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T H E   U N I V E R S I T Y   O F   M I C H I G A N

COLLEGE OF ENGINEERING
Department of Meteorology and Oceanography

OBSERVED TEMPERATURE PROFILES NEAR THE LAKE MICHIGAN SHORELINE

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ORA Project 08650

Supported by:
DEPARTMENT OF HEALTH, EDUCATION AND WELFARE
PUBLIC HEALTH SERVICE
DIVISION OF AIR POLLUTION
GRANT NO. AP 00380-01,02,03
WASHINGTON, D.C.

administered through:
OFFICE OF RESEARCH ADMINISTRATION   ANN ARBOR

January 1969

ACKNOWLEDGEMENTS

The author is greatly indebted to Mr. Anders Daniels for suggesting the details of the circuitry used for the instrumentation, and for his many helpful suggestions during the execution of this study; and to Prof. G. C. Gill for his assistance in selecting the instruments.

The writer also gratefully acknowledges the work done by Mrs. Ruthie Tolbert in typing the manuscript. Particular thanks is given to Dr. Alan Cole and Mr. Lars Olsson for reviewing the manuscript and making many useful suggestions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES
(continued)

LIST OF FIGURES
(continued)

ABSTRACT

A temperature measurement program using a continuous recording device on an automobile was carried out near the shore of Lake Michigan south of Grand Haven, Michigan, on several favorable days in the summer of 1967. This study provided a detailed illustration of the temperature distribution along a line perpendicular to the shore on mostly sunny days and under different prevailing wind situations.

Of the four days during which good data were obtained, one had a prevailing moderate westerly wind, another a prevailing easterly wind with a lake breeze gradually pushing inland from the west. On the two other days light southerly to southwesterly winds prevailed. A description of the instruments used and a brief account of the operational procedures are given. The temperatures have been plotted as a function of distance inland at various times of the day together with the winds recorded at different distances from the shore.

1. INTRODUCTION

The modification process of the air in the lower layer of the atmosphere when it crosses a sea-land interface has received increased attention recently. The effects of the land-water transition have many important implications for the atmosphere near the shoreline of a large body of water. Since the process is very complex, a theoretical study is not a satisfactory approach to the problem. It is therefore necessary to carry out an extensive field program to measure the rate of change in the physical properties of the air as it undergoes modification.

An ideal site for such a study is near the shore of a large lake in the interior of a continent in middle latitudes in spring and early summer, when the lake is quite cold with respect to the surrounding land. The generation of a lake breeze on a calm, clear day offers an especially good opportunity to observe the modification in temperature of the air from over the lake as it moves inland. For several years, the Department of Meteorology and Oceanography at the University of Michigan has maintained an observational program on the eastern shore of Lake Michigan to study mesoscale winds in general and lake breezes in particular. Instruments at stations at the shoreline and at different distances inland have continuously recorded wind speed and direction as well as temperature and humidity. Pilot balloons have been released to study winds aloft. Results of these studies have been presented by Moroz (1965) and by Olsson Cole, and Hewson (1968).

Lyons and Wilson (1968) have observed that during onshore flow in non-lake breeze situations, the eastern shore of Lake Michigan is cloudless, while cumulus clouds form about 25 km inland as the air gradually heats up on passing over land. Air temperature modification over a lakeshore has also been discussed by Bierly (1968). In the modification process, important changes take place in the stability and wind of the air in the lowest layer, thus profoundly effecting turbulence and diffusion near a shore as shown by Hewson and Olsson (1967). Thus the lake influence has important effects on local winds, cloudiness and convective precipitation, air pollution, and local climatology.

Thus it seemed appropriate to carry out a study in the summer of 1967, to provide a more detailed analysis of the air temperature near the lakeshore by using a continuous recording device on an automobile. This study had several objectives. First, to find a way of more clearly following the progress of the lake breeze front, i.e. the line of penetration of inward surging lake air, by noticing where a discontinuity in the temperature gradient is located. Second, to determine a typical temperature distribution near the lakeshore during different situations of prevailing wind caused by the heating of cool lake air when passing over land both during lake breeze and non-lake breeze situations. The second objective would indicate how fast the air is modified and how far the lake effect on air temperature reaches inland.

Automobile traverses have been made use of in the past by Sundberg (1950), Duckworth and Sandberg (1954), Summers (1965), and Daniels (1965) but only for measuring temperatures in cities. Few, if any, traverses, to the author's knowledge, have been made anywhere near a large lake or ocean.

2. LOCATION OF STUDY AND MEASUREMENT METHOD

2.1 Description of Location

The study was carried out on Michigan highway M-45 which runs east-west from Grand Rapids to the lake. The shore at this point is only slightly curved and runs north-south. Along the highway are 4 meteorological stations set up by the Department of Meteorology and Oceanography at the University of Michigan. They are located at the shoreline, 8 km, 16 km, and 24 km inland. Each is equipped with wind sensors on a tower, which continuously record wind speed and direction, in addition to a hygrothermograph which records temperature and relative humidity. Instruments located on WJBL-TV tower, 17 km south of M-45 and 10 km inland, record winds at 3 different levels and temperature lapse rate. The location together with the stations is shown in Figure 1.

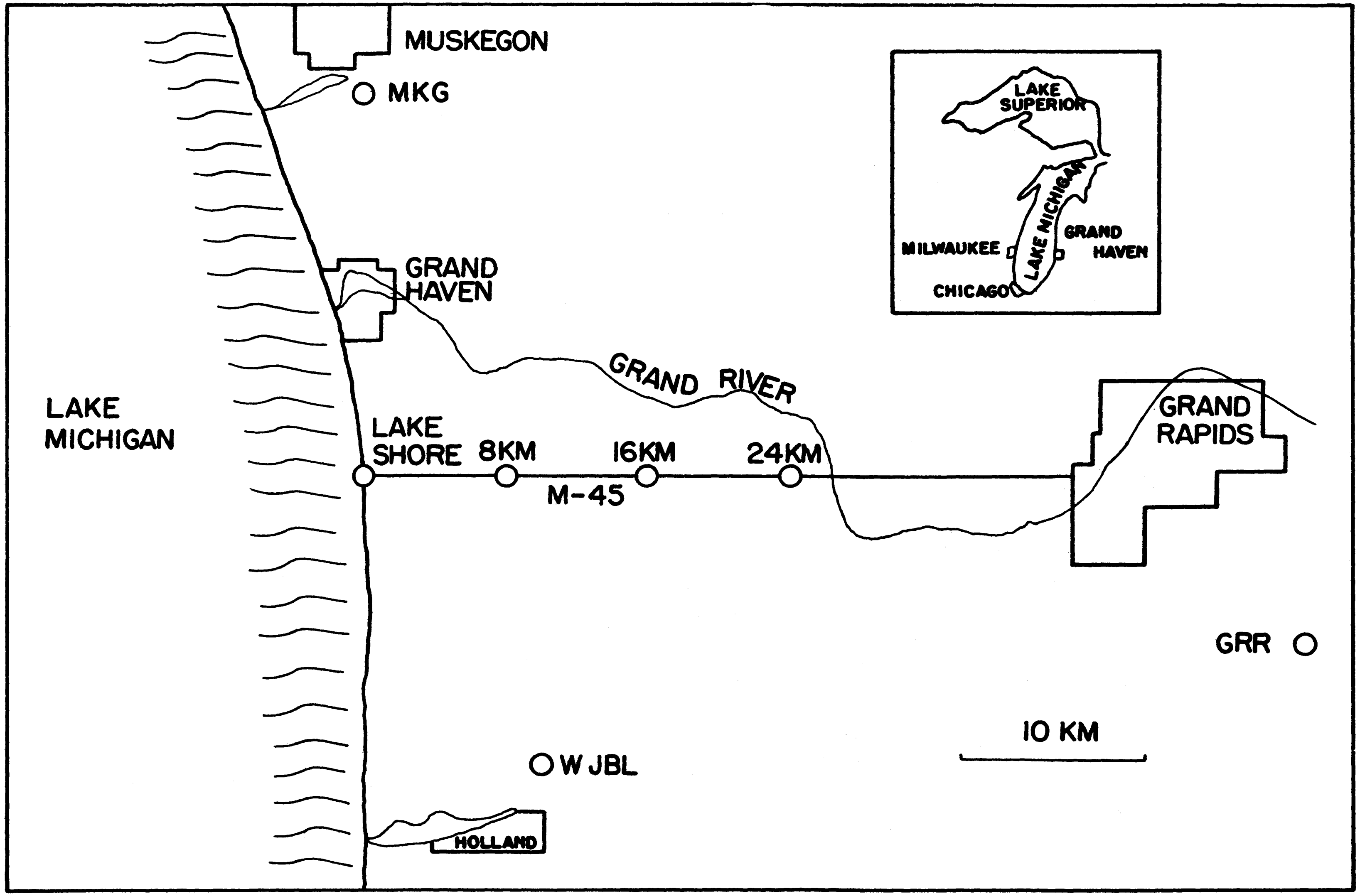

FIGURE 1. Location of observation stations on the eastern shore of Lake Michigan. Insert shows the location of the line of observations relative to Lake Michigan.

Sand dunes, with heights of up to 50 m above lake level, parallel the beach and extend 1 to 2 km inland. Beyond 3 km inland, the land is flat with relatively few trees and is uniformly developed for agriculture. The slope of the land from the shore to Grand Rapids is negligible.

2.2 Instrumentation and Setup

The temperature sensor used was a Yellow Springs number 408 thermister probe with a time constant of 0.8 seconds. The Wheatstone bridge circuit is sketched in Figure 2. By setting M_R, one determines the temperature of the midpoint of the scale, which allows for days with differing mean temperatures. The potentiometer, M_S, regulates the voltage across the bridge which determines the sensitivity - the amount the pen will swing for a certain increment of temperature. The circuit was powered by a 1.5 volt battery. The circuit was built into a small box with two dials to regulate the sensitivity and the midpoint temperature. The box had three outlets: one for the recorder, one for the probe, and one for a switch by which the circuit could be opened or closed. An Esterline Angus Model AW recorder was powered by the 12 volt car battery using a 115 volt, 60 Hertz AC inverter.

Artificial ventilation was provided by an aspirator in the lower end of a 4 foot vertical pipe with the thermister mounted at the top; the pipe also served as a radiation shield. The aspirator was tied to the inside of the right front door, and the pipe was pointed through the open window straight up so that the thermister was located one or two feet above the top of the car, Figure 3. The probe was pointed into the direction of motion of the car. This was found to be the most favorable position for the speed of the car didn't seem to effect the temperature recorded, and no vacuum effect was present.

2.3 Operational Procedure

In all runs, all operations were carried out by the driver. The rides always started at the shoreline station where the temperature was read from a hand carried Yellows Spring meter using a probe by Yellow Springs, model 403 mounted into the pipe next to the regular probe. The local time and the indicated temperature were marked on the chart. The range was adjusted so that the pen would stay on scale during the entire run. At 16 specific locations - each about 1.5 km apart - markings were made on the chart by breaking the circuit with the switch. The run usually went 20 km inland, where another temperature reading was taken and recorded on the chart, which estabilished a reference for abstracting the data. Since the runs took only about 20 minutes one way, diurnal temperature variations could be neglected.

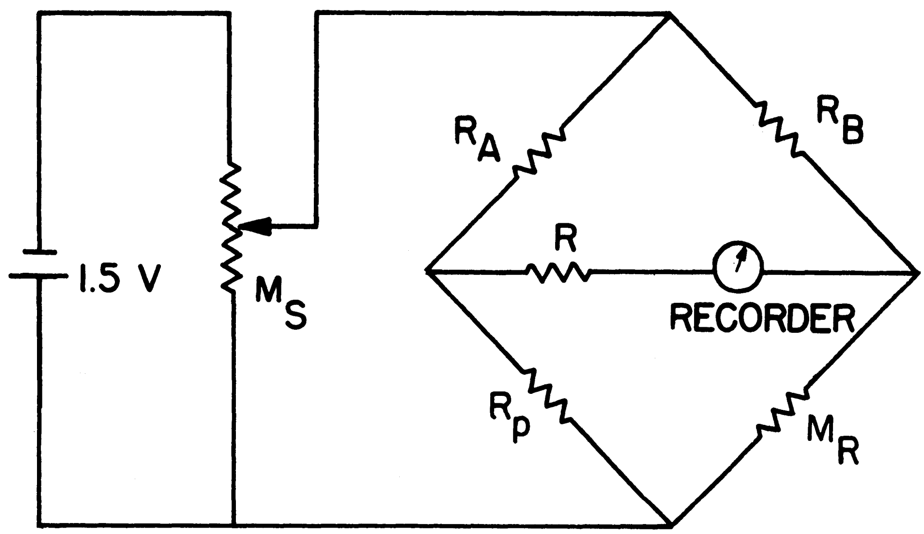

FIGURE 2. Circuit arrangement for measuring temperature. R_a and R_b are constant resistances of 1000 ohm each, R_p is the Yellow Springs No. 408 temperature probe, R is a 270 ohm resistor acting as a voltage divider. M_r is a 50,000 ohm potentiometer which is used to adjust the midpoint temperature. M_s is a 100 ohm potentiometer used to adjust the sensitivity.

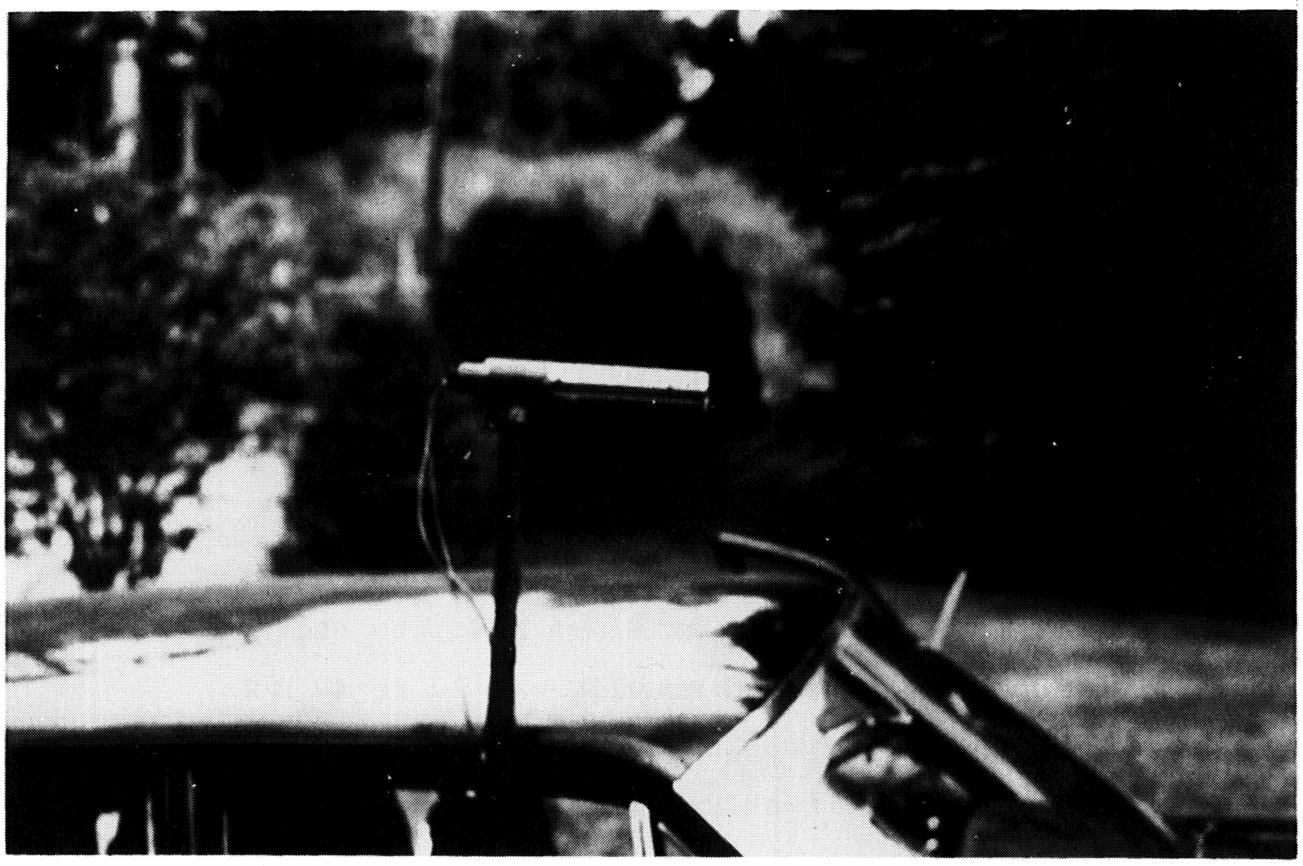

FIGURE 3. Ventilation pipe with radiation shield containing thermister probe mounted on automobile.

2.4 The time constant

The time constant of the thermister is supposed to be 0.8 seconds. However, because the recorder also has a time response, the system response is slower. The real time constant was determined by putting the probe in a small wind tunnel and exposing it to abrupt changes in temperature, and recording the response of the system. The time constant is defined as the time it takes for the system to respond to 63.2% of the total instantaneous change. After several tests, the time constant was estimated at 5.1 seconds. The time response formula is $T_1 - T = \Delta T\, e^{-t/\tau}$ where T_1 is final temperature, T is instantaneous temperature at time t, ΔT is the total change in temperature, and τ is the time constant. It follows then that

$$t = -2.3\,\tau \log \frac{T_1 - T}{\Delta T}.$$

Then for 90% of the change to take place $\frac{T_1 - T}{\Delta T} = 0.1$

and $t = 11.7$ seconds. If the car travels at 40 mph during the time that 90% of the total change is recorded, the car travels 210 m; at 60 mph it travels 314 m. Temperature gradients of 3°F per km have been observed at times near the shoreline, where the speed usually was 30 to 40 mph. Therefore, a lag of 210 m wouldn't effect the accuracy significantly. Inland, the temperature gradients were much weaker. The response was still so fast that the trace showed a lot of small scale fluctuations in temperature, often of the order of 1°F in less than 1 km, thought to be due to turbulent eddies and local effects.

2.5 Calibration

The system was calibrated using a sensitivity of 5 and a range of 90 on a 100 unit scale. Calibration was carried out by dipping the thermister in a water bath using different temperatures in a range from 60 to 80°F, the temperature range which usually existed during these studies. The response seemed surprisingly linear in this case as shown in Figure 4. Thus a linear scale was constructed and its validity could always be checked against the observed temperatures taken during each run. In Figure 5 is given the full temperature range for different midpoint temperatures (the temperature at the center of the scale).

3. THE DATA AND THE RESULTS

Good data were obtained on the following days between the times (EDT) listed:

July 2	1230 - 1355
July 6	0945 - 1055, 1220 - 1305, 1400 - 2118
July 8	1340 - 1203, 1730 - 1845
July 16	1120 - 1200, 1740 - 1820

All runs were made during mostly clear and sunny weather, under a variety of prevailing wind conditions. Westerly winds prevailed on July 2.

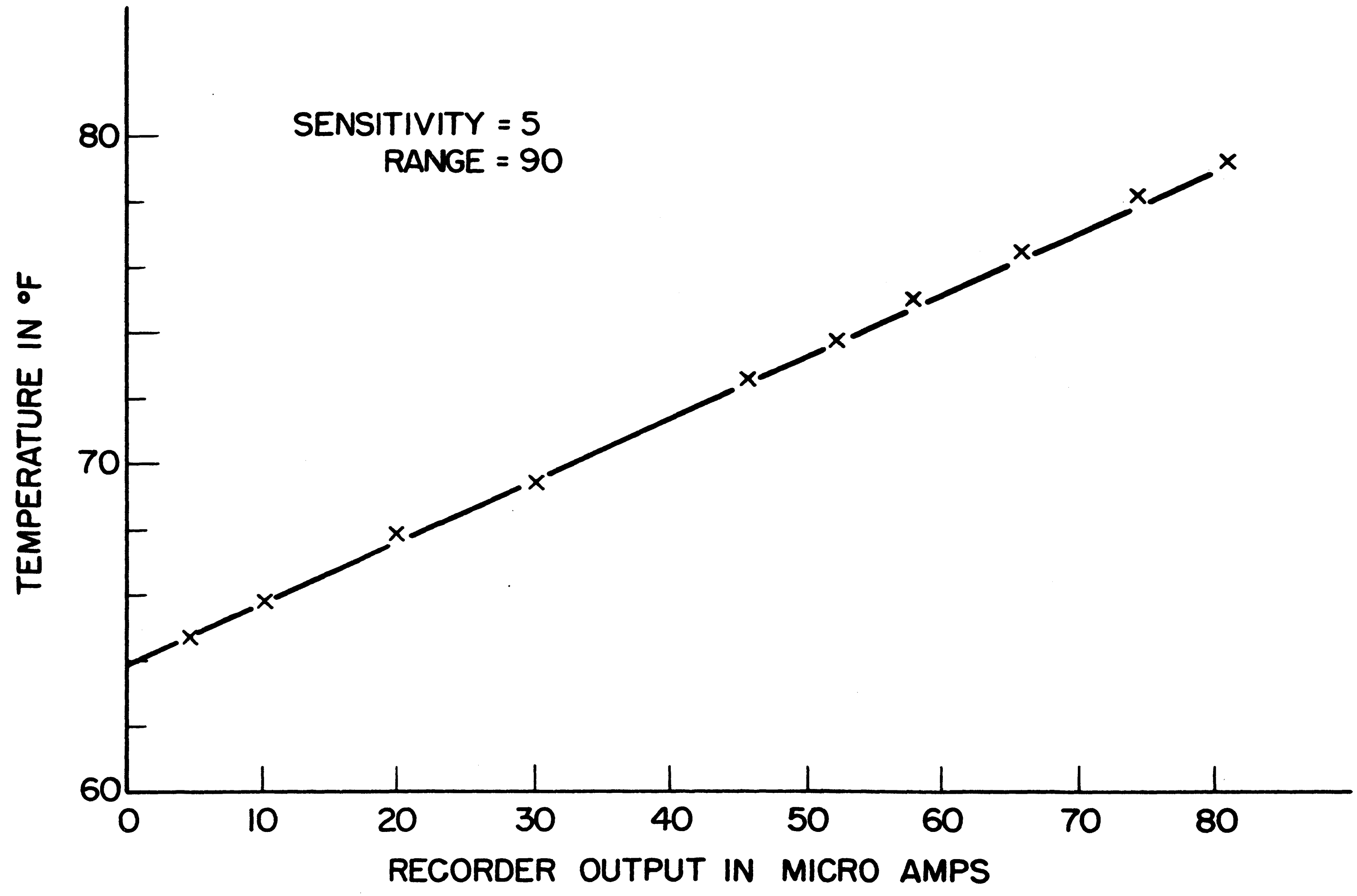

FIGURE 4. Calibration plot using a sensitivity of 5 and a range of 90 on a 100 unit scale. Midpoint is 71.4°F. Full scale temperature change is 14.1°F.

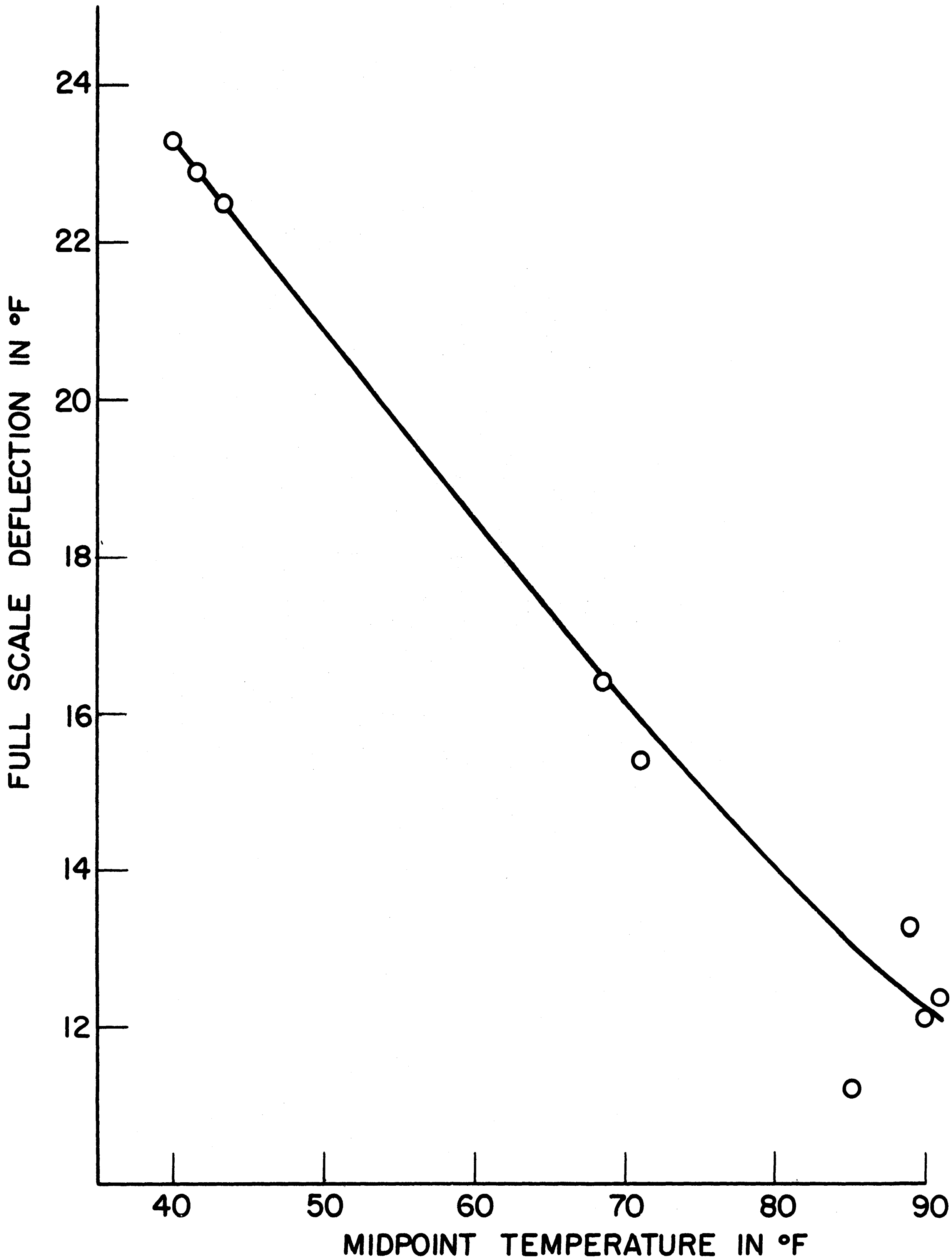

FIGURE 5. Full scale deflection of the recorder as a function of midpoint temperature.

Winds were easterly on July 6, while an ideal lake breeze was generated near the shore. On July 8 and July 16, southwesterly winds prevailed. Wind and temperature data were available from the M-45 stations and the WJBL - TV tower.

3.1 Results of July 2, 1967; Moderate Westerly Gradient Flow

The morning of July 2 was clear and sunny. A cold front had passed the day before and a northwesterly to westerly flow averaged about 4 m sec^{-1} at the shoreline in the morning. Toward noon, however, the wind started to back toward the W and WSW, Figure 6. Figure 7 shows the westerly and southerly components of the wind. At the stations inland, the wind increased during the course of the day, but at the shore the wind decreased. The sky was clear, but cumulus clouds were forming 20 km inland. Temperatures were taken along M-45 going 25 km inland, and along Port Sheldon Road 10 km to the south.

The ride lasted for 1.5 hr, and since temperatures were rising due to diurnal heating, the data were normalized to 1300 EDT assuming everywhere the rate of increase was similar to those observed on the temperature records at the stations. The route followed and the observed temperature field is plotted in Figure 8. Along M-45, the temperature increased gradually at the rate of 1°F km^{-1} from the shoreline inland to 10 km. Beyond that point, the temperature gradient was much smaller and approached the representative inland value. At Port Sheldon Road, isotherms

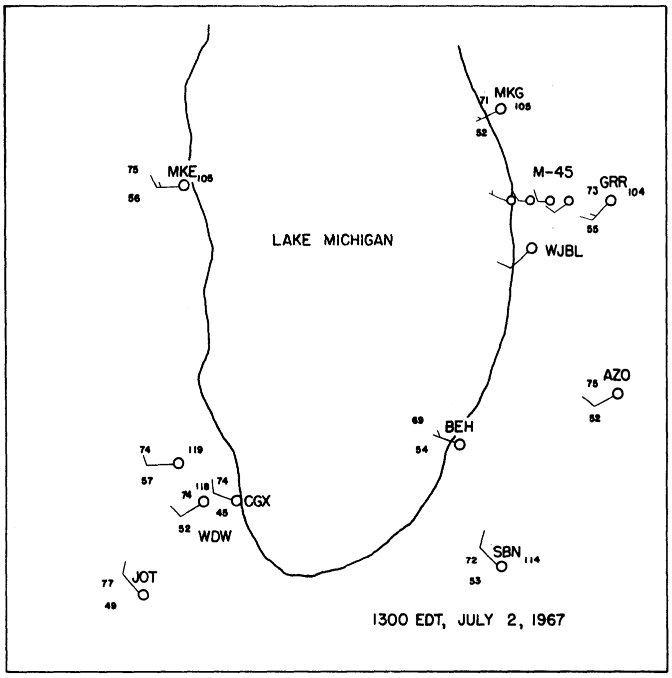

FIGURE 6. Mesoscale surface winds and temperatures around the southern basin of Lake Michigan at 1300 EDT, July 2, 1967.

were packed closer together with a gradient of 2°F km^{-1} observed between 4 and 6 km inland. Thus, the horizontal temperature gradient was not homogeneous along the shore. This might have been due to local effects caused by differences in topography and surface cover. Port Sheldon Road goes through gently rolling farmland with few trees. At 4 to 6 km from the shore there is an area of dense woods, and near the shore there are sand dunes covered with many trees, which might have been a factor causing the higher temperature gradient observed there.

At 1400 EDT, a long squall-line like cloud formation was seen in the NW, far out over the lake. At the shore the wind backed to SW and decreased, obviously due to the approaching disturbance over the lake. The cumulus clouds over land disappeared.

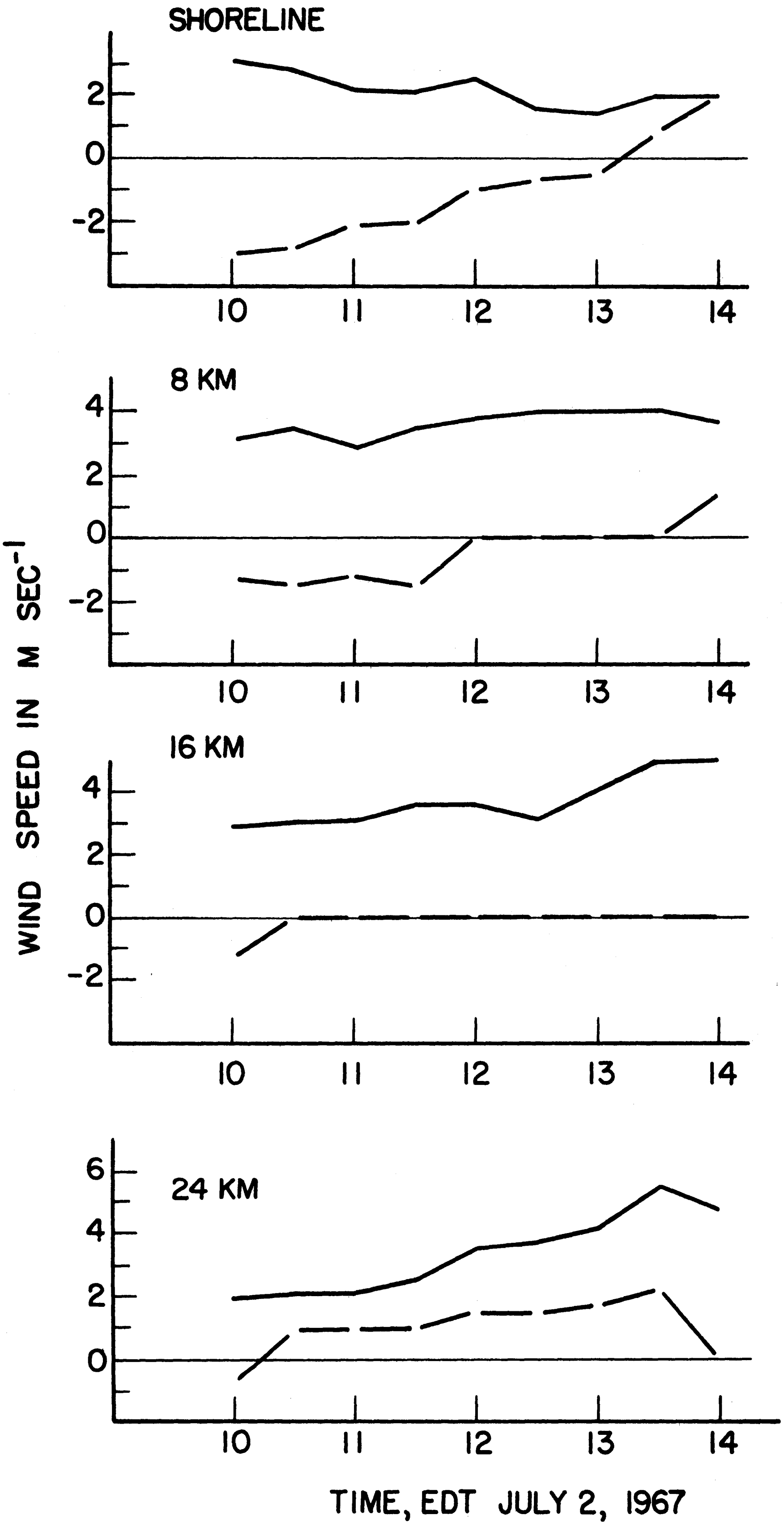

FIGURE 7. Westerly (solid line) and southerly (dashed line) components of the wind at the shore, 8 km, 16 km, and 24 km inland along M-45 for 1000 - 1400 EDT, July 2, 1967.

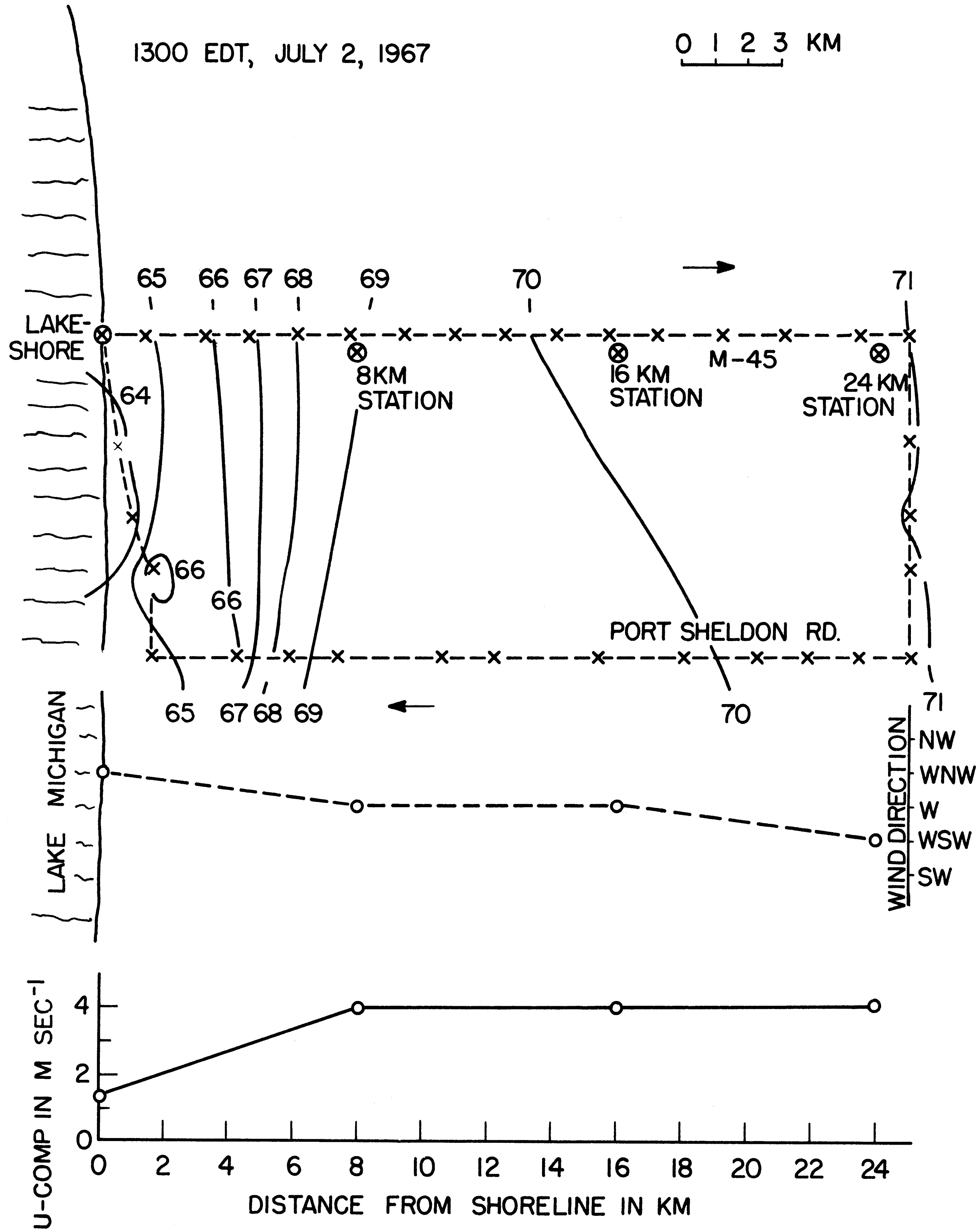

FIGURE 8. Temperature distribution observed, 1230 - 1355 EDT, July 2, 1967. Wind direction and westerly (u) component of the wind observed at 1300 EDT. Temperatures are in °F and normalized to 1300 EDT.

No more observations were carried out in the afternoon as a line of thunderstorms swept through around 1630 EDT.

This was an excellent case of modification of lake air as it moved inland. The temperature increased gradually from 64°F at the shoreline to 69°F at 8 km inland, and from there increased more slowly to 71°F at 25 km inland. The U.S. Weather Bureau station at Grand Rapids, 53 km inland, reported 73°F at the time which suggested that the effect could have reached beyond 25 km. If the westerly component of the wind was 3 m sec^{-1} and a temperature gradient of 1°F km^{-1} existed, the rate of temperature advection must have been about 10 to 11°F hr^{-1}. Since the temperature at any particular point was rising 1 to 2°F hr^{-1}, the rate of modification of the lake air as it traveled over land must have been somewhat greater than 10 - 11°F hr^{-1}.

<u>3.2 Results of July 6, 1967: An Ideal Lake Breeze Day</u>.

A high pressure area was located over the Great Lakes with a low to the south causing a light easterly flow of about 3 m sec^{-1}. As sunny weather prevailed, a lake breeze began to blow at the shore in the early afternoon working itself gradually eastward. The local situation is shown in Figure 9. Observations were made along M-45 all afternoon and early evening. Wind data plotted in Figure 10 indicate that the lake breeze started

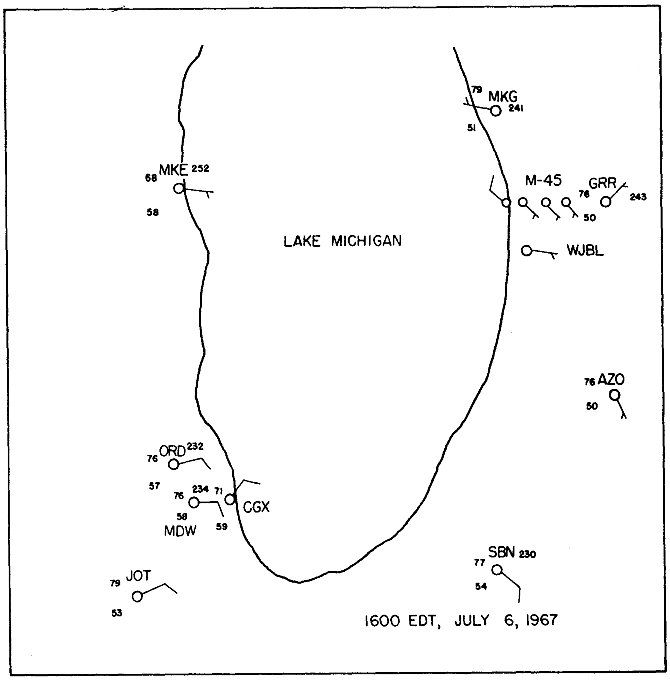

FIGURE 9. Mesoscale surface winds and temperatures around the southern basin of Lake Michigan at 1600 EDT, July 6, 1967.

at the shore at 1310 EDT, reached the 8 km station at 1730 EDT, and the WJBL station, 10 km inland, at 2020 EDT. The USWB station at Muskegon Airport (MKG), reported a wind shift by 1600 EDT. A temperature difference of 10°F between the air at the shore and the air far inland existed during the lake breeze. The penetration of the lake breeze front was quite slow because of the easterly gradient winds.

In Figure 11 through 22 are given some of the original chart traces from the runs made that day. (Notice that the horizontal scale is not linear due to the uneven motion of the car). Figure 11 and 12 illustrate the morning and early afternoon case before the lake breeze started. As easterly winds occurred everywhere, no lake influence on the temperature field was seen anywhere. The next run,

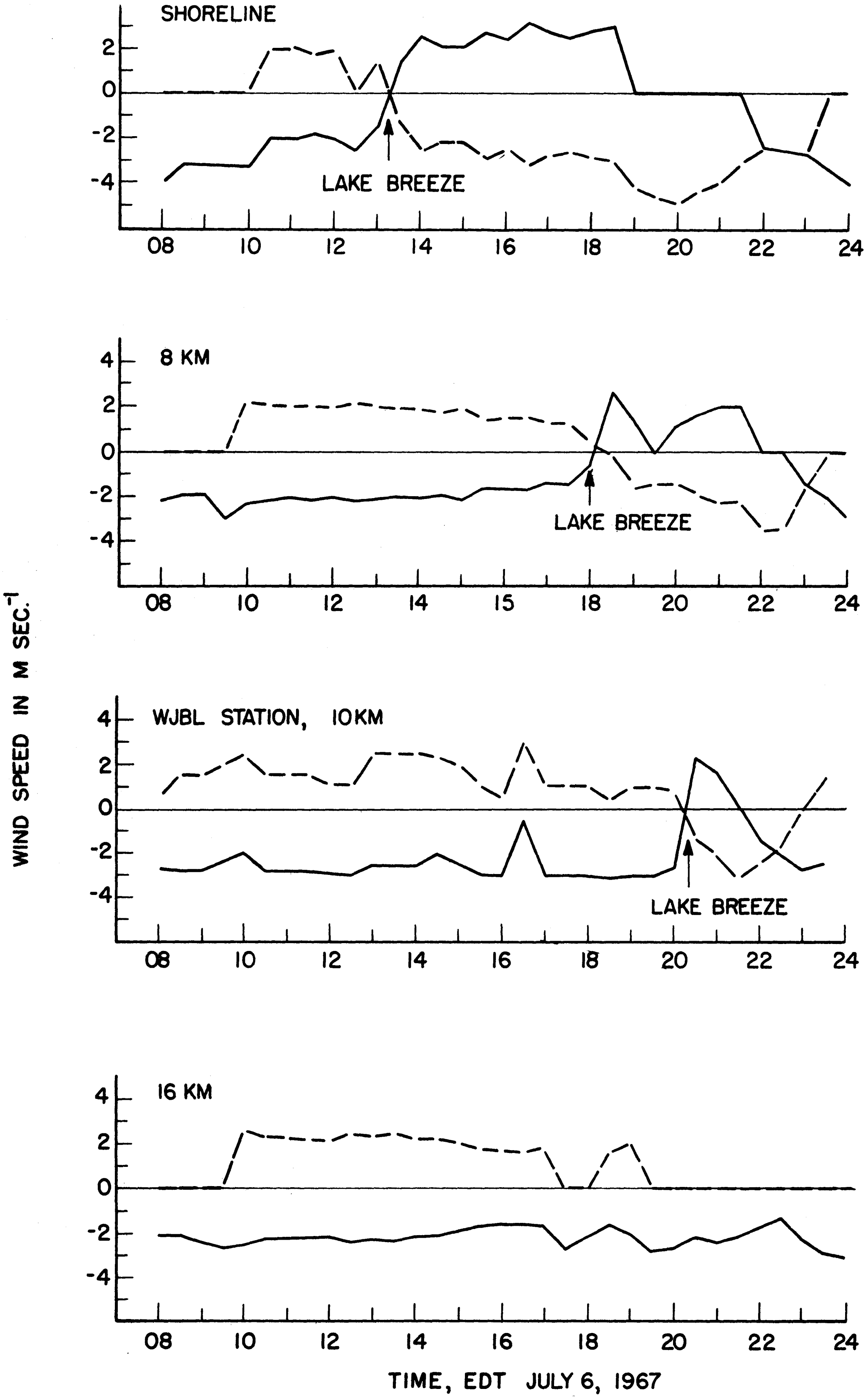

FIGURE 10. Westerly (solid line) and southerly (dashed line) components of the wind at the shore, 8 km, 16 km, and 24 km inland along M-45 for 0800 - 2400 EDT, July 6, 1967.

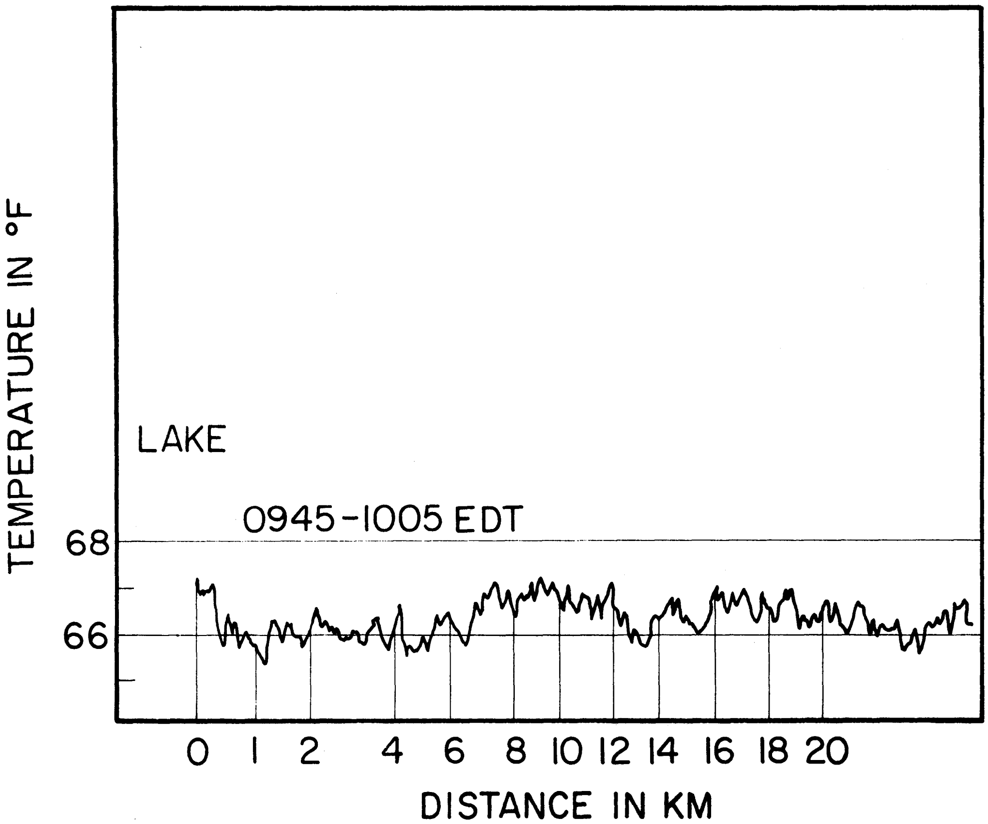

FIGURE 11. Temperature trace obtained along M-45 in the morning, 0945 - 1005 EDT, July 6, 1967.

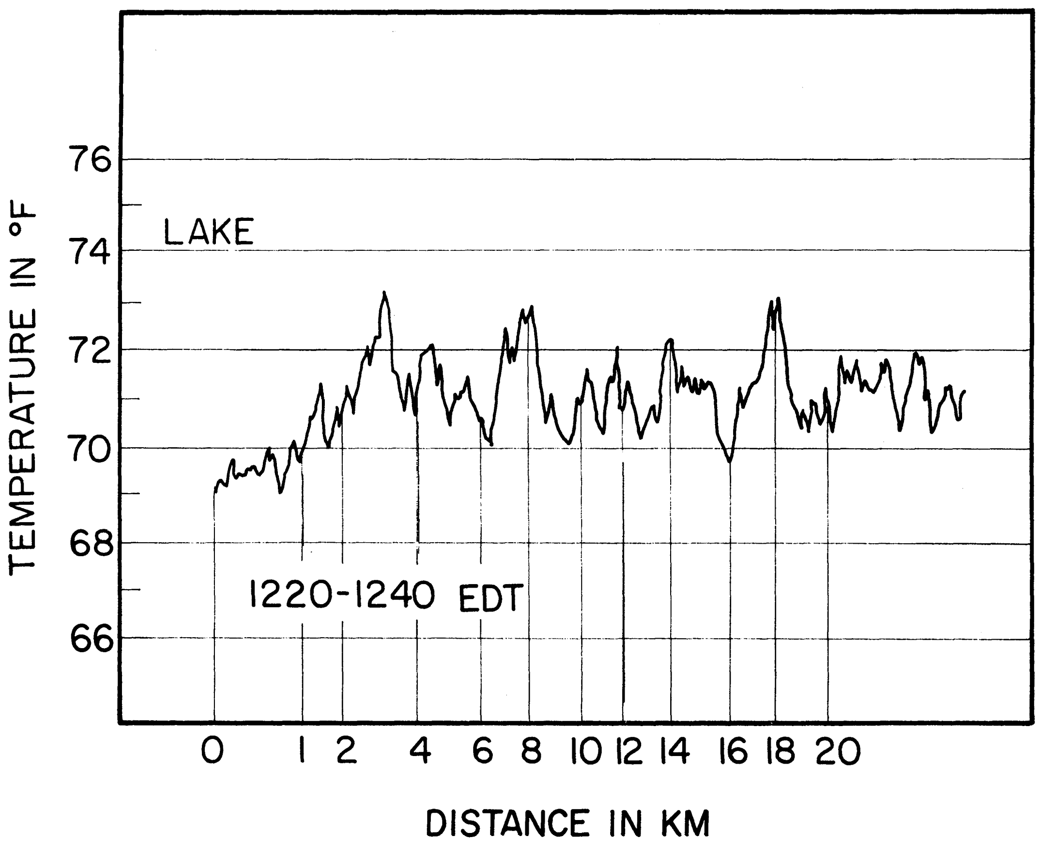

FIGURE 12. Temperature trace obtained along M-45 in early afternoon, 1220 - 1240 EDT, July 6, 1967.

started at 1415 EDT when the lake breeze had already advanced inland, indicated that the lake effect reached 3 km inland and showed a 4°F km^{-1} gradient near the shore, Figure 13. By about 1500 EDT, the lake effect reached 4 to 6 km inland, Figure 14. At this time the westerly component of the lake breeze was 2 to 3 m sec^{-1} at the shore. Thus rapid modification of the lake air took place as it traveled over land. By 1600 EDT, the temperature gradient reached 6 km inland, Figure 15 and 16. The strongest gradient was still present near the shore. At 1730 EDT, the gradient reached 8 km inland and at the same time the wind shifted to westerly at the 8 km station. In early evening the lake breeze had penetrated to about 10 km inland Figure 21 and 22. WJBL station, 10 km inland and 17 km south of M-45, had a wind shift to westerly at 2020 EDT. The sharp temperature jump 9 km inland at 2000 EDT, Figure 20, is difficult to account for, but may be due to local effects.

A summary of the data is plotted in Figure 23, which shows the variation in time and space of the temperature field. In the morning, the temperature gradient was absent as uniform heating took place everywhere. At 1300 EDT, when the lake breeze started, the temperature dropped slightly near the shore. As time went by, the temperature leveled off at points progressively further inland reaching 8 km inland by 1730 EDT. From then on, the progress of the front was difficult to follow as the temperature started to

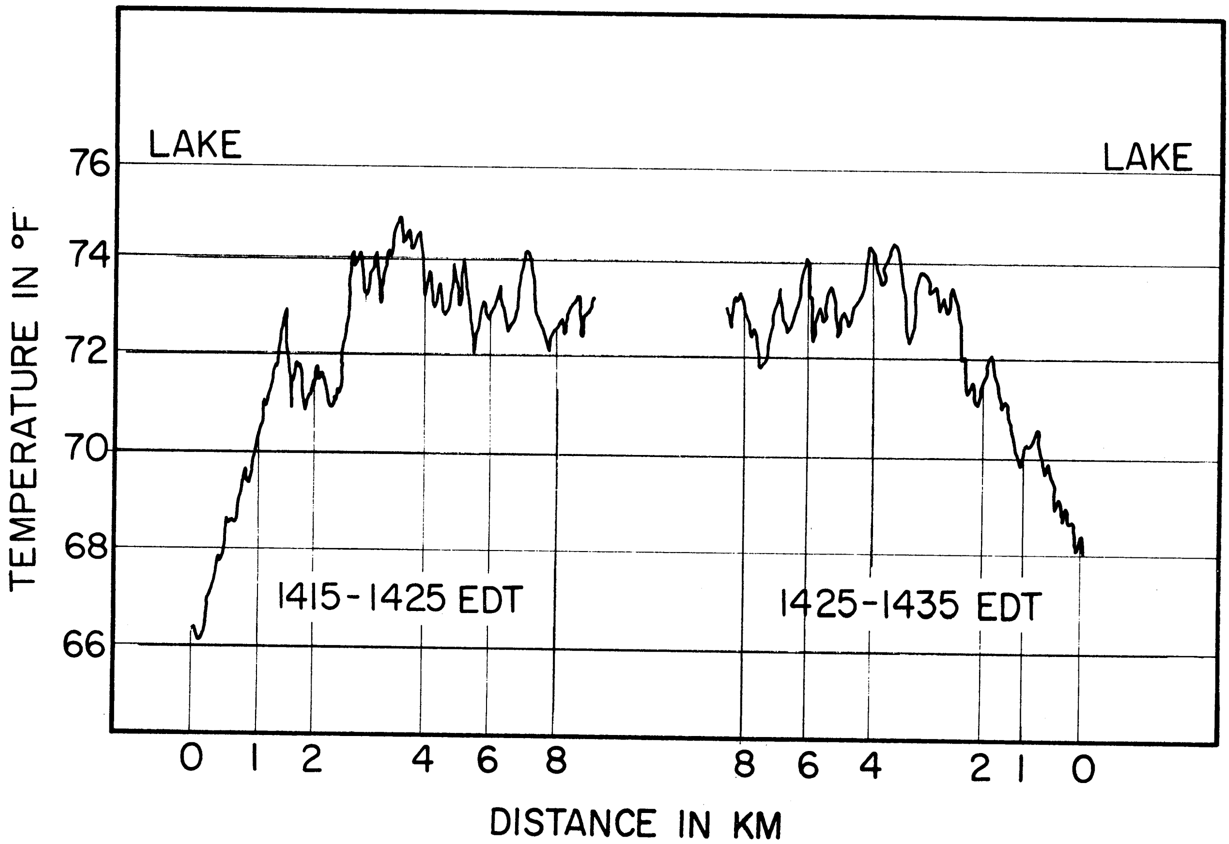

FIGURE 13. Temperature trace of the lake breeze, 1415 - 1435 EDT, July 6, 1967.

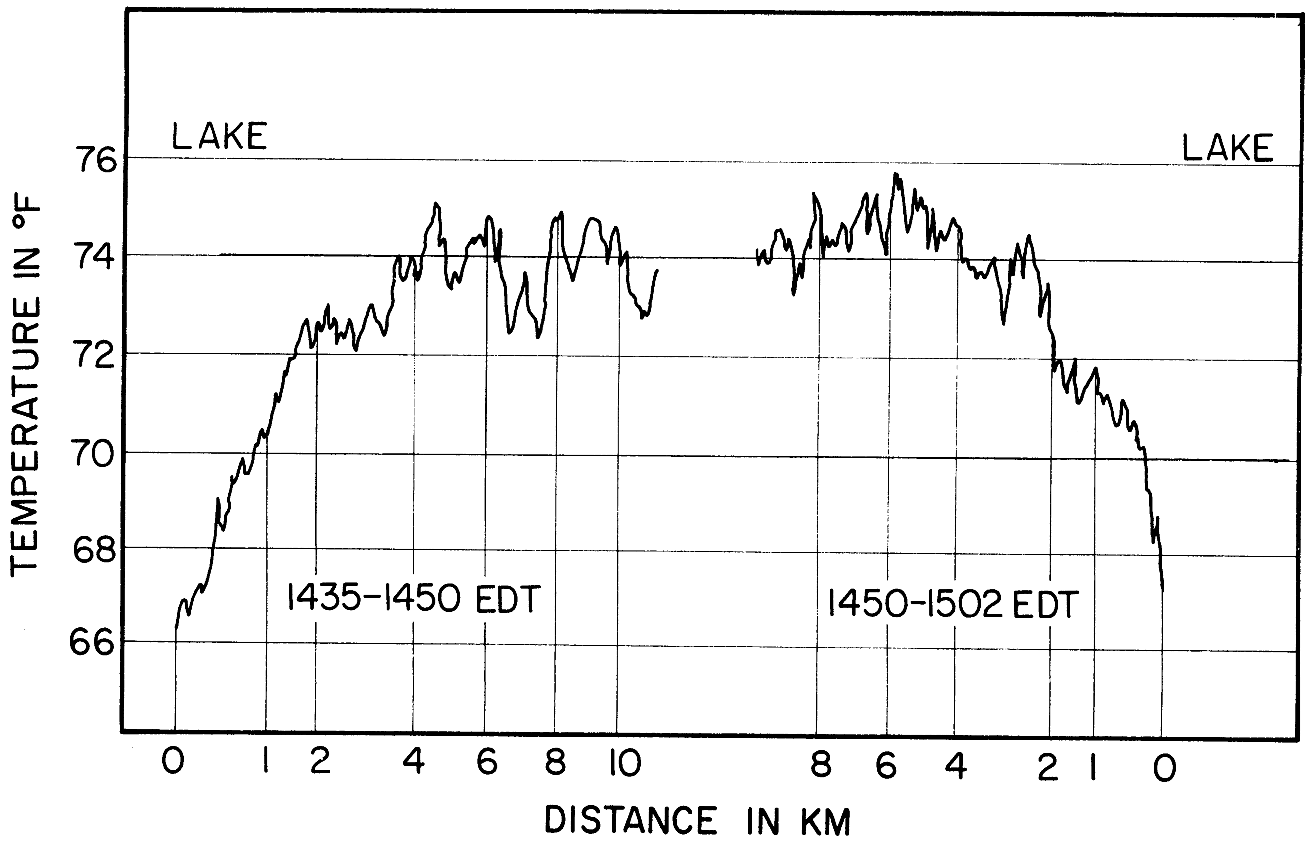

FIGURE 14. Temperature trace for 1435 - 1502 EDT, July 6, 1967.

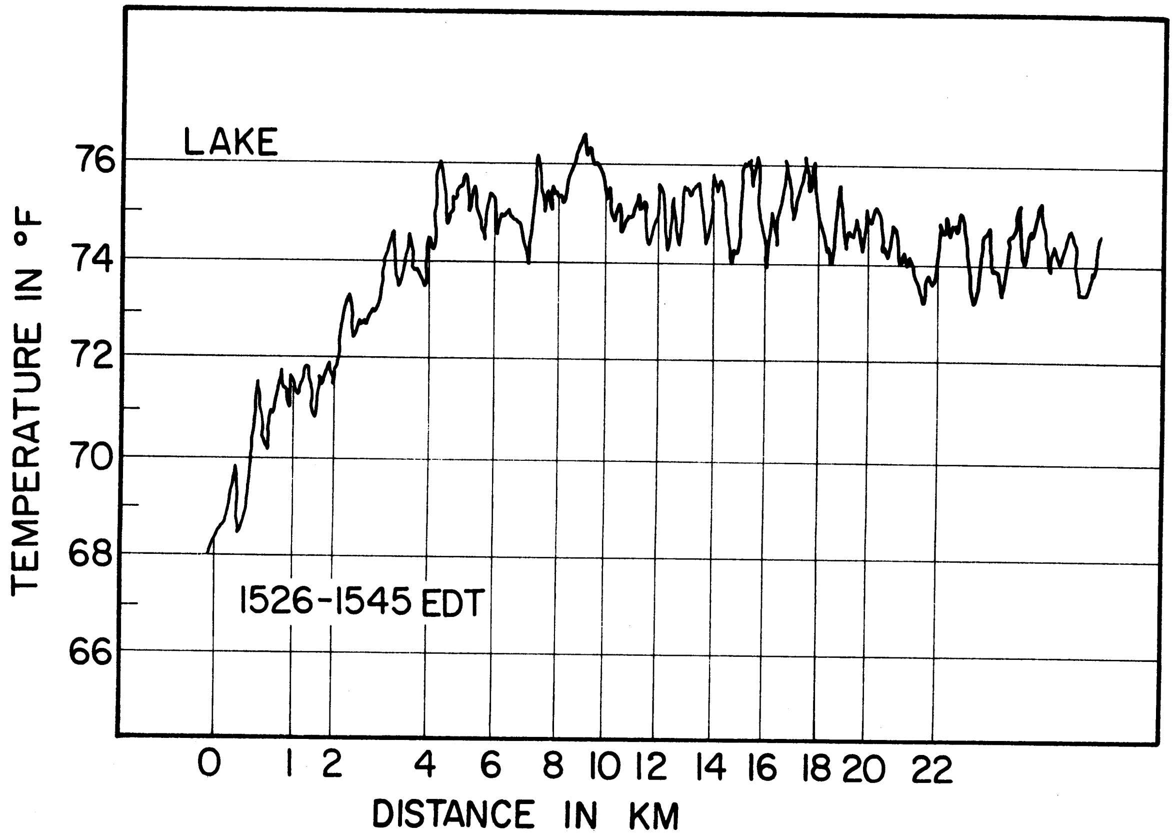

FIGURE 15. Temperature trace for 1526 - 1545 EDT, July 6, 1967.

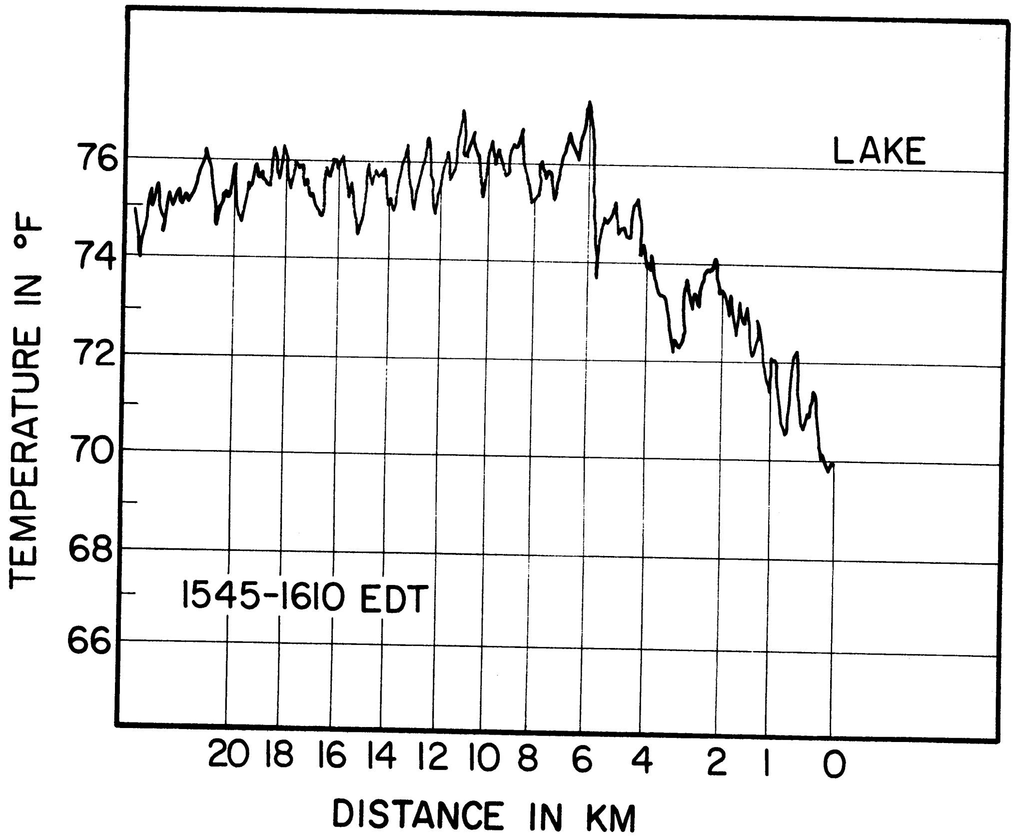

FIGURE 16. Temperature trace for 1545 - 1610 EDT, July 6, 1967.

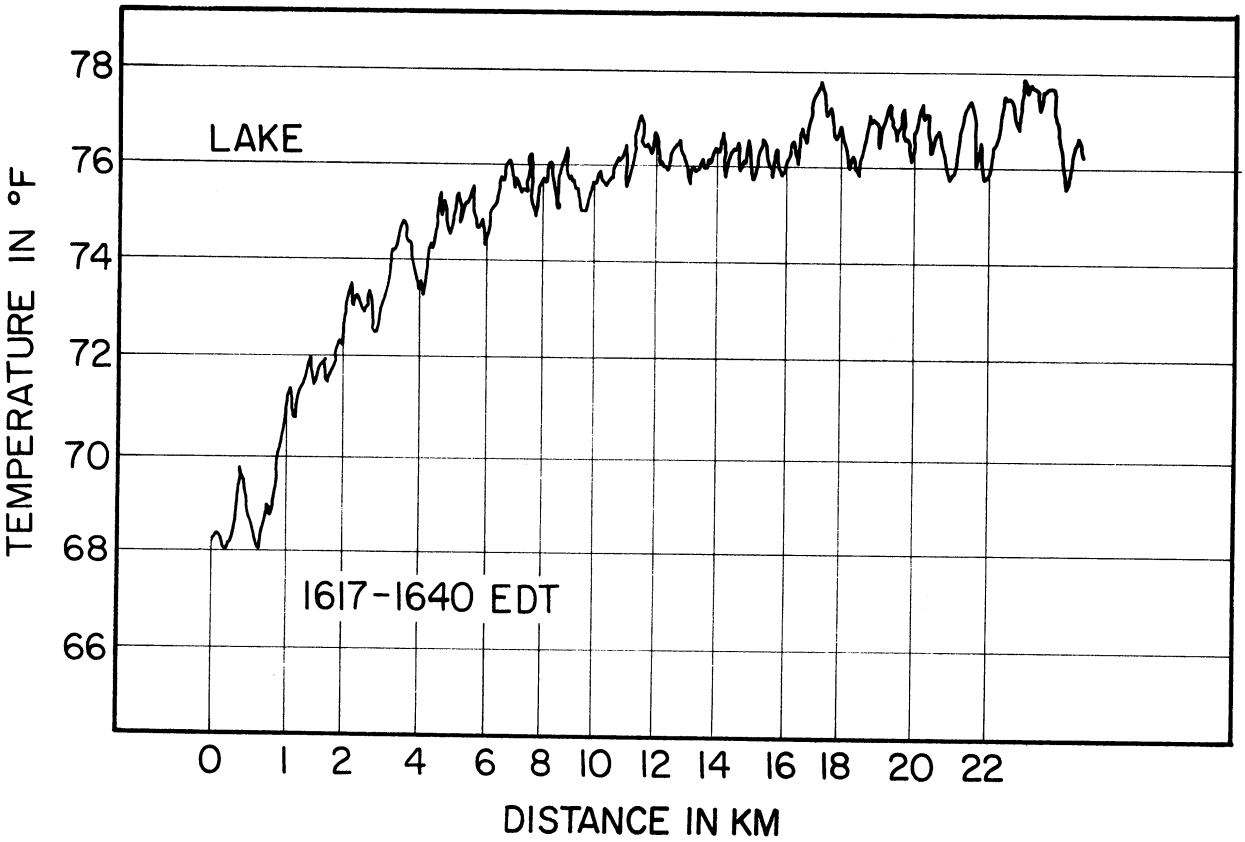

FIGURE 17. Temperature trace for 1617 - 1640 EDT, July 6, 1967.

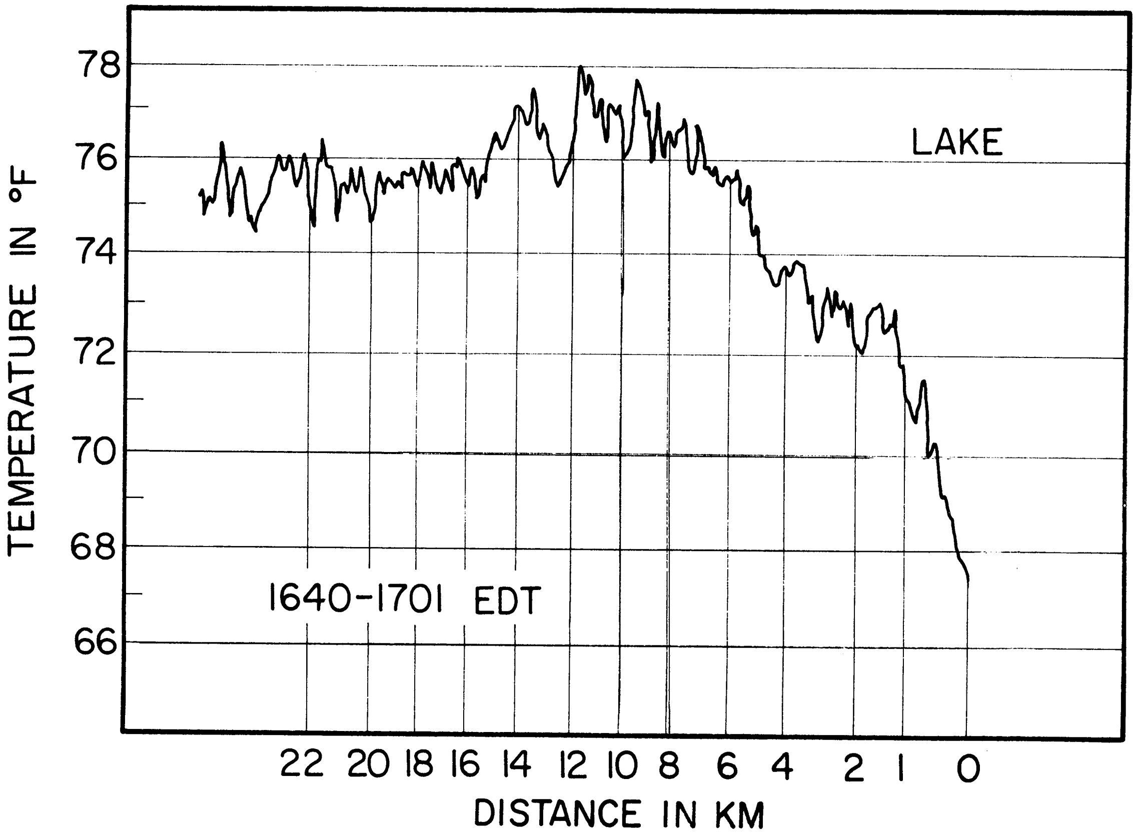

FIGURE 18. Temperature trace for 1640 - 1701 EDT, July 6, 1967.

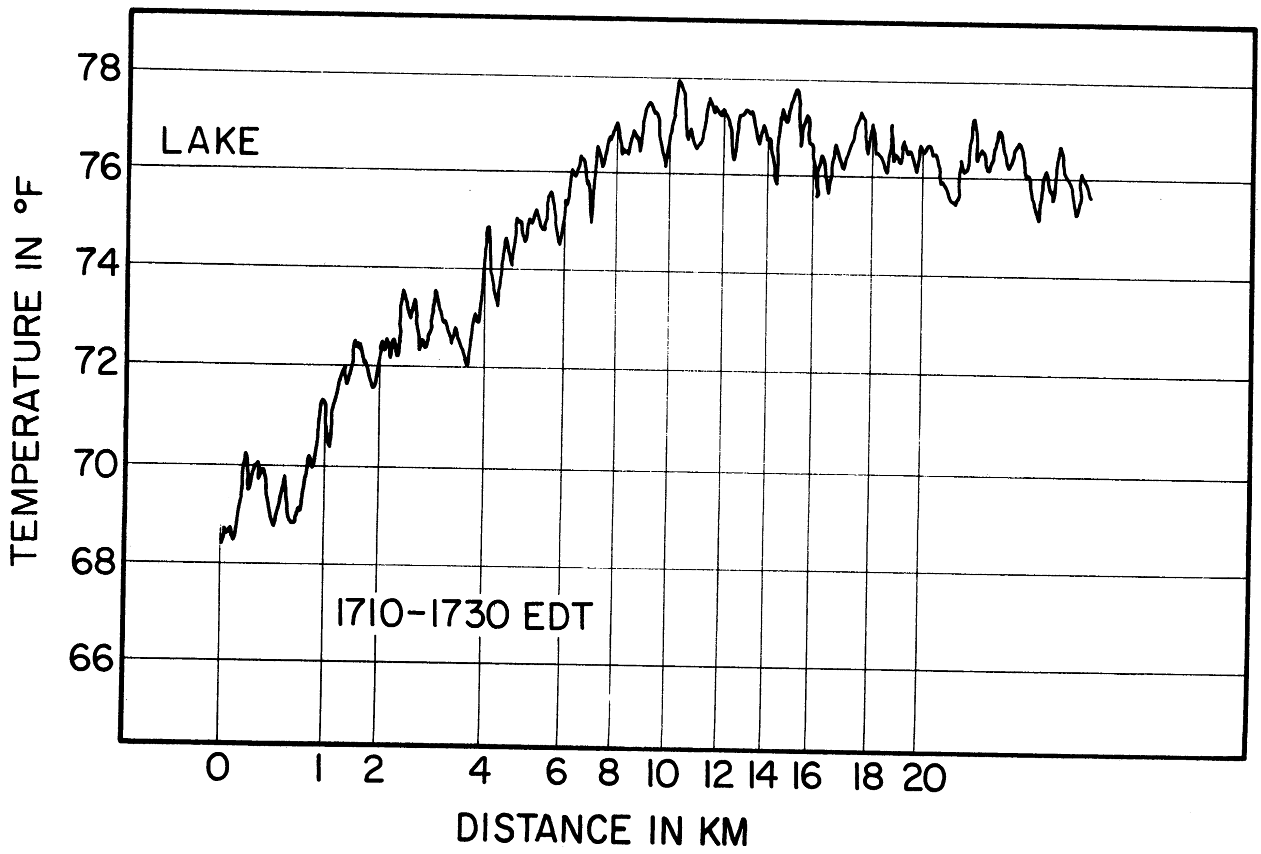

FIGURE 19. Temperature trace for 1710 - 1730 EDT, July 6, 1967.

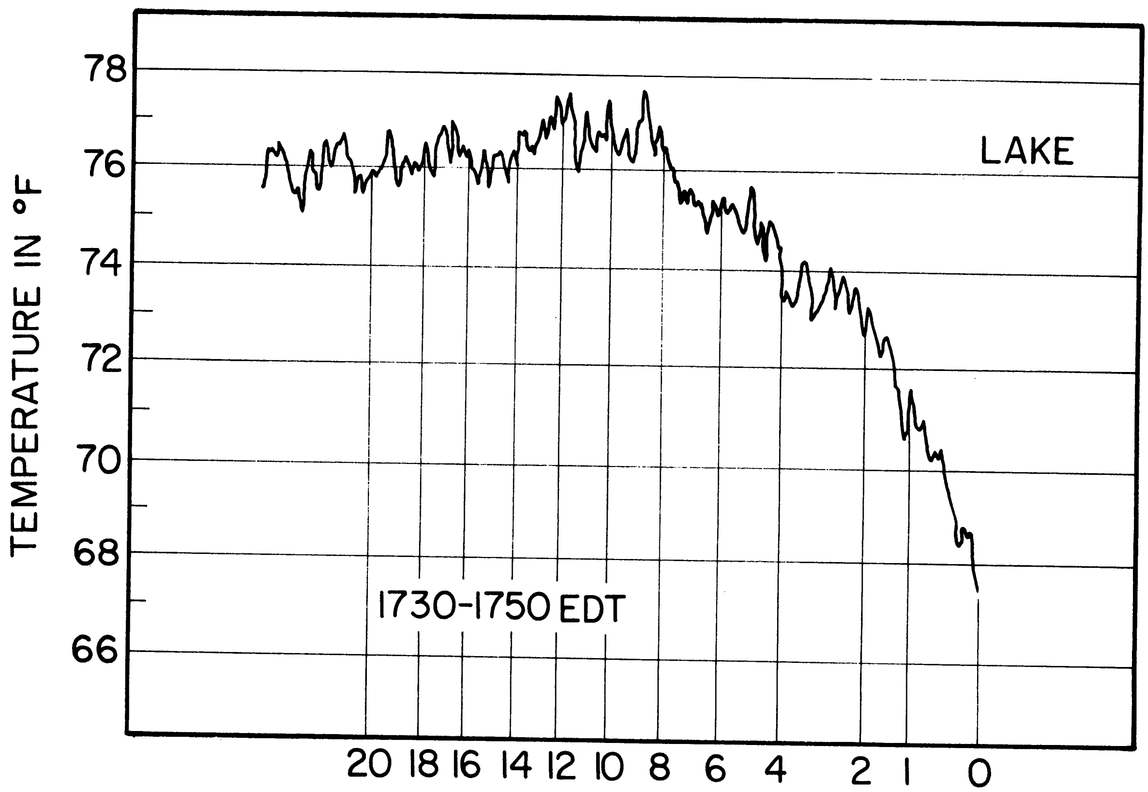

FIGURE 20. Temperature trace for 1730 - 1750 EDT, July 6, 1967.

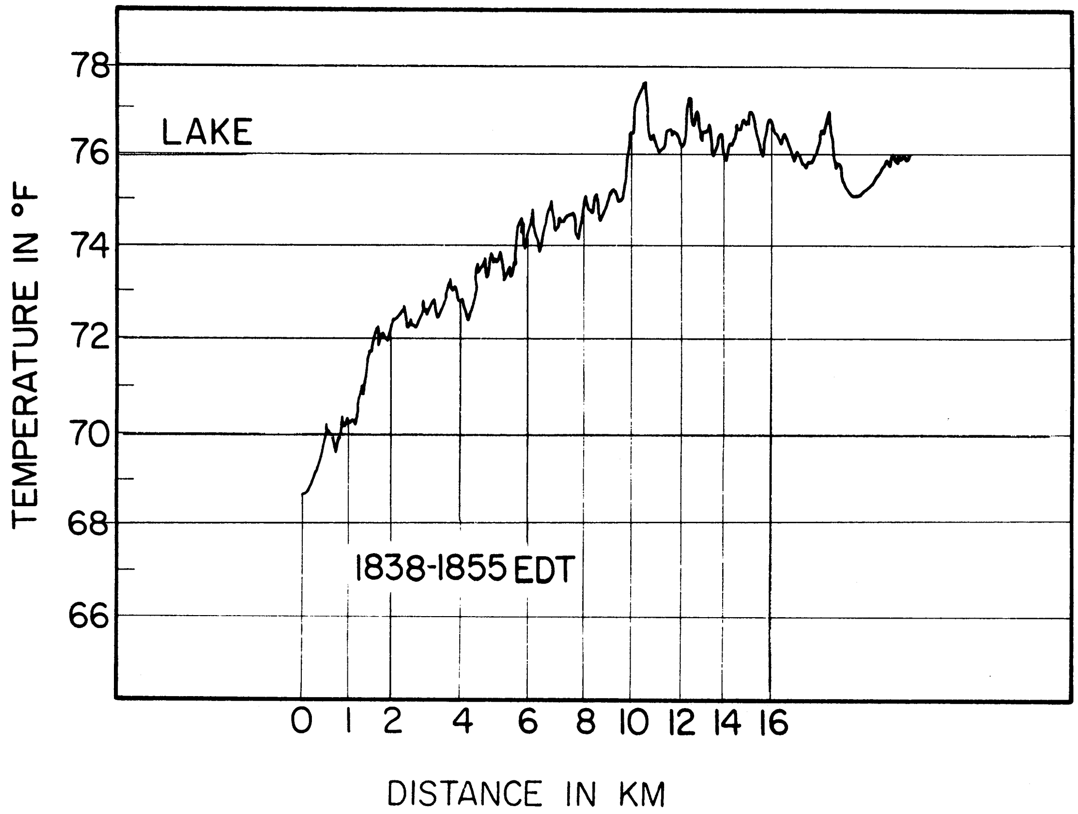

FIGURE 21. Temperature trace obtained during early evening, 1838 - 1855 EDT, July 6, 1967.

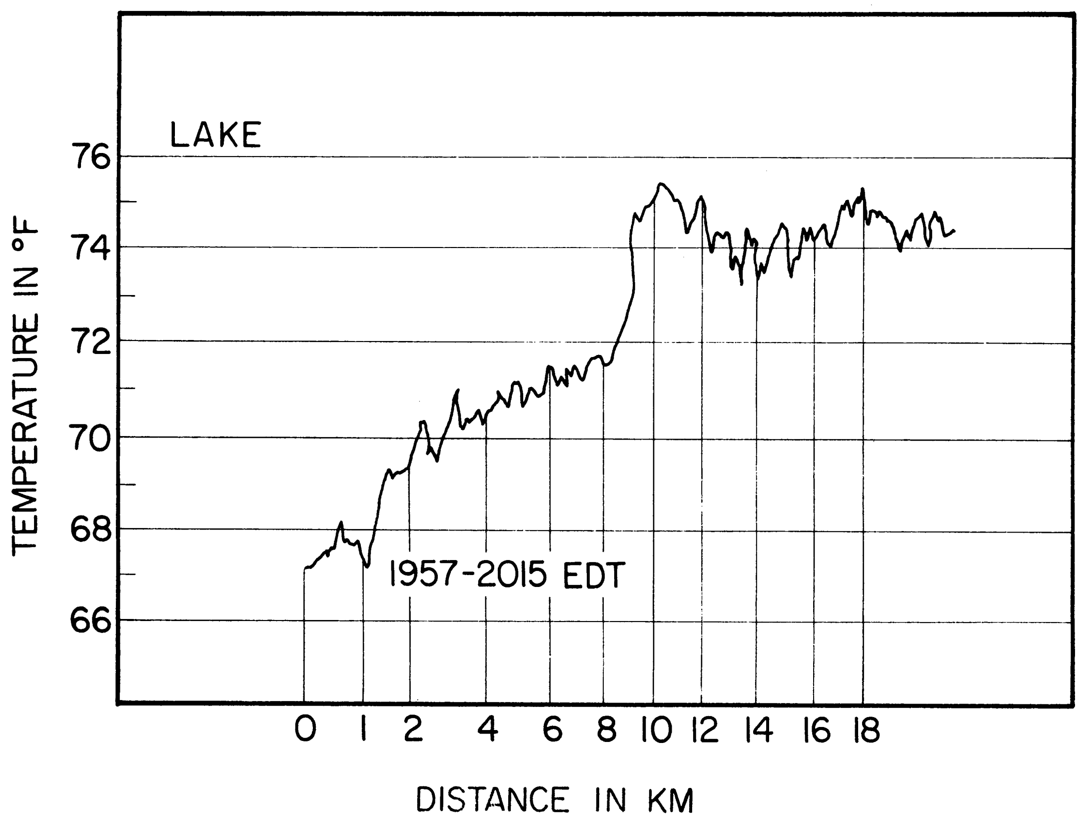

FIGURE 22. Temperature trace for 1957 - 2015, July 6, 1967.

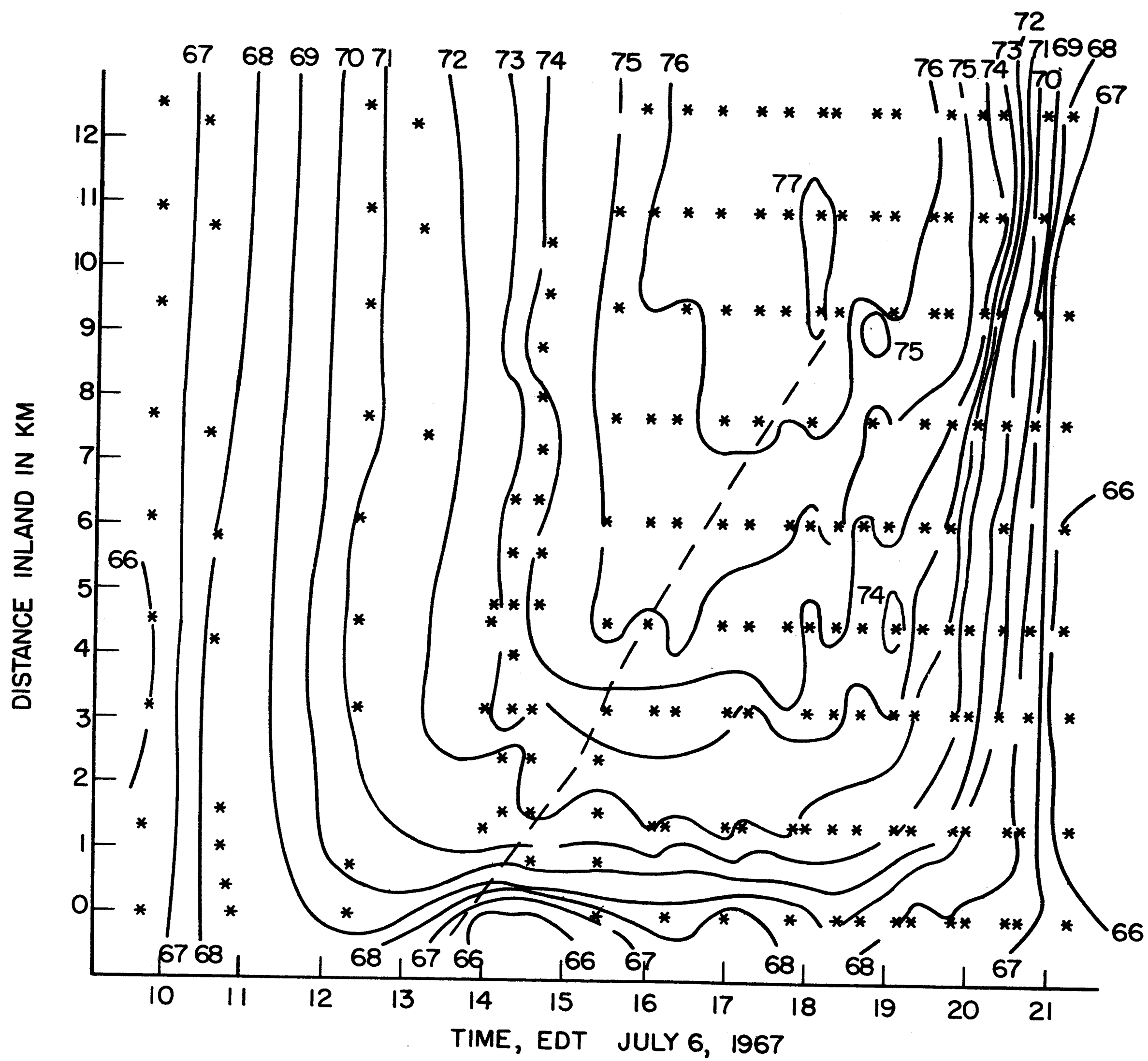

FIGURE 23. Temperature distribution on the lake breeze day of July 6, 1967. Temperature are in °F. Dashed line shows position of the lake breeze front.

drop everywhere due to decreased insolation.

As gradients formed in the afternoon, the isotherms in Figure 23 oscillated in small waves. This may have been either due to inaccuracies in the sensor or to a pulsating behavior of the lake breeze front. It has been suggested by Moroz (1965) that the lake breeze front penetrates at an irregular rate. In this manner the lake air sweeps past a certain point, stalls so that warming takes place before a fresh surge of cool lake air sweeps through.

The progress of the lake breeze could be followed well by this method; the temperature changes seem to agree with the times of the wind shifts at the 8 km station, the WJBL tower, and the USWB station at Muskegon Ariport. Modification of air was quite rapid and when the front was well inland, the temperature gradient across it was quite weak.

3.3 Results of July 8, 1967; Weak Southwesterly Gradient Flow.

On July 8, winds were light between south and southwest as a high pressure center was located over the east coast and a trough was approaching from the west. The local situation is represented in Figure 24. The prevailing wind at the stations along M-45 , Figure 25, was southwesterly at 3-4 m sec^{-1} with a westerly component of 2 - 3 m.sec^{-1} the shoreline station, however, had a predominantly southerly flow with only some slight westerly component in the afternoon. The sky was mostly clear, with only some light cumulus clouds present.

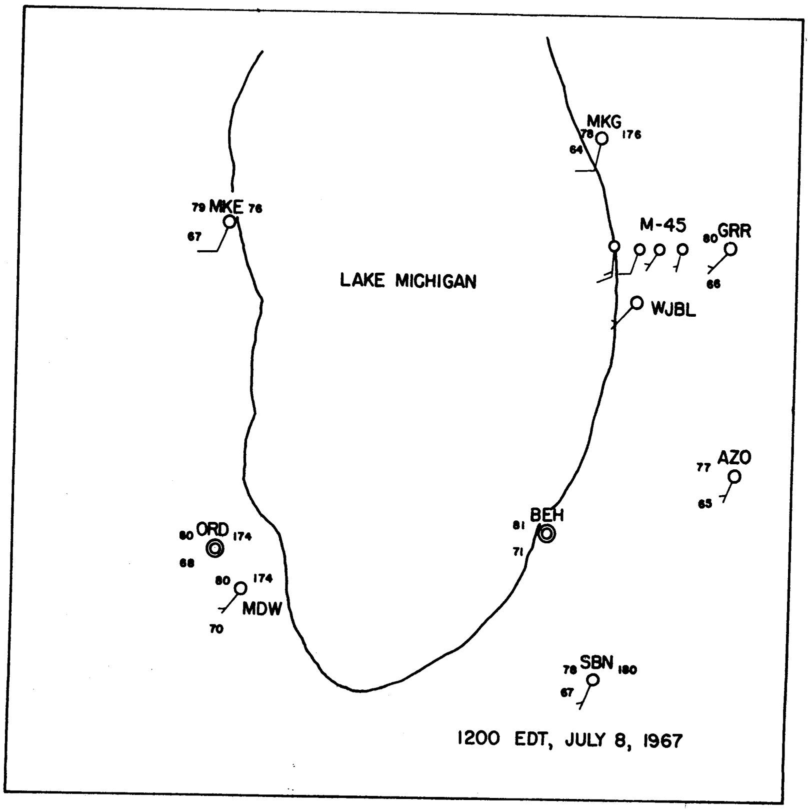

FIGURE 24. Mesoscale surface winds and temperatures around the southern basin of Lake Michigan at 1200 EDT, July 8, 1967.

Two runs were made that day: one around noon and one in late afternoon. The run of 1130 - 1203 EDT is plotted in Figure 26. Temperatures inland reached 78°F while at the shore it was 72°F. A gradient of 1.5°F km^{-1} was found the first 2 km inland. The gradient got progressively weaker further inland and the temperature leveled off at 8 km. The plot for 1810-1845 EDT, Figure 26, shows a temperature of 75°F at the shore and 83°F inland. The profile looks quite similar to the one at noon. The temperature gradient was again 1.5°F km^{-1} near the shore, and the temperature leveled off 14 km inland.

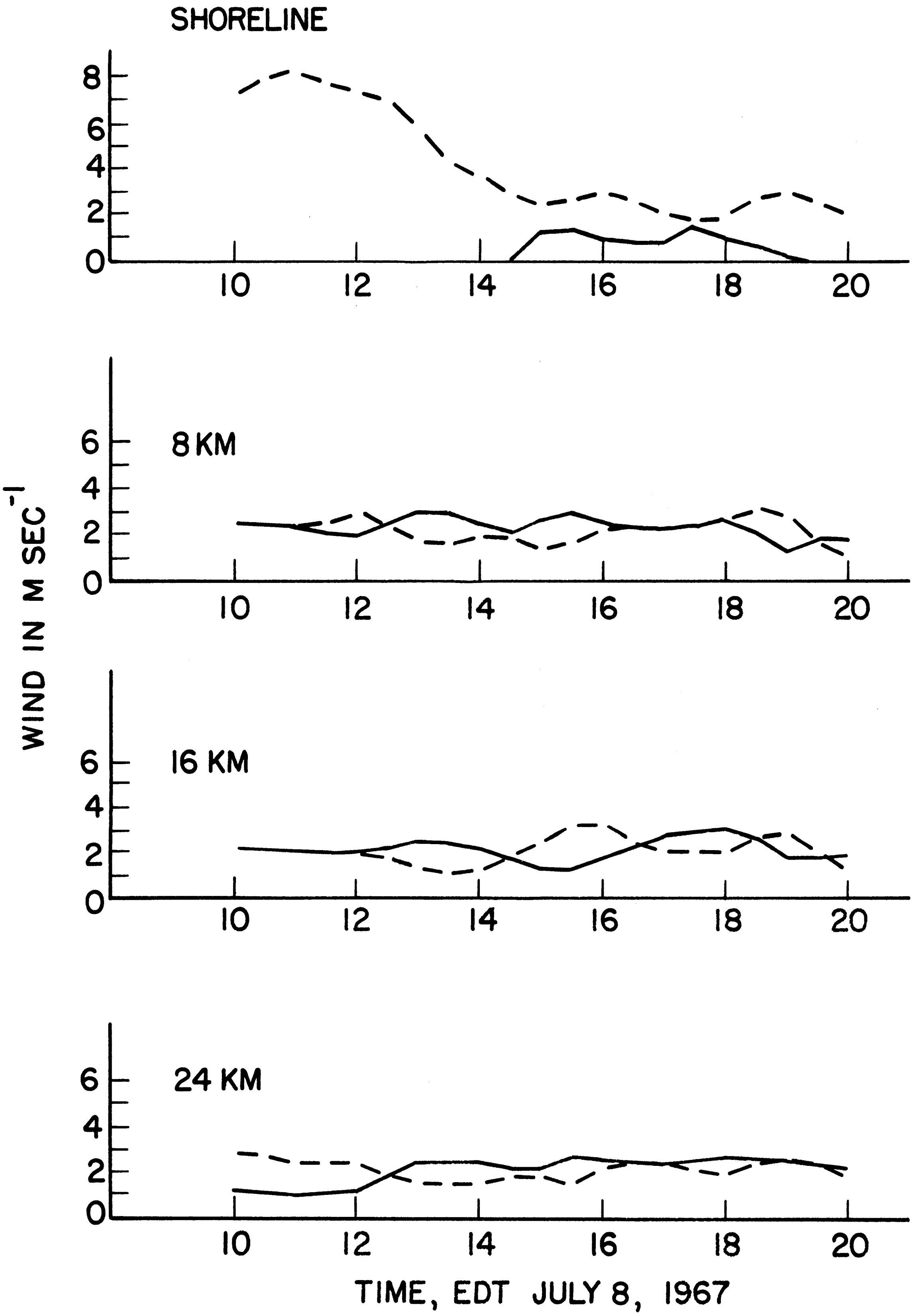

FIGURE 25. Westerly (solid line) and southerly (dashed line) components of the wind at the shore, 8 km, 16 km, and 24 km inland along M-45 for 1000 - 2000 EDT, July 8, 1967. The plot has been smoothed.

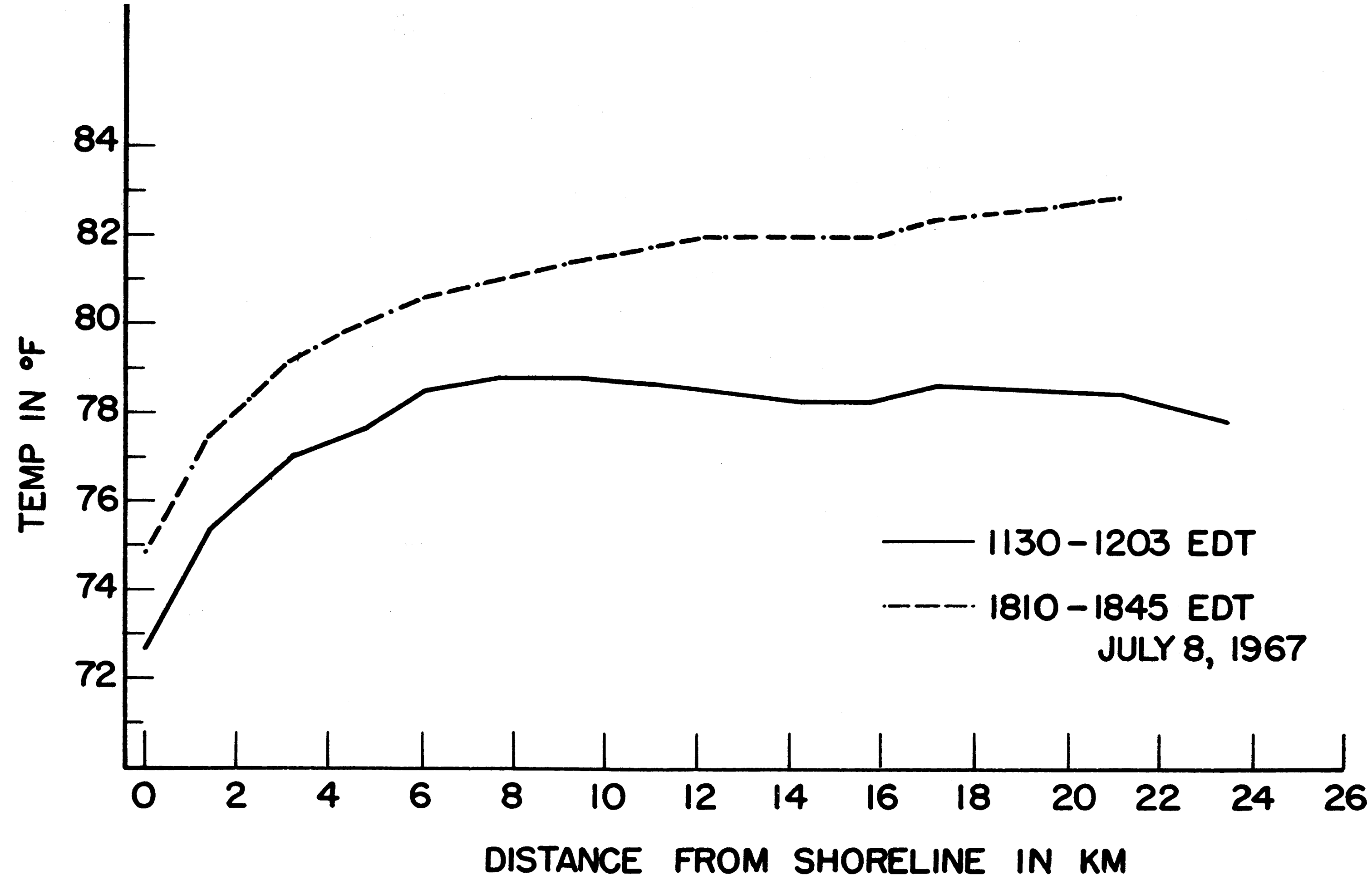

FIGURE 26. Temperature profiles along M-45, at 1340 - 1203 EDT and 1810 -1845 EDT, July 8, 1967.

3.4 Results of July 16, 1967; Weak Southwesterly Gradient Flow.

The situation was quite similar to that of July 8 as a light southwesterly wind prevailed, Figure 27. The westerly component of the winds inland was 2 - 4 m sec^{-1} while at the shoreline southerly winds prevailed, Figure 28. The winds from the 8 km station were missing. Fair weather prevailed all day. Again two runs were made: one around noon and one in late afternoon. The results are plotted in Figure 29. Between 1120 and 1200 EDT, temperatures ranged from 64°F at the shore to 69°F further inland. The gradient was strongest at the shore, about 1.2°F km^{-1}, and ceased 10 km inland. Between 1740 and 1820 EDT, the corresponding temperatures were 69°F and 74°F. A gradient of 1.0°F km^{-1} existed near the shore and the temperature leveled off 12 km inland.

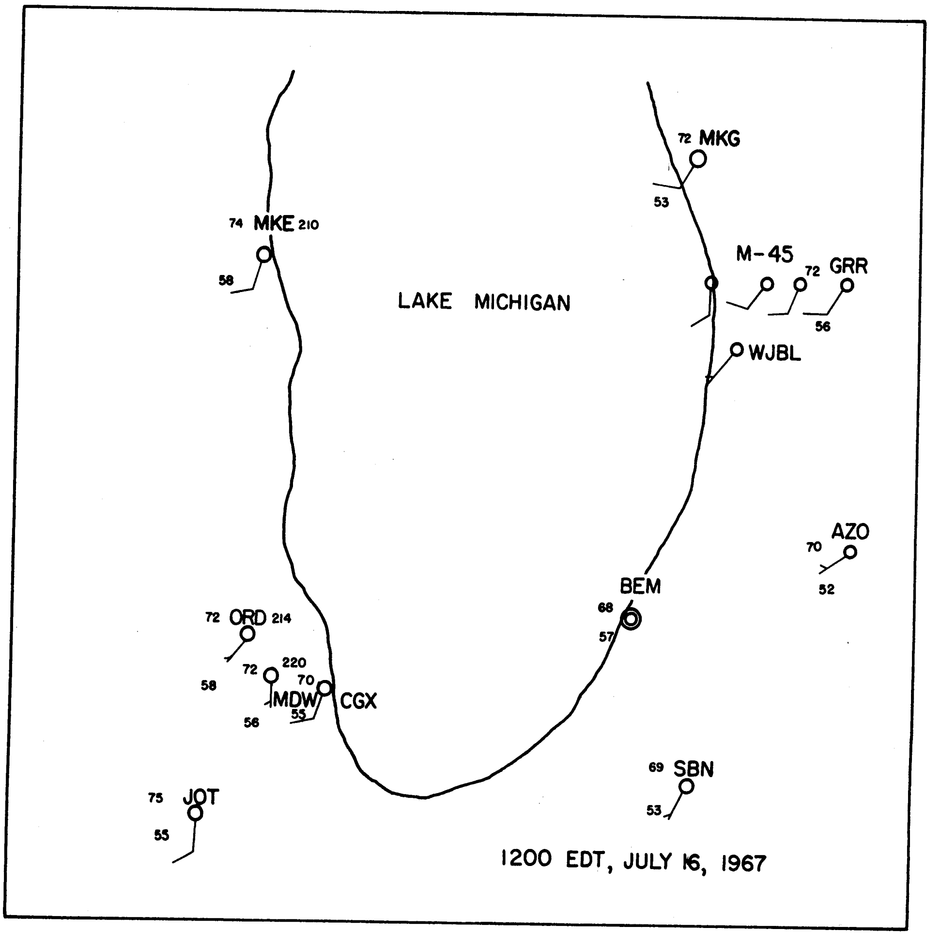

FIGURE 27. Mesoscale surface winds and temperatures around the southern basin of Lake Michigan at 1200 EDT, July 16, 1967.

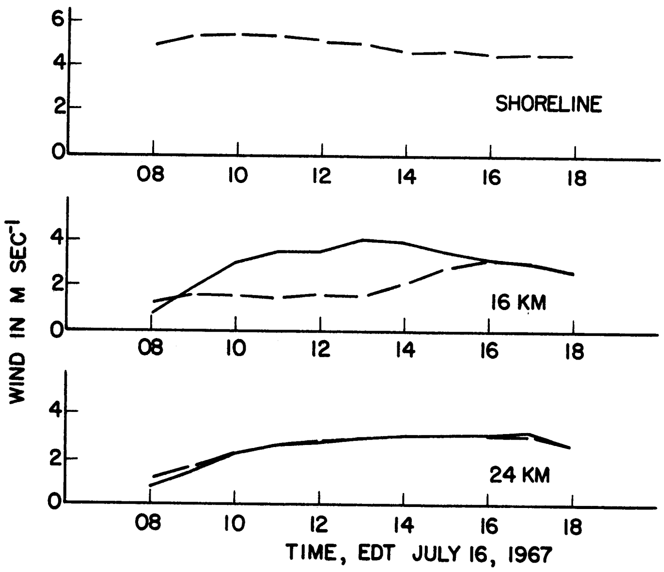

FIGURE 28. Westerly (solid line) and southerly (dashed line) components of the wind at the shore, 16 km, and 24 km inland along M-45 for 0800 - 1800 EDT, July 16, 1967. The plot has been smoothed.

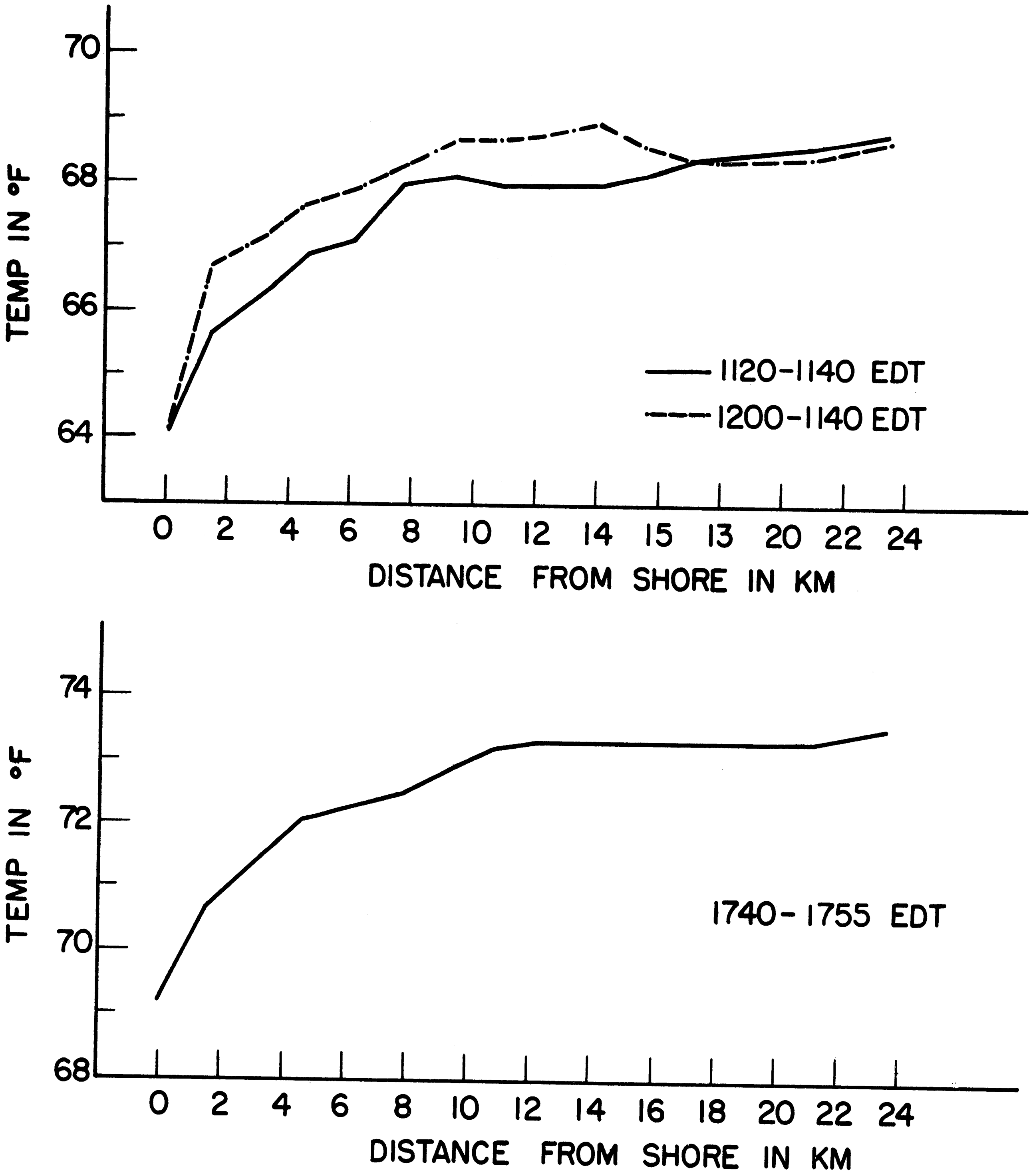

FIGURE 29. Temperature profiles along M-45, at 1120 - 1200 EDT and 1740 - 1755 EDT, July 16, 1967.

4. SUMMARY AND CONCLUSIONS

The results did show different temperature distributions under several different wind situations. With moderate westerly winds, the lake influence extended furthest inland and the temperature increased quite uniformly from the shore to about 10 km inland, beyond which the gradient became small. With light southwesterly winds, a noticable lake influence did not reach as far inland, and a relatively strong temperature gradient was confined to within a few km from shore. With a lake breeze during an easterly gradient wind, the temperature gradient changed rather abruptly inland at the lake breeze front; and the strongest gradient was observed within 2 km from the shore. Thus the inland penetration of the lake effect seems to be a function of the strength of the onshore component of the wind.

When a lake breeze had penetrated some distance inland, the air right behind the front was only slightly cooler than the air ahead of it. At a particular location inland, the passage of the lake breeze front caused the air temperature to level off rather than drop. Only at and near the shoreline was the temperature observed to drop as the lake breeze front passed after which it held steady.

The position of the lake breeze front on July 6 as estimated from the temperature traces agreed quite well with the observed wind shifts at the stations. However, this estimation is accurate to only within 1 or 2 km for several reasons. First, the accuracy of our system is not precisely known. Second, though the response of the system has been measured in the laboratory, it is hard to judge how it actually responds in the field where rapid, small scale oscillations in temperature act on the system. Third, many local differences in the nature of the underlying surface cause irregularities which in different degrees mask temperature differences. For example, a wooded area and an open field would have different effects on the temperature and the wind. Finally, the boundary between the lake air and the land air becomes less pronounced further inland because of the modification of the lake air and mixing of air across the lake breeze front.

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