CURRENTS, TEMPERATURES, AND DIVERGENCES OBSERVED IN EASTERN CENTRAL LAKE MICHIGAN DURING MAY-OCTOBER 1984

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ABSTRACT. An array of four instrumented moorings covering an area of 150 km² was in place approximately 40 km offshore in eastern central Lake Michigan during May-October 1984. Each mooring supported current meters at the depth levels 5, 10, 20, 30, 50, and 100 m, and a thermistor chain between 6 and 46 m depth. The current velocity data were used to compute the divergence and curl across the array area at each depth level. Two or three events of large southeastward currents, north-south alternating wind bursts, upwelled thermocline, and increased positive divergence and negative curl were observed from mid-August to early September.

1. INTRODUCTION

During May-October 1984 a triangular-shaped array of four pairs of instrumented moorings collected data approximately 40 km offshore in eastern central Lake Michigan (Figure 1). The mooring pairs were spaced 10 and 17 km apart, and each pair supported EG&G vector-averaging current meters (VACMs) at 5, 10, 20, 30, and 50 m depth and at 1 m above the bottom, and a thermistor chain between 6 and 46 m depth (Figure 2). The primary moorings (1, 2, 3, and 4) supported the VACMs at 10, 20, 30, and 50 m depth, and the secondary moorings (1A, 2A, 3A, and 4A) supported the VACMs at 5 m depth and 1 m above the bottom, and the thermistor chains. The position, water depth, and deployment and recovery times for each mooring pair are listed in Table 1. Data from the VACMs on mooring 4 at 3, 5, 7, and 9 m above the bottom were used to study the velocity structure within the bottom Ekman layer (Saylor and Miller, 1986, 1988). Readers interested in bottom boundary layer phenomena are directed to the 1988 paper.

This report contains plots of the current velocities (Figure 3 and Appendix A), water temperatures (Appendices B and C), divergence and curl computed across the array area at each depth level (Appendices C and D), and meteorological data (Figure 4) from the National Data Buoy Center (NDBC) buoy 45007 in south central Lake Michigan (see Figure 1 for location). These data show the spatial (both horizontal and vertical) and temporal variability of the currents and thermal structure in Lake Michigan during spring and summer.

2. DATA DESCRIPTION

The water depth and starting and stopping times of the data collection period are listed for each instrument in Table 2. All moorings except 1 and 1A were deployed at their intended water depths, so the reference and actual depths are equal (for the VACMs at 1 m above the bottom, the reference depth is 100 m). All instruments yielded full data returns except VACM 556 (mooring 3, 50 m), which malfunctioned from deployment until July 13, and VACM 571 (mooring 3A, 100 m), which malfunctioned during the periods July 15-16 and August 1-8.

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The velocity and temperature data were recorded by the VACMs at 15-minute intervals, and later averaged at hourly intervals. The thermistor data were recorded at hourly intervals. The meteorological data (barometric pressure, air temperature, and wind stress computed from velocity at 5 m above the lake surface) were measured from the NDBC buoy at hourly intervals. All aforementioned hourly data are herein referred to as “raw” data. A Cosine-Lanczos filter with a 60-point taper (40-hour half-power point), described by Mooers and Smith (1968), was applied to all raw data. Unless otherwise noted, all computations and data presentations described here use the filtered data.

3. COMPUTATIONS

To examine the variability of the currents and temperatures, and to provide evidence of upwelling and downwelling events, the divergence \( \nabla \cdot \mathbf{V} \) and curl \( \nabla \times \mathbf{V} \) of the horizontal current velocity field \( \mathbf{V} = u \mathbf{x} + v \mathbf{y} \) (where boldface denotes vector quantities, \( u \) and \( v \) are the measured velocity components, and \( \mathbf{x} \) and \( \mathbf{y} \) are unit vectors in the east and north directions) were computed across the array area at each depth level (Appendix C). The water temperatures are also plotted in Appendix C for comparison with the divergences (positive divergence in the surface layer indicates upwelling, negative divergence indicates downwelling). To examine the spatial scale of the variability, the divergence was also computed separately (Appendix D) across each of the three small triangles (see Figure 1) of the array area.

The wind stress (Figure 4) was computed using \( \tau = C_d W^2 \), where \( W \) is the measured wind speed and \( C_d(W) \) is the drag coefficient computed using the method of Liu and Schwab (1987). Under the assumption of no air-sea temperature difference (i.e., neutral stability), \( C_d \) becomes an almost linear function of \( W \). For the data in Figure 4, the minimum, maximum, mean, and standard deviation values of \( C_d \) are 0.00012, 0.00215, 0.00102, and 0.00026.

Figure 1.—Location and schematic diagram of the array of instrumented moorings. The curl and divergence (Appendix C) are computed across the big triangle (123), and the separated divergences (Appendix D) are computed across the smaller, labeled triangles (124, 234 and 134).
Figure 2.—Schematic diagrams of the moorings indicating current meter (VACM) and thermistor depths. Data from the five near-bottom current meters on mooring 4 were described by Saylor and Miller (1988).

4. DATA PRESENTATIONS

At the two offshore locations (moorings 1 and 2), the monthly-averaged current velocities (Figure 3) were very small from May to August. Inshore (moorings 3 and 4), the currents were also very small in June and July, although the northeastward surface layer drift (above 20-30 m depth) in July appears well correlated with the weaker surface flow offshore. During August a strong southeastward surface current and a weaker east-southeastward current developed at the most shoreward and center moorings (3 and 4), respectively. Comparing the bidaily-averaged currents (Appendix A) and the wind stress (Figure 4) shows that the strong southeastward surface currents characterized the lake’s response to the north-south-alternating, 2-day-long wind bursts that occurred after mid-August. The wind was steady and southerly during the last week in August, but abruptly changed to a pattern of mostly north-south-alternating, 2- to 4-day-long intense wind stress impulses that continued throughout much of September.

During September, the monthly-averaged inshore currents (Figure 3) were southward throughout the surface layer, while the offshore currents were strongly sheared throughout the entire water column (i.e., southwestward flow at mooring 2 and mostly northeastward flow at mooring 1). The divergent surface flow (i.e., volume outflow from the surface layer) suggested from this pattern was confirmed by computation at each depth level (Appendix C). During the last week in August the computed divergence became increasingly large and positive (i.e., volume outflow), especially in the surface layer, and remained so throughout most of September.
### Table 1.

<table>
<thead>
<tr>
<th>Mooring</th>
<th>Latitude (deg min sec)</th>
<th>Longitude (deg min sec)</th>
<th>Water Depth (m)</th>
<th>Deployment Date</th>
<th>Recovery Date</th>
<th>Recovery Time (EST)</th>
<th>Distance Between Moorings (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>43° 05′ 44.0″</td>
<td>86° 42′ 47.4″</td>
<td>107</td>
<td>May 10 0945</td>
<td>Oct. 16 1415</td>
<td>275</td>
<td></td>
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<tr>
<td>2</td>
<td>42° 56′ 07.4″</td>
<td>86° 42′ 35.1″</td>
<td>97.3</td>
<td>June 6 1025</td>
<td>Oct. 16 1015</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>2A</td>
<td>42° 56′ 09.9″</td>
<td>86° 42′ 33.7″</td>
<td>97.3</td>
<td>June 6 1120</td>
<td>Oct. 16 1210</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>43° 00′ 54.0″</td>
<td>86° 31′ 28.7″</td>
<td>91</td>
<td>May 10 0920</td>
<td>Oct. 16 1525</td>
<td>430</td>
<td></td>
</tr>
<tr>
<td>3A</td>
<td>43° 01′ 08.2″</td>
<td>86° 31′ 37.8″</td>
<td>91</td>
<td>May 10 1110</td>
<td>Oct. 15 1200</td>
<td>430</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>43° 00′ 52.1″</td>
<td>86° 39′ 00.0″</td>
<td>97.3</td>
<td>June 6 1755</td>
<td>Oct. 15 1015</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>4A</td>
<td>43° 00′ 55.1″</td>
<td>86° 38′ 58.8″</td>
<td>97.3</td>
<td>June 6 1840</td>
<td>Oct. 15 1100</td>
<td>88</td>
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### Table 2.

<table>
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<tr>
<th>Instrument</th>
<th>Moor- Type and #</th>
<th>Reference/ Actual Depth* (m)</th>
<th>Start Point Date</th>
<th>Start Point Time (EST)</th>
<th>Stop Point Date</th>
<th>Stop Point Time (EST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VACM 347</td>
<td>1A</td>
<td>5 / 8</td>
<td>May 10 1200</td>
<td>Oct. 16 1300</td>
<td></td>
<td></td>
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<tr>
<td>VACM 572</td>
<td>1</td>
<td>10 / 6.3</td>
<td>May 10 1300</td>
<td>Oct. 16 1300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 279</td>
<td>1</td>
<td>20 / 16.3</td>
<td>May 10 1700</td>
<td>Oct. 16 1300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 352</td>
<td>1</td>
<td>30 / 26.3</td>
<td>May 10 1200</td>
<td>Oct. 16 1300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 552</td>
<td>1</td>
<td>50 / 46.3</td>
<td>May 10 1200</td>
<td>Oct. 16 1300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 575</td>
<td>1A</td>
<td>100 / 107</td>
<td>May 10 1200</td>
<td>Oct. 16 1300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 3 5 3</td>
<td>2A</td>
<td>5 / -</td>
<td>June 6 1400</td>
<td>Oct. 16 1100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 5 8 4</td>
<td>2</td>
<td>10 / -</td>
<td>June 6 1300</td>
<td>Oct. 16 0900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 275</td>
<td>2</td>
<td>20 / -</td>
<td>June 6 1300</td>
<td>Oct. 16 0900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 570</td>
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<td>30 / -</td>
<td>June 6 1300</td>
<td>Oct. 16 0900</td>
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<td></td>
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<tr>
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<td>Oct. 15 1200</td>
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<td></td>
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<tr>
<td>VACM 315</td>
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<td>30 / -</td>
<td>May 7 1100</td>
<td>Oct. 15 1200</td>
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<td></td>
</tr>
<tr>
<td>VACM 556</td>
<td>3</td>
<td>50 / -</td>
<td>July 13 0200</td>
<td>Oct. 15 1200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 571</td>
<td>3A</td>
<td>100 / 90</td>
<td>May 7 1300</td>
<td>Oct. 15 1200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 555</td>
<td>4A</td>
<td>5 / -</td>
<td>June 6 2100</td>
<td>Oct. 15 1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 550</td>
<td>4</td>
<td>10 / -</td>
<td>June 6 2100</td>
<td>Oct. 15 0900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 274</td>
<td>4</td>
<td>20 / -</td>
<td>June 6 2000</td>
<td>Oct. 15 0900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 349</td>
<td>4</td>
<td>30 / -</td>
<td>June 6 2000</td>
<td>Oct. 15 0900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 569</td>
<td>4</td>
<td>50 / -</td>
<td>June 6 2000</td>
<td>Oct. 15 0900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VACM 574</td>
<td>4A</td>
<td>100 / 101</td>
<td>June 6 2000</td>
<td>Oct. 15 0900</td>
<td></td>
<td></td>
</tr>
<tr>
<td>THERM 316</td>
<td>1A</td>
<td>6-46 / 9-49</td>
<td>May 10 1200</td>
<td>Oct. 16 1300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>THERM 313</td>
<td>2A</td>
<td>6-46 / -</td>
<td>June 6 1400</td>
<td>Oct. 16 1100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>THERM 315</td>
<td>3A</td>
<td>6-46 / -</td>
<td>May 7 1300</td>
<td>Oct. 15 1200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>THERM 305</td>
<td>4A</td>
<td>6-46 / -</td>
<td>June 6 2100</td>
<td>Oct. 15 1000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The reference (intended) depths are the VACM depth levels (5, 10, 20, 30, 50, and 100 m) referred to throughout this report (the VACMs at 100 m reference depth were actually 1 m above the bottom). The reference and actual depths of the instruments on moorings 1 and 1A differ because of fathometer error during the mooring deployment.
Figure 3.--Monthly-averaged currents computed from the raw data at each depth level for each mooring. The sticks point toward the direction the current is heading (north is up).

From mid-August until September 7, the thermocline (Appendices B and C) was determined to be steadily upwelling (most notable inshore at the 20 and 30 m depth levels), but thereafter abruptly downwelled to its normal, late-summertime depth level (about 24-28 m). The upwelling thermocline correlated well with the divergent surface flow during the same period. The divergent surface flow would have caused a lowering of the still-water level by about 1 m if it had not been balanced by convergence (volume inflow) at some deeper level. Interestingly, convergence was not observed at the 50 or 100 m depth levels (Figs. C.5 and C.6). Also, the divergence occurred mainly across the offshore triangle of moorings (triangle 1, Appendix D).

Sample plots of the raw velocity and temperature data during August and September from 20 m depth at moorings 1 and 3 (Appendix E) reveal intense and omnipresent near-inertial-period oscillations (of about 18-hour period) of the thermocline surface. It is believed that the modulation of the inertial oscillation envelope is due to the concurrent propagation of basin-scale internal waves of near-inertial periodicity (Mortimer, 1971). The observed thermocline oscillations were used in a study of primary production variations caused by thermocline depth fluctuations (Fahnenstiel, et al., 1988).

5. REFERENCES


Figure 4.—Low-pass filtered, bidaily-averaged wind stress (bottom panel, the sticks point toward the direction the wind is heading), barometric pressure (middle panel), and air temperature (top panel) at 5 m above the water surface in south central Lake Michigan (see Figure 1 for location).
Appendix A: Bidaily-Averaged Currents

Stick diagrams of low-pass-filtered, bidaily-averaged currents for each mooring, at the following depths:

- Figure A.1–5 m
- Figure A.2–10 m
- Figure A.3–20 m
- Figure A.4–30 m
- Figure A.5–50 m
- Figure A.6–100 m

The sticks point toward the direction the current is heading (north is up).
Currents: -5 m

Mooring #4

Mooring #3

Mooring #2

Mooring #1

Lake Michigan 1984

Figure A 1
Currents: -10 m

Mooring #4

Mooring #3

Mooring #2

Mooring #1

Lake Michigan 1984

Figure A.2
Currents: -2° m

Mooring #4

Mooring #3

Mooring #2

Mooring #1

Lake Michigan 1984

Figure A.3
Currents: -50 m

Mooring #4

Mooring #3

Mooring #2

Mooring #1

Lake Michigan 1984

Figure A.5
Figure A.6

Lake Michigan 1984

Mooring #1

Mooring #2

Mooring #3

Mooring #4

Currents: -100 m
Appendix B: Thermistor Temperatures

Plots of low-pass-filtered thermistor temperatures for the following moorings:

Figure B.1–Mooring 1
Figure B.2–Mooring 2
Figure B.3–Mooring 3
Figure B.A–Mooring 4

Thermistors 1-11 were located at the corresponding depths indicated on the left vertical axis. The heavy vertical lines indicate the period of usable data.
Thermistor Temperatures (°C): Mooring #2

Lake Michigan 1984

Figure B.2
Appendix C: Temperatures, Divergences, and Curls

Plots of low-pass-filtered temperatures for each mooring (bottom panel), and divergences and curls (top panel) computed across the big triangle (see Figure 1), at the following depths:

Figure C.1–5 m
Figure C.2–10 m
Figure C.3–20 m
Figure C.4–30 m
Figure C.5–50 m
Figure C.6–100 m

For clarity, the temperature curves are offset along the vertical axis by the indicated offset value.
Temperature and Divergence: -5 m

Offset = 2.0 °C

Lake Michigan 1984

Figure C.1
Temperature and Divergence: -10 m

-offset = 2.0 °C

Lake Michigan 1984

Figure C.2
Temperature and Divergence: \(-20\) m

Offset = 3.0 °C

Lake Michigan 1984

Figure C.3
Figure C.4

Temperature and Divergence: -30 m

Offset = 4.0 °C

Lake Michigan 1984
Offset = 0.3 °C

Lake Michigan 1984

Figure C.5
Temperature and Divergence: -100 m

Offset = 0.5 °C

Lake Michigan 1984

Figure C.6
Appendix D: Separated Divergences

Figure 7. Plots of low-pass-filtered divergences computed across the three small triangles (see Figure 1), at the following depths:

- Figure D.1—5 m
- Figure D.2—10 m
- Figure D.3—20 m
- Figure D.4—30 m
- Figure D.5—50 m
- Figure D.6—100 m
Divergences (Separated): -10 m

Triangle #3

Triangle #2

Triangle #1

Lake Michigan 1984

Figure D.2
Divergences (Separated): −20 m

Triangle #3

Triangle #2

Triangle #1

Lake Michigan 1984

Figure D.3
Divergences (Separated): -30 m

Triangle #1

Triangle #2

Triangle #3

Lake Michigan 1984

Figure D.4
Divergences (Separated): -50 m

Triangle #3

Triangle #2

Triangle #1

Lake Michigan 1984

Figure D.5
Lake Michigan 1984

Figure 0.6
Appendix E: Raw vs. Filtered Data

Sample plots comparing the raw and the low-pass-filtered data during the months of August and September at 20 m depth. Shown are the u-component of current, v-component, and temperature for moorings 1 (Figures E.1-E.3) and 3 (Figures E.4-E.6).
Raw and Filtered Data: Mooring #1 -20 m

Lake Michigan 1984

Figure 6.3
Raw and Filtered Data: Mooring #3 -2° m

Lake Michigan 1984

Figure E.4
Raw and Filtered Data: Measuring #3 -20m

-50 -40 -30 -20 -10 0 10 20 30 40 50

V (cm/s)

AUGUST SEPTEMBER

Lake Michigan 1984

Figure E.5
Raw and Filtered Data: Mooring #3 -20 m

Temperature (°C)

Lake Michigan 1984

Figure E 6