Verh. Internat. Verein. Limnol.	28	365–369	Stuttgart, February 2002

Tracking coastal flow with surface drifters during the episodic events Great Lakes experiment

M. J. McCormick, G. S. Miller, C. R. Murthy, Y. R. Rao and J. H. Saylor

Introduction

In the coastal regions of large lakes and oceans, the horizontal gradients of dissolved chemicals and suspended materials are often far greater in the offshore than in the alongshore direction. Therefore, the mechanisms driving cross-isobath circulation play a critical role in maintaining the water quality in coastal regions. In the Laurentian Great Lakes the absence of any tidal currents and their smaller basin geometry, relative to oceanic conditions, leaves a velocity field that is dominated by wind forcing. Time variability in the surface wind stress in both magnitude and direction results in a relatively weak background circulation pattern (BELETSKY et al. 1999). Under conditions like these there is a greater potential impact for storms to be a major mechanism for the offshore flux of coastal materials.

As part of a National Science Foundation- and NOAA-sponsored study, an extensive array of fixed current meter moorings and satellite-reporting drifting buoys were used in the coastal region of southeastern Lake Michigan, as part of an effort to determine the statistics associated with offshore and longshore transport. The observational program began in the fall of 1997 and ended in early summer 2000.

With recent improvements in Lagrangian positioning technology, with GPS and sophisticated microprocessor-equipped drifters, they have become even more useful tools for studying coastal circulation. PAL et al. (1998) and SANDERSON (1987) used drifters to help describe the mixing and circulation characteristics of Lakes Ontario and Erie, respectively. In this report, findings are described from a Lagrangian experiment in April 1999 on the coastal waters of Lake Michigan.

Experiment

Fixed current meter moorings may well describe the temporal transport for most of the water column except for difficulties in measuring the near-surface flow field. Surface drifting buoys can track the near-surface flow and when used in sufficient numbers they can provide details on the large-scale flow as well.

To estimate the Lagrangian flow statistics and their relevant Lagrangian time and spatial scales, a total of 25 CODE-type drifters were deployed at several sites in Lake Michigan. The CODE-type drifters have excellent water-tracking ability with little wind-induced slippage (DAVIS 1985). Clearwater Instrumentation's ClearSat GPS/ARGOS drifters were used exclusively for the Lagrangian measurements. The buoys are configured with a 1 × 1-m cruciform drogue, which renders a center-of-effort of approximately 0.8 m below the water surface. Attached to the drifter bottom was an 8-m long cable, 3 mm in diameter, terminated with a 1-kg Danforth type anchor. Midway down the cable a small float was attached to make the assembly neutrally buoyant and decouple its motion from the drifter, while letting the anchor hang no more than 5 m below the drifter. The low drag profile of this assemblage was estimated to have little impact on the drifter's trajectory, yet would help to save the buoy from possible destruction by anchoring it out of the surf zone. The GPS positions were fixed at 30-min time intervals and internally stored and encoded to allow data compression for up to 17 positions to be transmitted over ARGOS and thereby enable high resolution coverage through remote access.

The drifrers were deployed over the first 2 weeks in April 1999 at five locations. Each deployment episode consisted of one drifter at each of the five sites. This would be repeated in 2 days, weather permitting, until all of the drifters were deployed. This strategy would enable large spatial coverage and it would also provide some information on the temporal variability. The stations were located along the 20-m depth contour and the buoys were deployed by personnel from the United States Coast Guard, operating from stations near Chicago, Illinois; Michigan City, Indiana; and St. Joseph, Michigan. Two of the sites were near Chicago, two were near Michigan City (Michigan City East, MCE and Michigan City

0368-0770/02/0028-000365 $ 1.25

West, MCW), and one just west of St. Joseph (SJ). Figure 1 shows the study location and a composite of all available trajectories reported from 22 of the drifters.

Results and discussion

The curvilinear nature of the southern Lake Michigan basin requires that the drifter data be transformed in order to resolve the longshore and offshore velocity components. The technique selected for this study was to use the 20-m depth contour as an indicator of longshore and cross-isobath flow when compared against drifter data. Other approaches to define the offshore direction, such as calculating the local slope from bathymetric data, may be superior to this choice. However, examination of bathymetric charts suggests that the coastal region and shoreline are well approximated by the 20-m contour.

The longshore direction was estimated by averaging the calculated bearings of the 20-m bathymetric data over approximately 15-km intervals. The spatially averaged bearing's directional reference was chosen so that the positive longshore direction would be in a counter-clockwise direction when following the 20-m

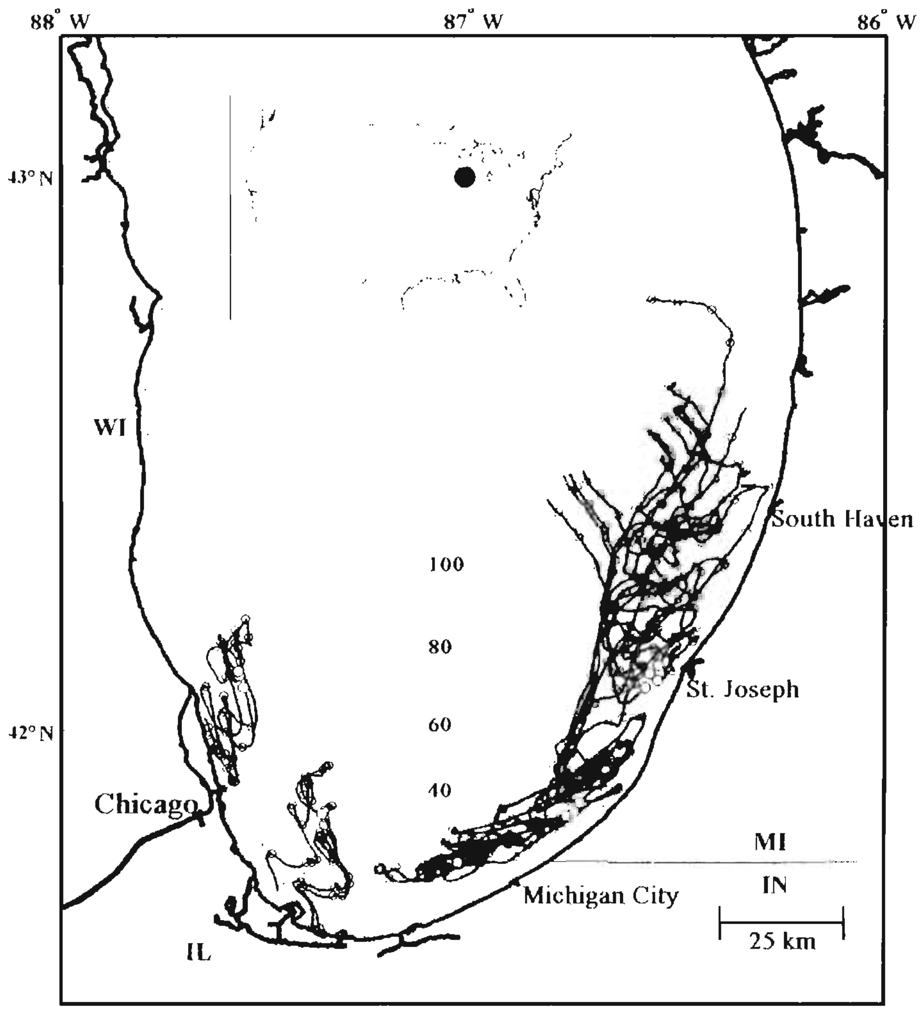

Fig. 1. Twenty-two drifter tracks from April 1999 on southern Lake Michigan. Various line makers are displayed every 24 h. The inset highlights the study region of Lake Michigan.

contour around the basin. Using a right-handed coordinate system, a positive cross-isobath velocity would always be directed onshore, while a negative value would indicate offshore transport. Once these bearings were determined, the offshore (u_1), and longshore (u_2) velocities for each drifter were calculated from the data by

$$u_1(t) = s(t)\sin(\theta(t) - \phi(x, y)) \\ u_2(t) = s(t)\cos(\theta(t) - \phi(x, y)) \tag{1}$$

where, t, time; s, speed; θ, drifter direction; and Φ, longshore bearing that is closest to the drifter at time t. The drifter's speed and direction were calculated from the GPS data.

The entire set of trajectories from all drifters is shown in Fig. 1. Numerous reversals are evident in each trajectory due to lack of uniformity, in both space and time, of the surface winds. Seven of the longest drifter tracks (>20 days) were examined in detail and their tracks are shown in Fig. 2. Also shown in Fig. 2 is a progressive vector diagram of a particle traveling at 1.5% of the wind speed, as measured from the mid-lake meteorological buoy. Buoy meteorological data were recorded by the NOAA National Data Buoy Center. Although the mid-lake wind data show the winds there to be coming predominantly from the north-east, there are coastal data that suggest that significant wind curl can exist on sub-basin scales. Therefore, proper correlation between drifter trajectories and wind forcing requires that the wind field be resolved on fine spatial scales, which will be addressed in future work. Wind data like that shown in Fig. 2 are included for qualitative purposes only.

The Lagrangian time and length scales estimate the time and distance over which the drifter's motion remains correlated. If the drifter's trajectory were able to absolutely track a given parcel of water then the drifter-derived scale estimates would more accurately describe the surface flow than when water parcels are poorly tagged due to buoy slippage. Wind- and wave-induced slippage, in general, increase dispersion, and under these conditions the calculated Lagrangian time and length scales may underestimate the true time and spatial distances over which the flow field is correlated. Nonetheless, Lagrangian statistics are consistent with similarly designed and configured drifters, such that they do provide useful insights into system dynamics. PADUAN & NIILER (1993), among others, described procedures for calculating the Lagrangian integral time and length scales. All of the calculations were based upon various applications of the residual velocity fluctuations and in particular, the velocity autocorrelation function. The velocity autocorrelation functions for the offshore and longshore velocities are

$$R_i(\tau) = \frac{\frac{1}{T}\int_0^{(T-\tau)} u_i(t)u_i(t+\tau)dt}{\langle u_i'^2 \rangle} \tag{2}$$

where $R_i(\tau)$, velocity autocorrelation function as a function of the time lag, τ; i, 1, 2 the offshore and longshore directions, respectively; T, total time period of integration; and u', $u - \langle u \rangle$ where the angle brackets represent a time average over T. Using Equation 2, the Lagrangian integral time-scale (T^L) is defined as

$$T_i^L = \int_0^{T_0} R_i(\tau)d\tau \tag{3}$$

where the upper limit of integration (T_0) is defined as the first zero crossing of the autocorrelation function. Similarly, the Lagrangian integral length-scale (L) is found by multiplying Equation 3 by the rms residual velocity.

$$L_i = \langle u_i'^2 \rangle^{1/2} \int_0^{T_0} R_i(\tau)d\tau \tag{4}$$

Examination of Figs. 2 and 3 and Table 1 suggest that the net basin circulation appears to be as a single cyclonic gyre. Each of the drifters showed a net positive counter-clockwise longshore velocity with an overall mean longshore velocity of 3.2 cm/s. Frequent reversals in the flow field are evident from both the drifter tracks and by the large difference between the drifter's scalar speed and velocity averages. Cor-

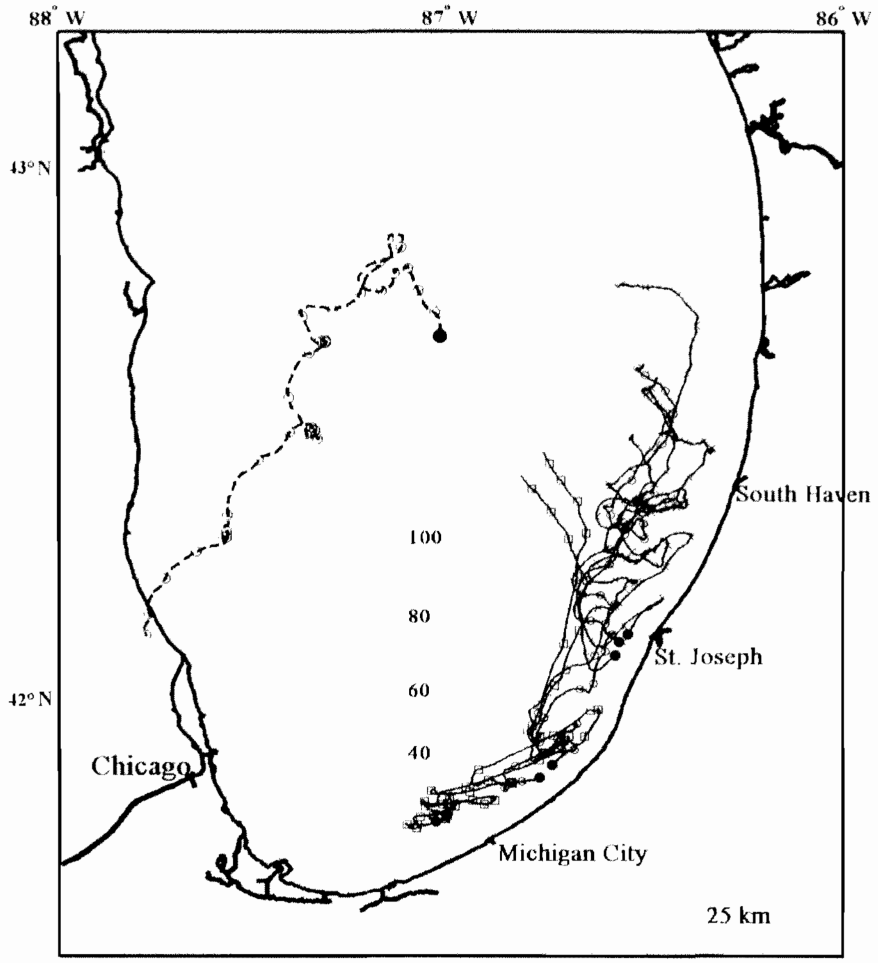

Fig. 2. Seven of the longest drifter tracks from Fig. 1. The solid circles depict the starting locations, with the **×** representing drifters from SJ, squares depict drifters from MCW, and open circles track drifters from MCE. Line markers are displayed every 24 h.

respondingly, each of the drifters showed a net offshore transport with an overall mean velocity of 1.3 cm/s. Over a 3-week time interval, the drifters traveled a total excursion distance of approximately 145 km with a net cyclonic transport of 58 km accompanied with a net offshore displacement of 24 km.

The Lagrangian integral time and length scales showed far greater variability than seen in the velocity data (Fig. 3 and Table 1). Not unexpectedly, the longshore flow showed much higher correlation times and longer correlation distances than observed in the offshore data. Overall mean integral longshore scales of 32.4 h and 8.1 km were calculated, compared to offshore scale values of 8.1 h and 3.1 km. The statistics based upon drifters released at SJ suggest a more isotropic flow in that region while the MCW results showed a preference for higher offshore correlations, in direct contrast with MCE which showed a longshore dominance. Both MCW and MCE showed closer agreement in drifter trajectories deployed 5 days apart from the same site, than between the two sites for drifters deployed at the same time. Furthermore, the relatively little dispersion shown by the drifters from MCW and MCE compared to SJ suggests complex circulation result-

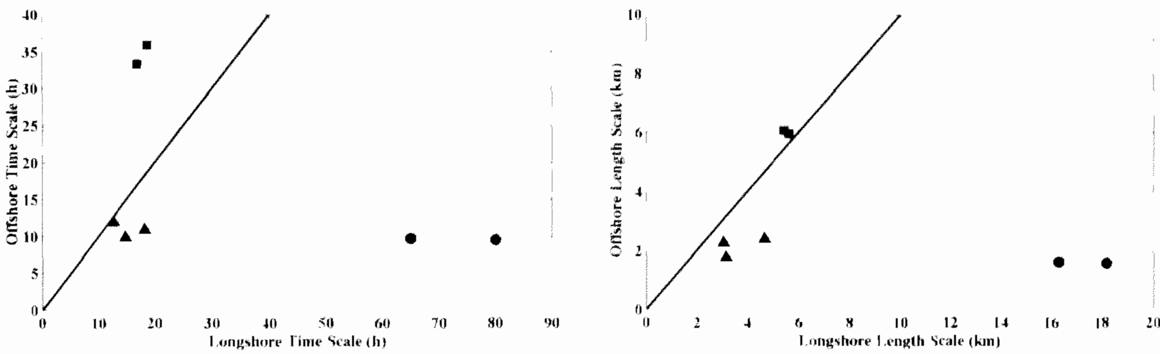

Fig. 3. Comparison of the offshore and longshore Lagrangian integral time (left) and length (right) scales. The solid circles correspond to MCE, the solid squares refer to MCW, and the solid triangles refer to SJ.

Table 1. Lagrangian statistics for April 1999 in southern Lake Michigan.

Drifter ID, deployment site and dates (DOY)	Mean speed (cm/s)	Mean longshore velocity (cm/s)	Mean offshore velocity cm/s)	Lagrangian integral time-scale (h)		Lagrangian integral length-scale (km)	
				longshore	offshore	longshore	offshore
22575, MCW (92.75–120.5)	8.6	2.9	−1.7	18.7	35.9	5.4	6.1
1622, MCW (98.0–120.5)	8.8	3.8	−1.9	17.0	33.3	5.6	5.9
22578, MCE (92.75–120.5)	7.6	3.5	−1.1	80.0	9.5	18.2	1.6
1161, MCE (98.0–120.25)	7.6	4.0	−1.2	65.1	9.7	16.3	1.6
21825, SJ (95.75–120.25)	8.1	3.6	−1.3	18.2	10.9	4.7	2.4
22579, SJ (97.75–120.5)	7.8	2.6	−0.8	12.7	11.9	3.1	2.3
22580, SJ (100.0–120.5)	7.2	2.4	−1.0	14.9	9.8	3.2	1.8
Overall mean	8.0	3.2	−1.3	32.4	17.3	8.1	3.1

ing from the interaction between coastal wind features with basin scale dynamics, and local bottom topography. Future efforts will employ detailed descriptions of the overwater wind field, as well as model simulations of the entire southern basin, in an attempt to quantify the temporal and spatial evolution of the Lagrangian velocity field.

Acknowledgements

We thank the USCG personnel for their help with deploying the drifters. A special thanks goes to Terrence C. Miller of GLERL for all of his efforts with this program including drifter repair, recovery and an attitude that in large part made this experiment possible. (GLERL Contribution Number: 1192)

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Authors' addresses:

M. J. McCormick, G. S. Miller, J. H. Saylor, NOAA, Great lakes Environmental Research Laboratory, 2205 Commonwealth Blvd., Ann Arbor, MI 48105, USA.

C. R. Murthy, Y. R. Rao, National Water Research Institute, CCIW, Burlington, Ontario L7R 4A6, Canada.