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# OBSERVATIONS OF CONCURRENT DRIFTING BUOY AND CURRENT METER MEASUREMENTS IN LAKE MICHIGAN[1]

**Anne H. Clites**
*National Oceanic and Atmospheric Administration*
*Great Lakes Environmental Research Laboratory*
*2205 Commonwealth Blvd.*
*Ann Arbor, Michigan 48105*

*ABSTRACT. Data generated by satellite-tracked drifting buoys released in the Great Lakes are being used to study lake circulation and test trajectory prediction models. Before data from drifters can be used with confidence, the water-tracking accuracy of the drifters must be known. During the winter of 1983, drogued drifters were released in Lake Michigan in the vicinity of an array of vector-averaging current meters. Several times during the next 3 months, the drifters moved within a few kilometers of one of the current meters and remained in the vicinity for up to 30 hours. The average wind effect that best aligns the currents measured by the moored current meters and the currents from drifter paths is 0.76% of the wind speed. This value is the weighted average of the wind effects calculated for seven separate cases, which ranged from 0.06% to 2.09% of the wind speed. The average value is in good agreement with theoretical estimates and field test results. The horizontal coherence of the currents within 5 km was fairly high as revealed by comparisons between drifter trajectories and current meter progressive vectors. The separation distance between the vectors was generally under 1 km while drifter path length ranged from 4 to 9 km. Results indicate that during these encounters, about 25% of the variability between current trajectories estimated by drifting buoys and current meter measurements is explained by a simple wind correction. The remaining discrepancy is attributed to wave action (Stokes drift) and data limitations such as a lack of overlake wind conditions.*
*ADDITIONAL INDEX WORDS: Water currents, physical processes, physical properties, satellite technology, remote sensing.*

## INTRODUCTION

Remotely tracked drifting buoys are used in various applications in limnology and oceanography to track a water parcel. The modern version of the drift bottle, these drogued devices are a good source of current data. The tracks generated by drifters are of interest for testing predictive circulation and trajectory models for both practical, e.g., search and rescue operations or oil spill containment, and theoretical applications. However, for any application of these data, it must be known how effective the drifter is as a water parcel label. This is a complex problem, as no completely accurate method to "tag" a water parcel is available. A more conventional current measuring device is the current meter. This paper will address the degree of comparability between fixed (Eulerian) and drifting (Lagrangian) current measuring devices.

The Great Lakes Environmental Research Laboratory began using small (30 kg) drogued satellite-tracked drifters in 1982 to verify a predictive circulation model. Since then, more than 18,000 km of tracks have been generated in the Great Lakes. In February 1983, three of these drifters were released in Lake Michigan in the vicinity of an array of vector-averaging current meters (VACMs). During the next 3 months, the drifters occasionally moved within a few kilometers of one of the moorings and remained in the vicinity for from several hours to over a day. The resulting data set consists of over 130 hours of concurrent Langrangian and Eulerian current measurements in seven separate interaction events ranging in length from 9 to 30 hours. Since this data set's very existence was coincidental, it has several inherent problems. The interactions are

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brief. No over-lake winds are available. Also, three of the four VACM moorings encountered by the drifters were located over a major topographic ridge where the circulation pattern is known to be complex. Despite these drawbacks, the data merit at least a brief analysis because they comprise one of only a few such sets of concurrent drifter buoy and current meter measurements.

The focus of this analysis will be the drifter movement. A drifter track is the result of an integration of all the forces acting on the drifter and its drogue: current, wind, and waves. Wave effects will be not be addressed due to lack of data. The VACM data will be used to represent the mean current against which the drifter movement will be compared. Since a small portion of the drifter's hull is exposed to the air, the drifter track is not a measure of the currents alone, but includes a certain amount of associated wind contamination. This wind effect has been calculated theoretically and measured in the field. For each interaction between VACM and drifter, the wind effect that most closely aligns the drifter vector with the current meter vector will be calculated. Finally, in addition to estimating the wind effect associated with these drifters, the percentage of variability between current meter and drifter vectors that is explained by this wind effect will be determined.

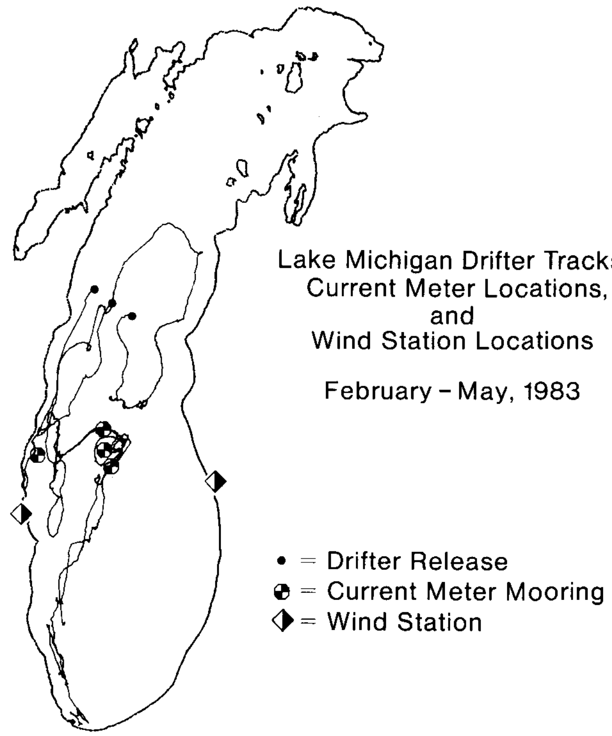


*FIG. 1. Location map showing drifter tracks, VACM mooring sites, and wind stations.*

## METHODS AND RESULTS

The three drifters were released from a car ferry between Ludington, Michigan, and Kewaunee, Wisconsin (Fig. 1). Each drifter remained in the lake until it beached, approximately 3 months later. The drifters' locations are estimated by the Doppler shift of signals transmitted to TIROS polar-orbiting satellites. Position calculations are accomplished by the ARGOS system in Toulouse, France. The positioning has been shown to be accurate to about 0.3 km in the Great Lakes (Pickett *et al.* 1983).

The drifters used in this experiment were mini-TOD's manufactured by Polar Research Laboratory in Carpinteria, California. The drifter is designed to ride low in the water and to carry a drogue for better current tracking. The drogue further increases the underwater surface area and thus reduces the relative effect of the wind operating on the exposed part of the drifter. The smaller the wind effect the less the buoy "slips" through the water relative to the current. The window shade drogue used was 3.5 m long by 0.6 m wide. The surface area ratio between the submerged and exposed parts of the drifter/drogue assembly is 25 to 1. Using the method of estimating slippage (with appropriate drag coefficients) due to wind developed by Kirwan *et al.* (1975), this equates to a 0.7% slippage. Thus, theoretically, the drifter's path is the resultant of 100% of the current and 0.7% of the wind. Various field tests comparing drifter motion to a dye patch have shown this windage figure to be reasonable (Pickett *et al.* 1983, McCormick *et al.* 1985). Now the question becomes, if a small percentage of the wind vector is used to "correct" the drifter track, how will the corrected track compare to the data recorded by the VACMs?

It is important to note that these data were collected under barotropic conditions. The VACMs were moored at depths of 15, 47, and 50 meters below the surface. The drifter with the described drogue assembly tracks the current at about 5 meters below the surface. In a stratified system, these depth differences would have to be resolved as the current velocities would be depth dependent.

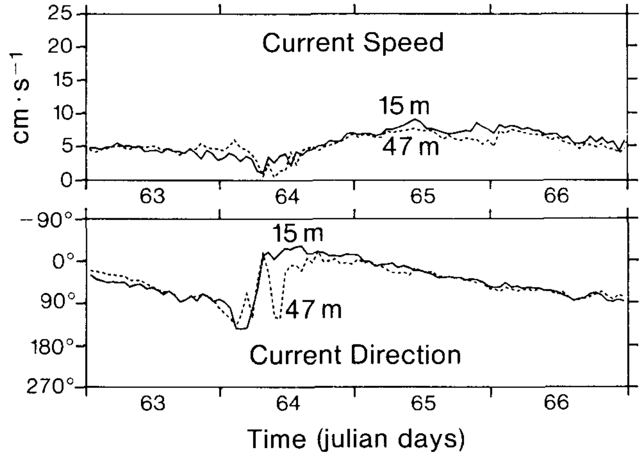


*FIG. 2. Current speed and direction for current meters at different depths on the same mooring. VACMs at 15 m and 47 m below the surface reveal vertical coherence of currents during this study.*

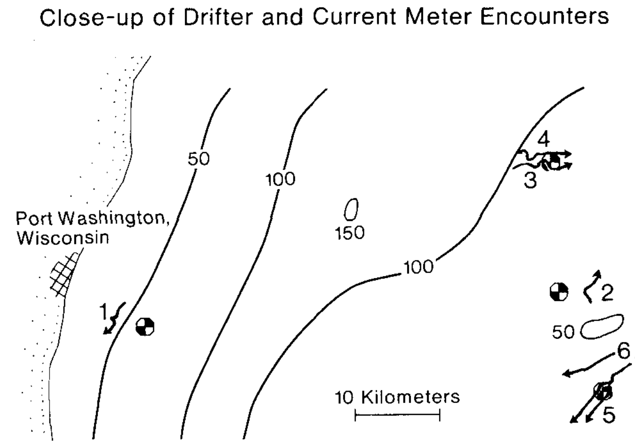


*FIG. 3. Close-up of seven cases during which a drifter remained within 5 km of a VACM for several hours. Bathymetry is shown in meters.*

The lack of significant current shear in the vertical profile is illustrated in Figure 2 which shows current speed and direction for two VACMs on the same mooring. In this figure, VACMs were moored at 15 m and 47 m below the surface in about 50 m of water. This 4-day record is representative of the rest. Speeds at depth may be slightly less, but direction is basically the same. Because of this, the assumption is made that the currents are vertically uniform.

The first step in the analysis was to standardize the three types of data. Drifter position fixes were obtained at irregular intervals; on average, eight fixes per day for each drifter. These positions were interpolated to hourly values. So as not to bias the results by tripling the size of the data base, every third position value from the interpolated data set was used in the analysis. Current meter data were recorded by the EG & G Savonius rotor VACMs at 15-minute intervals and then averaged to hourly values. Because these events took place in the winter and overlake winds were not available, wind data were obtained from the Milwaukee, Wisconsin, and Muskegon, Michigan, airports. These records were very similar. For the mid-lake cases, the two winds were simply averaged. For case No. 1, which took place in the Wisconsin coastal current, only Milwaukee winds were used. Wind stations are shown in Figure 1.

The seven interactions that took place involved three drifters and four current meter moorings (Fig. 3). Table 1 is a summary of details about each interaction. A 5 km cutoff was chosen based on the size of an inertial circle in Lake Michigan. A smaller cutoff value was attempted, but resulted in a data set too small for analysis. Using a 10 km cutoff yielded much poorer results. General observations of the horizontal coherence scales of surface currents (Boyce 1974) in the Great Lakes are on the order of 10 km, so the 5-km figure used here seemed to be a reasonable conservative boundary. To graphically summarize the entire data set, progressive vector diagrams of currents inferred from drifter trajectories, VACM measurements, and 2% of the wind vector were developed for each of the seven cases (Fig. 4). This wind percentage was chosen for ease of display. In all but one case, the drifter trajectory was offset from the current meter trajectory in the direction of the wind. Both current and drifter trajectories are to the right of the wind in most cases, as would be expected due to the Coriolis force. The angle of separation between the drifter vector and the current meter vector is generally 10°–40°. The drifter speeds were 1.0–1.5 times as great as the current meter speeds. The average angle of separation between the wind vector and current meter vector was 75°. This is much higher than wind/surface current deflection angles found in Lake Michigan (Saylor 1964) and the oceans (Kirwan *et al.* 1979, Peterson 1985).

The next step was to determine how much of the discrepancy between the current meter and drifter

*TABLE 1. Conditions*

| Case | Duration (hours) | Initial Separation (km) | Drifter Path (km) | Average Wind Speed (m/s) | Current meter depth from surface (m) |
|---|---|---|---|---|---|
| 1 | 18 | 3.4 | 4.5 | 5.4 | 15 |
| 2 | 12 | 3.8 | 3.9 | 6.1 | 15 |
| 3 | 27 | 4.2 | 7.4 | 1.7 | 50 |
| 4 | 27 | 3.9 | 6.6 | 1.7 | 50 |
| 5 | 9 | 0.8 | 3.9 | 5.8 | 47 |
| 6 | 12 | 4.5 | 5.5 | 5.7 | 47 |
| 7 | 30 | 4.4 | 9.6 | 5.0 | 47 |

vectors could be explained by the wind. It is assumed that the current meter measurements are equivalent to the "true" current at the drogue center-of-effort. Using the relationship:

$$C = D - aW \quad (1)$$

where a = wind factor
$C$ = current meter vector
$D$ = drifter vector
$W$ = wind vector

the scalar wind factor, a, represents the fraction of the wind vector needed to align the drifter and current meter vectors. This was determined separately for each of the seven cases by minimizing the error between current and drifter trajectories. The resulting wind percentages ranged from 0.06% to 2.09% (Table 2). The average value, weighted by number of hours, was 0.76%.

To determine how well the wind explains the difference between the current meter and drifter, these wind percentage figures were used to calculate a predicted current vector (or, a "corrected" drifter vector) according to equation 2. The individually calculated wind factors (a) were used here.

$$C_p = D - a \cdot W \quad (2)$$

where $C_p$ = predicted current vector.

These results are shown in the form of progressive vector diagrams in Figure 5.

As a measure of the accuracy of the current prediction, the root mean square (rms) difference between observed and predicted currents was calculated in terms of distance as:

$$E_a = \left(\frac{1}{n}\sum_{i=1}^{n} \left| (C_i - C_{pi})\Delta t_i \right|^2\right)^{1/2} \quad (3)$$

where n is the number of observations (hours divided by 3) and $\Delta t$ is 3 hours. This quantity was compared to the rms difference between current inferred from the observed drifter trajectory and the trajectory calculated from current meter observations,

$$E_b = \left(\frac{1}{n}\sum_{i=1}^{n} \left| (C_i - D_i)\Delta t_i \right|^2\right)^{1/2} \quad (4)$$

The ratio of these two quantities is

$$\text{Error Ratio} = E_a/E_b$$

which provides an estimate of the accuracy of the predicted trajectory. If this ratio is equal to 1, the prediction is no better than the uncorrected drifter trajectory. The closer the ratio is to zero, the better the prediction of the current trajectory by equation 2. It is assumed that $E_b$ is never zero, because current meter and drifter measurements are not identical due to wind and waves. Error ratios range from 0.2 to 0.99. The results for the seven cases are summarized in Table 2.

## DISCUSSION

One of the goals of this analysis was to determine what wind effect value was appropriate to use to "correct" the drifter track, making it a better estimator of near-surface currents. As seen in Table 2, the weighted average for the windages calculated was 0.76%. This value compares well with those determined theoretically (0.7%) and in field studies (0.51%) by McCormick *et al.* (1985).

Another goal was to see how much of the discrepancy between drifter and current meter movement can be accounted for by making a simple wind correction. Using the wind percentages which

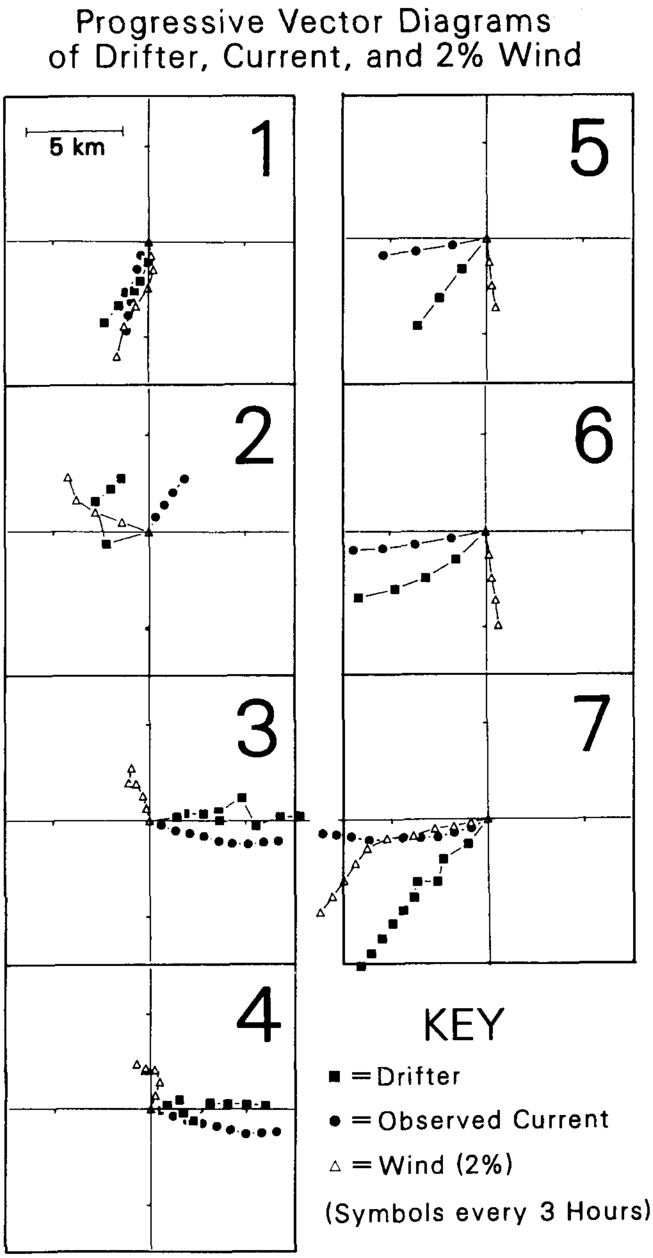


*FIG. 4. Progressive vector diagrams of VACM, drifter, and 2% of the wind for all cases. Note that the VACM and drifter did not have the same origin but are shown that way on the graph for purposes of comparison.*

were calculated separately for each interaction, current trajectory predictions were derived for each case as "corrected" drifter movement. The quality of these predictions was measured by comparing the rms differences between observed and predicted currents to those found between observed current and current inferred from drifter trajectories (equations 3, 4, and 5). The error ratio, $E_a/E_b$, indicates whether the prediction was an improvement over the uncorrected drifter trajectory. It is a measure of the amount of difference between VACM and drifter vectors *not* accounted for by the wind correction. For example, in case 6, 23% of the difference is not explained by making the wind correction; conversely, 77% of the difference is attributed to the wind. Note that these error ratios are only a measure of the importance of the wind correction, they do not summarize the difference between the drifter and VACM vectors.

It should be noted that windage is clearly not the only difference between Eulerian and Lagrangian measurements. Stokes, in 1847, first derived his second order wave theory which suggests that there is mass transport in the horizontal due to wave motion. Stokes drift was later defined by Longuet-Higgins (1969) as the net horizontal drift experienced by a particle due to wave motion:

$$\text{Lagrange} = \text{Euler} + \text{Stokes}$$

The Stokes velocity may, depending on time and space scales, exceed the Euler component and may also oppose the direction of the mean current. The size and true definition of Stokes drift has been controversial (Ramster and Durance 1975), but its existence as an important component of Lagrangian motion is not disputed. Nath and Hudspeth (1983) estimated the effects of surface waves on spar, spherical, and discus drifting buoys in a wave flume. They found the Stokes drift to be more pronounced for spar buoys (the mini-TOD is a spar buoy). Although the data set does not include any wave information, it must be acknowledged that waves could be a significant factor in the difference between current meter and drifting buoy measurements.

When looking at the results in Figure 5, it is helpful to consider the conditions present during each case. In cases 1 and 7 the error ratio is effectively equal to 1, implying the wind accounted for little of the difference between the drifter and current meter vectors. Case 1 took place within 10 km of the Wisconsin shoreline. The hydrodynamics of the coastal zone may account for this high error ratio, as wind may be less important here than in the open lake due to the strength of the coastal current. Murthy (1973), however, obtained favorable results in a comparison between drifters and current meters conducted in the coastal zone of

*TABLE 2. Model results*

| Case | Windage a (%) | Corrected RMS Difference $E_a$ (km) | Observed RMS Difference $E_b$ (km) | Error Ratio $E_a/E_b$ |
|---|---|---|---|---|
| 1 | 0.06 | 0.72 | 0.73 | 0.99 |
| 2 | 1.33 | 2.21 | 3.29 | 0.67 |
| 3 | 0.84 | 1.19 | 1.47 | 0.81 |
| 4 | 0.65 | 0.94 | 1.36 | 0.69 |
| 5 | 2.09 | 0.93 | 2.95 | 0.32 |
| 6 | 1.05 | 0.46 | 2.00 | 0.23 |
| 7 | 0.47 | 4.19 | 4.26 | 0.93 |
| Weighted Average | 0.76 | 1.75 | 2.27 | 0.74 |

Lake Ontario. A close look at the results for case 1 (winds are more visible in Fig. 4) reveals the drifter and VACM are in good agreement for both speed and direction, despite the high error ratio, indicating that some other force besides wind, perhaps wave action and resulting Stokes drift, is causing the difference between them.

Looking at case 7 (Fig. 5), it appears that a shift in wind from east to northeast is quickly reflected by the drifter but not the current meter. This illustrates the lag time between forcing (wind) and response (currents). In a large system such as Lake Michigan, the response to a change in overlake winds is gradual even under barotropic conditions. A seen in the progressive vector diagram, the drifter responds quickly to the change in wind direction, while the VACM reveals the persistence of current patterns. For this case, if a lag of several hours was inserted between the wind and current vectors the results would be better, in effect allowing the currents to "catch up" with the wind. It should also be noted that there was a greater discrepancy between wind directions recorded in Milwaukee and Muskegon for this case than for any other.

The best results—cases 5 and 6—were from the shortest interactions, 9 and 12 hours. For these cases, the wind correction accounted for 68% and 77% of the difference between drifter and current meter. The rms difference, $E_a$, in case 6 of 0.46 km is approaching the position accuracy of the drifter (0.3 less than 1 km while in case 6 it was 4.5 km. Yet, the results for the two cases are very similar. This affirms the assumption about horizontal coherence, at least in this case.

In cases 1, 3, and 4, wind accounts for only 20-30% of the difference between vectors. It is tempting to conclude that the longer the interaction, the less useful are windage estimates for explaining the difference between drifter and current meter vectors. Because cases 3 and 4 were during a period of extreme calm (12 hours of 0 wind recorded at both airports) wind would not be expected to be a factor in the difference between trajectories. Another likelihood is that the airport winds do not reflect true overwater conditions. Translating the land-based wind speeds and directions to their overwater equivalents may improve results. Using equations based on the air-water temperature differential described in Schwab (1983), the overlake wind speeds would be increased by from 1 to 5 m/s over land-based speeds. There would also be a clockwise rotation between overland and overwater wind vectors of 6°–10°. This would appear to significantly improve the results in cases 1 and 7.

The question of what the drifter is really tracking is of critical interest to the many diverse users of Lagrangian platforms. Drifters have been used not only to verify predictive trajectory models but also as free-floating biological sampling stations (Scavia and Fahnenstiel 1987). For either application, it is important to understand any bias in the drifter motion that could affect interpretation of data. The weighted average error ratio for all cases is 0.74, which means only 26% of the difference between drifter and VACM progressive vectors was accounted for by the wind. This leaves most of the difference to be explained by other factors, such as Stokes drift or lower-than-expected coherence in the current structure. If the current meter measurements are accepted as the true mean current, it can be concluded that these drifters are not tracking the same current, even under barotropic conditions

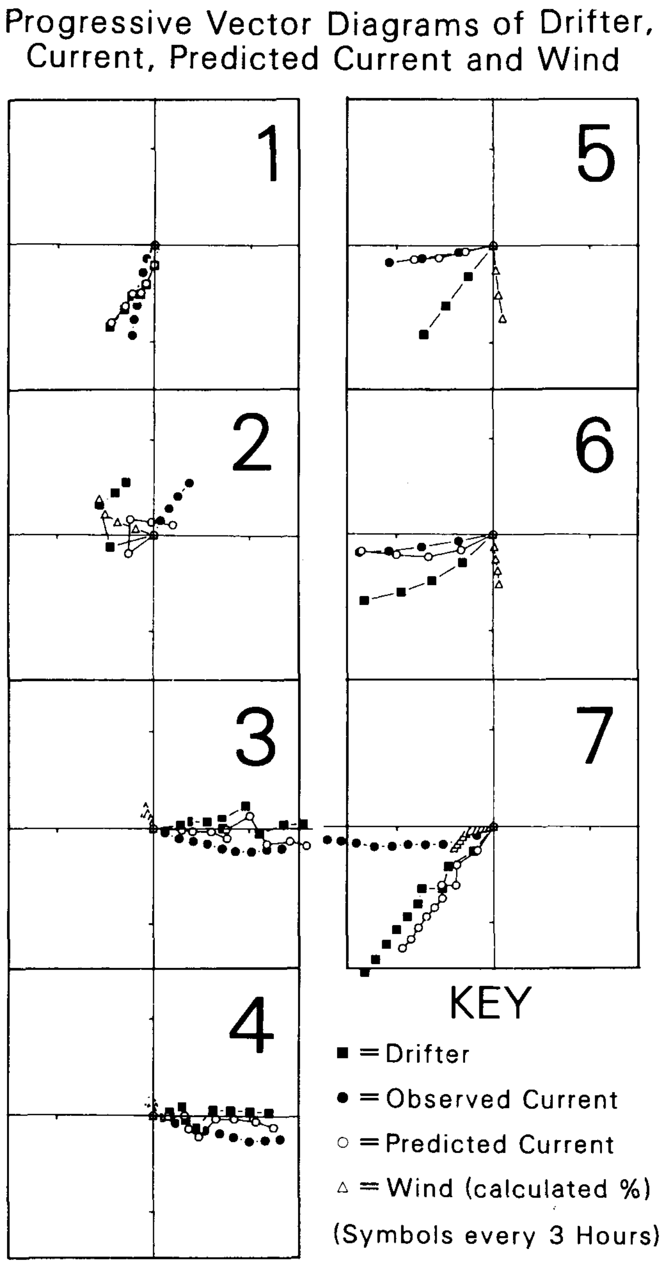


*FIG. 5. Progressive vector diagrams of VACM, drifter, calculated percentage of wind, and predicted current. See analysis in Table 2.*

over short time periods. However, the actual separation distances between VACM and corrected drifter progressive vectors ($E_a$ in Table 2) are quite small; in most cases less than 1 km when distance traveled ranged from 4 to 9 km. Given that the different current measurements were made up to 5 km apart, this indicates a good degree of horizontal coherence during most of these interactions.

However, the area in which most of the drifter/current meter interactions took place is one of complex current patterns. The three closely spaced moorings (Fig. 3) were positioned over the mid-lake topographic ridge which separates the southern and northern basins of Lake Michigan. The deep VACMs were only about 3 m above the bottom. Monthly statistics (Saylor and Miller, personal communication) revealed significant differences between the three moorings just over 10 km apart. These differences remain unexplained. The assumption was made that currents were horizontally coherent within 5 km. While this appears, based on the data, to be a reasonable assumption, it is likely that coherence problems are contributing to the unexplained difference between drifter and current meter measurements.

## SUMMARY AND CONCLUSIONS

A data set involving drogued drifting buoys and concurrent VACM measurements from Lake Michigan was examined. Trajectories were compared, and the amount of the discrepancy attributable to drifter windage was calculated for each case. The results in terms of separation distance were surprisingly good, with typical separations of less than 1 km distance traveled ranged from 4 to 9 km. The assumption of a horizontal current coherence scale of 5 km seemed to be accurate, although on a broader scale, about 10 km, the horizontal coherence was very low. The average wind effect that best aligns the drifter and current meter vectors was 0.76%. This figure agrees well with the value 0.7% determined theoretically and with the value 0.51% measured in a dye study. For the entire data set, only about 25% of the difference between the measurements made by drifter and VACM can be explained by the wind effect alone. The rest may be attributable to wave action, coherence problems, or data deficiencies. Caution is urged when using drifters to estimate deeper currents even during isothermal conditions over short time periods.

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