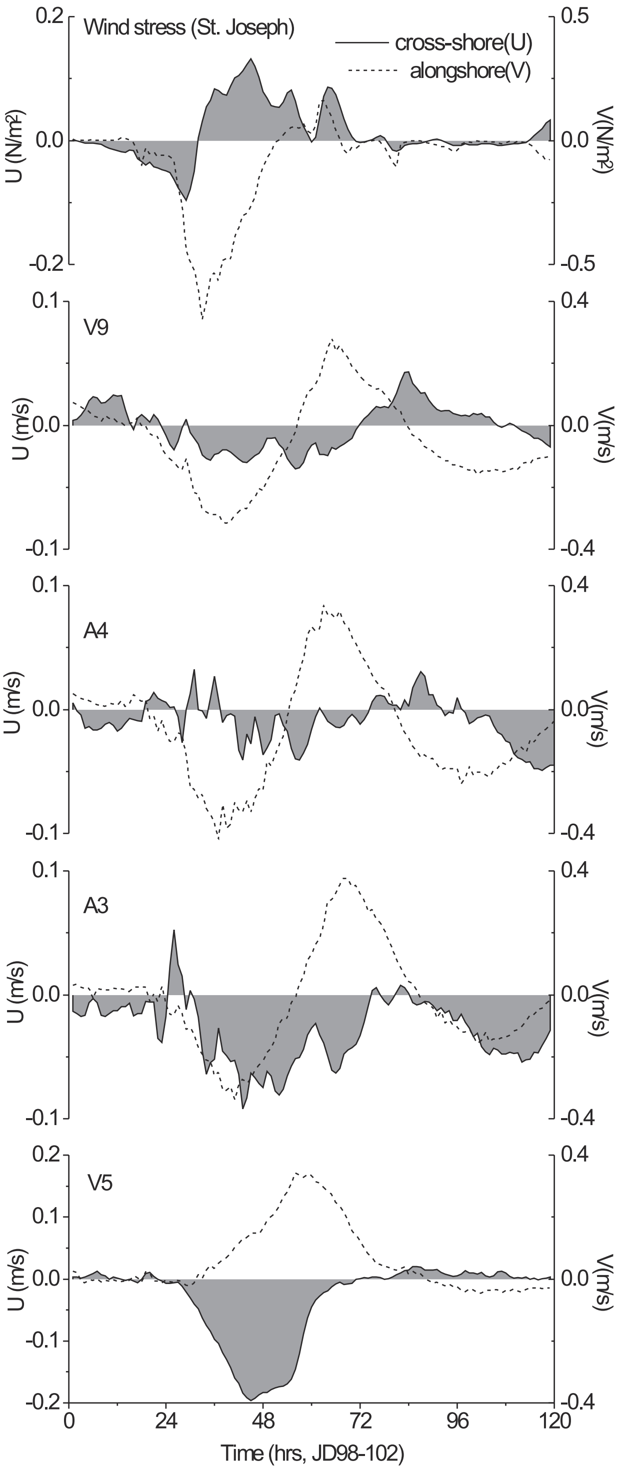

Figure 5. Time series of depth-averaged alongshore (V) and cross-shore (U) components of currents at selected stations. Positive values represent northward and onshore currents.

topographic response due to the influence of bottom friction [*Simons*, 1983].

4. Influence of a Northerly Storm

[9] The net depth-averaged seasonal currents during the winter are directed towards the north (Figures 4a and 4b). The mean alongshore currents at both cross-sections (N & S) increased offshore, whereas cross-shore currents exhibited onshore flow in the coastal region, with much stronger offshore flow occurring at the deeper stations. The mean currents show similar structure throughout the water column indicating the barotropic nature of the currents during the season. Figure 5 displays alongshore and cross-shore components of wind stress at St. Joseph and depth-averaged currents at selected stations during a northerly storm episode from April 8 to April 12, 2000. The strong northerly winds ($\sim$18 m/s) on April 9 reversed the currents in the shallow region. The cross-shore currents exhibited short-period oscillations. The currents to the south of the northern transect shows significant offshore transport associated with storm forced winds (see Table 1). Once storm has withdrawn the currents tend to flow as an oscillation of nearly 4 days period. Figures 4a and 4b also show the mean values of depth-averaged currents during April 8 to April 11, 2000. The alongshore currents reversed in the opposite direction under the influence of prevailing winds within 10–12 km from the shore at the northern transect. 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) the offshore transport significantly increased at the mid-depth stations. The alongshore currents show that the nearshore currents under the influence of local winds flowed southwards in a narrow band of 4 km, and the currents in the mid-depth region flowed in the opposite direction. This suggests that the response of coastal currents along the east coast of Lake Michigan is due to the combination of direct wind forced currents in the shallow region and a forced two-gyre vorticity wave in offshore waters. The cross-shore flow may also be associated with the Ekman veering of bottom boundary layer currents. Off southeastern shore of Lake Michigan the observed net northward longshore currents can produce an offshore component to flow near the bottom. The veering of the velocity vector in an anti-clockwise direction is observed at several stations. The veering angle varied by nearly 8–10° from 1 meters above bottom (mab) to 10–15 mab.

5. Conclusions

[10] The winter currents in southern Lake Michigan are barotropic, and the vortex mode identified earlier in offshore waters is also evident in the data from coastal waters. The net seasonal currents during the winter season flow predominantly alongshore and towards the north. During a northerly storm episode the mean current speeds increased significantly, and the currents within 10 km of shore followed the surface wind stress while further offshore the circulation was oppositely directed. The cross-shore and alongshore transports showed opposite trends from mean winter to storm episodes. Furthermore, these observations suggest that the topographically steered coastal currents in combination with vortex modes in the lake are major mechanisms for the offshore transport.

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