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OBSERVATIONS OF THE FALL OVERTURN OF LAKE MICHIGAN[1]

Temperature records from buoy stations occupied by the U.S. Public Health Service (Great Lakes-Illinois River Basins Project) have been examined for the winter seasons of 1962–1963 and 1963–1964. These data have yielded direct, quantitative evidence of the fall overturn process that occurs in large lakes having a well-developed summer thermocline. The temperature recorders were a Bourdon-tube-driven stylus scribing on waxed chart paper. The temperature span was 0 to 30C on a 70-mm scale. A clock-driven motor transported the paper in steps every 30 min. The timebase of the recording was a transport of ⅙ cm in 30 min.

Each station had a temperature recorder at 10, 15, 22, 30, and 60 m, and every subsequent 30-m level down to the bottom. All of the data were read to the nearest indicated 0.1C. The overall accuracy of carefully calibrated temperature recorders appeared to be about ± 0.3C. Temperature corrections were applied from calibration marks put on the charts before the meters were set on station and again after they were removed from the water. The recorders were on station from the first week of December until the end of April. The locations of the temperature recording stations mentioned in this paper are shown in Fig. 1.

The operational definition for the determination of wind-mixing at any given level was that there should be a fluctuation of the temperature greater than 0.3C within the day. A short-term rise of the temperature at a given level indicated that warmer water had been mixed downward by the influence of the wind.

The most dramatic evidence of wind-driven mixing into the lower layers of the lake was the temperature recording from

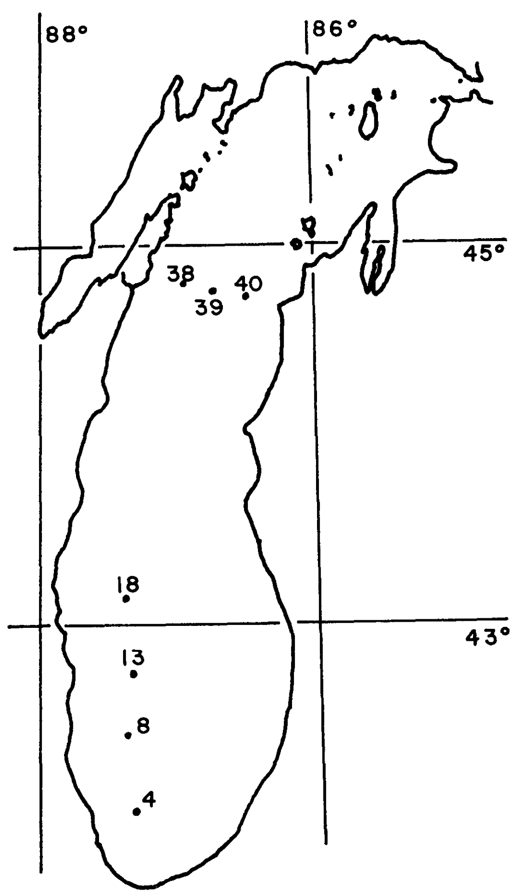

FIG. 1. Index map showing locations of selected temperature recording stations.

[1] Contribution No. 57 from the Great Lakes Research Division, University of Michigan. The research was supported by the Atmospheric Sciences Section, National Science Foundation Grant GP-2411.

TABLE 1. *Temperature record, Station 39, 16–19 December 1962, depth 240 m, recording interval 30 min, 44°45′N lat, 86°45′W long, no temperature calibration*

Time ending	Date 16 Dec	17 Dec	18 Dec	19 Dec
0130	6.0	6.5	7.0	7.0
0300	6.0	6.8	7.0	6.9
0430	6.0	6.9	7.0	6.8
0600	6.0	6.9	7.0	6.9
0730	6.0	6.9	6.9	6.9
0900	6.0	6.9	6.7	6.7
1030	6.1	6.9	6.8	6.7
1200	6.1	6.9	6.8	6.4
1330	6.1	6.9	6.8	6.1
1500	6.0	6.9	6.8	6.1
1630	6.0	6.9	6.9	6.1
1800	6.1	7.0	6.9	6.1
1930	6.1	7.0	6.9	6.1
2100	6.1	7.0	6.9	6.1
2230	6.1	7.1	6.8	6.1
2400	6.3	7.1	7.0	6.1

the 240-m level at station 39 (44°45′N lat, 86°45′W long) during December 1962. Unfortunately, this specific instrument was not adequately calibrated for absolute accuracy but yielded reliable relative readings. From 2 through 14 December 1962, the indicated temperature at the 240-m level was 6.0C with occasional slow drifts to 5.9C or 6.1C. Evidences of wind-mixing began to appear on 14 December. Table 1 presents the temperatures as read for the period 16 through 19 December. Sufficient mixing occurred to raise the temperature from 6.1C at 2230 on 16 December to 6.5C at 0130 on 17 December and to 6.9C at 0430 on 17 December.

A summary of the temperature readings during the periods defined as wind-mixing at the 240-m level of station 39 during the 1962–1963 season (Table 2) shows that during the 10-day period of 15–25 December, the average temperature of the water at this level was raised by 0.4C. The magnitude and speed of the temperature fluctuations at this level indicate that they were a wind-driven phenomenon, and not the result of a gradual heating or cooling of the water of the lake. The net change of the average temperature demonstrates that the observed fluctuations were the result of a true mixing process and not merely a measurement of an internal wave, seiche, or any similar event.

TABLE 2. *Wind-mixing at Station 39, 15–25 December 1962, depth 240 m, 44°45′N lat, 86°45′ W long, no temperature calibration*

Date	Temperature, C Avg	High	Low	Avg preceding day	Avg following day
15 Dec	6.1	6.3	6.0	6.1	
16 Dec	6.1	6.3	6.0		
17 Dec	6.9	7.1	6.5		
18 Dec	6.9	7.0	6.8		
19 Dec	6.4	7.0	6.1		6.2
22 Dec	6.2	6.5	6.0	6.2	
23 Dec	6.3	6.6	6.1		
24 Dec	6.5	6.7	6.3		
25 Dec	6.5	6.7	6.4		6.5

Six stations were occupied during the 1962–1963 season, and 18 stations were occupied during the 1963–1964 season. All of the records from the 1963–1964 season were examined for indications of storm mixings. These indications have contributed to a description of the fall overturn and cooling of the water mass of the lake. As the water is cooled from the surface, the summer thermal stratification is reduced, and the depth of the mixed layer increases until wind-driven mixing occurs down to the bottom of the lake basin.

Table 3 shows the date of occurrence of the first wind-mixing observed at 30-m and greater depths during the 1963–1964 season. The winter of 1963–1964 was considerably warmer than that of 1962–1963. The upper recorders (10-, 15-, and 22-m) were generally above the thermocline and would be expected to show evidences of mixing throughout the year. Because of the late starting date of the temperature records, it is uncertain whether the first mixing date for the 30-m level is the first actual mixing of the fall season. The depth of mixing generally increases with the onset of winter. Station 39 was not occupied during the 1963–1964 season.

Comparison of the first mixing statistics with the weekly average temperature data (computed for each of the temperature re-

TABLE 3. *Date of occurrence of first observed wind-mixing, November and December 1963, January 1964*

Depth (m)	Date	Station
30	23 Nov	4, 13, 18
60	30 Nov	8, 18
90	3 Dec	38
120	3 Dec	38
150	9 Dec	38
180	1 Jan	40

corders and reported elsewhere, Heap and Noble 1965; Noble 1965) shows some broad features that describe the mixing process. When the upper levels of the lake have cooled to approximately 10C, mixing occurs at a depth of 30 m. As the lake further cools to 7–8C the water is mixed to 60 m. Cooling another degree permits mixing at 90 m, and by the time the lake has reached 4–5C the water is mixed down to the bottom.

The weather conditions given by the daily weather maps have been examined for each of the days with significant mixing. The maps show that the winds occurring on the days of deep mixing are not extraordinary (670–890 cm/sec). Thus, for average winds and the neutrally stable condition existing within the isothermal lake, the wind stress is sufficient to cause major vertical circulation of the water mass.

A detailed description of the current profiles to depth in Lake Michigan has been given by Verber (1965). In particular, Verber describes a storm passage on 12 September 1963 that had a 6-hr windspeed of 17 m/sec. The current speed at station 39 at 180-m depth increased from 3 to 8 cm/sec during the same 2-hr period.

It has been suggested (R. A. Ragotzkie, personal communication) that the sudden return of temperature to 6.1C at station 39 on 19 December 1962 may have been an indication of a major advective change, rather than of wind-driven mixing. However, the author feels that such a rapid return to a stable temperature configuration is consistent with a wind-driven phenomenon.

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A DRIFT BOTTLE STUDY IN NORTHERN CALIFORNIA

Bodega Head, California (38°18′N lat, 123°04′W long), is located some 93 km north of San Francisco. The head is a prominent feature of this portion of the coastline, jutting out from the mainland at the terminus of a relatively low-lying spit. It was at this location that the Pacific Gas and Electric Company had proposed the building of a nuclear-powered electric generating plant.

The marine waters surrounding Bodega Head would be vital to such a plant. Seawater would be circulated through plant condensers and returned to the ocean to carry away excess heat. The water would also be used to dispose of small amounts of radioactive liquid wastes discharged under controlled conditions into the circulating water. Thus, much information about the ocean and tidal waters adjacent to the head was needed. In 1960 the company began a preliminary investigation of the adjacent