Meteorological Patterns Associated With High Ozone Concentrations during the Lake Michigan Ozone Study

Steven R. Hanna
Constance M. Haga
Joseph C. Chang

Sigma Research Corporation
234 Littleton Road, Suite 2E
Westford, MA 01886

INTRODUCTION

The Lake Michigan Ozone Study (LMOS) includes portions of Wisconsin, Illinois, Indiana, and Michigan, where ozone levels in urban and rural areas sometimes exceed the federal standard of 12 pphm. Most of the ozone-forming precursor emissions are believed to originate in the urban/industrial areas around Gary, IN, Chicago, IL, and Milwaukee, WI. Precursor emissions and locally produced ozone from the urban/industrial areas are sometimes transported northward along the lakeshore areas of eastern Illinois and Wisconsin, and eastward and northeastward toward the shoreline areas of Indiana and western Michigan, such that ozone exceedances occur at distances of 100 to 200 km downwind.

The four states surrounding Lake Michigan are required to accurately design, evaluate, and implement additional emission control measures to reduce the number of violations of the federal standard for ozone in the region. Revised State Implementation Plans (SIPs), based on photochemical reactive grid modeling, must be prepared and submitted to the US EPA. In order to accomplish this, the four states are carrying out LMOS, which includes a comprehensive field measurement program, and the development and evaluation of advanced mesoscale meteorological and air quality models. The field measurement program took place in the summer of 1991 and the data are now available for analysis.

Our role in this multi-faceted research program is to assist in the analysis of the data from the 1991 field program, and in addition, data from earlier, less extensive field studies in years prior to 1991. Our emphasis is on establishing connections between patterns evident in the meteorological and the ozone data. We will come up with a so-called "conceptual model" that will be used to guide the development of the three-dimensional numerical model. The results reported in this paper are based on a study of surface weather maps and ozone observations during two multi-day ozone episodes prior to the 1991 field program. The analysis is intended to demonstrate that there are certain patterns that repeat themselves during each ozone episode. Similar analyses will be performed using data from the 1991 field program.

METHOD OF ANALYSIS

Each summer a few multi-day ozone episodes occur in the LMOS region. During the past three decades, most studies of ozone have centered on southern California, where high values of ozone concentrations are generally strongly correlated with warm temperatures, and the regional ozone plume is often transported from the source area to distant rural areas[1]. In the Lake Michigan area, the same correlations occur[2,3], but they are complicated by the presence of the Lake and by the effect of "weather" phenomena such as clouds, rain, and frontal passages. These weather phenomena are absent from southern California in the summer, but must be considered around Lake Michigan.

We chose two ozone episodes (20-24 July 1987 and 2-5 July 1990) for analysis. Ozone observations were available from several stations, as shown in the map in Figure 1[4,5]. Four stations were singled out for special analysis:

Milwaukee	(in the source region on the west-lake shore)
Kewaunee	(the northernmost rural west-lake shore station in 1987)
Newport	(the northernmost rural west-lake shore station in 1990)
Muskegon	(east-lake shore station)

NWS surface weather maps were obtained for these two time periods and were redrawn to show only the major features (see Figure 2). Winds and clouds from four major airport stations (Green Bay, Milwaukee, Chicago, and Muskegon) are plotted on the figures. Also included are frontal positions and cloudy areas. Finally, each map indicates the boundary of the major regional ozone plume, which is drawn by hand based on subjective analysis of the ozone observations.

In order to better illustrate differences in the position of the regional plume and their relation to meteorological patterns, time series plots of ozone concentrations from special station pairs are presented (e.g., see Figure 3). The top plot contains data from two stations on the west-lake shore--one in the source region and one in the rural area, and the bottom plot contains data from two stations on either shore of the lake.

ANALYSIS OF 20-24 JULY 1987 EPISODE

The ozone episode that took place on 20-24 July 1987 was marked by exceedances of the federal standard on all five days. The LMOS region was situated on the northwest side of a high pressure system throughout the period. A sequence of 20 surface weather maps, spaced at 6 hr intervals during the period, is plotted in Figure 2, along with the boundaries of the regional ozone plume at each time. It is seen that passing fronts, clouds, rain, and wind shifts strongly influence the ozone pattern.

On the first day (20 July), a regional ozone plume extends towards the northeast (NE) over the lake, but a squall line wipes out the high ozone concentrations as it passes through. On the second day (21 July), ozone begins to build at the source region but is diluted by a line of storms in the evening.

On 22 July and 23 July, skies remained clear long enough for a regional ozone-laden air mass to build up and be transported northward up the lake axis, with ozone being transported onto both shores with the sea breeze. This regional plume gradually veered towards the NE on 23 July, as surface winds increased and also veered. As a result, the northern boundary of the plume pulled away from the western lake shore at the northern end.

The regional plume dissipated during the day on 24 July as clouds and occasional showers spread over the region.

The variations in the position of the regional ozone plume are further illustrated in the time series from pairs of individual stations in Figure 3. The top figure shows two stations on the west-lake shore--Milwaukee, representing the source region; and Kewaunee, representing a rural region farther north. The build-up of ozone in the source region is evident on 21 July, when concentrations in Milwaukee are more than twice those in Kewaunee. However, under the influence of southerly winds, the regional plume reaches Kewaunee by 22 July, when concentrations at the two stations are similar.

The bottom figure shows rural stations on both lake shores, illustrating how Muskegon (on the east lake shore) is more apt to be in the regional plume when winds are out of the southwest (20 and 23 July). On the day (22 July) with south winds, concentrations are similar on both shores.

ANALYSIS OF 2-5 JULY 1990 EPISODE

The results in Figures 4 and 5, for the 2-5 July 1990 episode, are similar to the results for the 1987 episode. However, there is more "weather" passing through the region in the 1990 episode, and maximum ozone concentrations are not as high. This episode was observed as part of a preliminary LMOS 1990 field study[5].

On 2 and 3 July the regional ozone plume was transported by southeasterly winds up the western lake shore, as seen in Figure 4. During the mid afternoon of 3 July a weak warm front, oriented N-S, passed over the lake, causing winds to veer to the SW and increase to about 15 mph. As a result, the regional plume veered to the NE and concentrations increased on the east lake shore. Finally, on 4 and 5 July, two cold fronts passed through, diluting the ozone plume down to background values. It is interesting to note that late on the afternoon of 4 July, the northern part of the lake was located in clean, post-frontal air, while the southern part of the lake was still located in the polluted air mass.

The top part of Figure 5 shows time series of ozone concentrations from two stations on the west-lake shore, showing how transport from the source region (Milwaukee) led to high concentrations in the rural area (Newport) on 3 July. As the winds veered to the SW late on 3 July, concentrations began decreasing in the rural areas along the northern part of the west lake shore.

The bottom part of Figure 5 shows non-urban stations on the west lake shore (Newport) and the east lake shore (Muskegon). The Muskegon ozone concentrations are generally less than the Newport ozone concentrations until the warm front passes through late on 3 July, turning the regional plume so it was oriented more towards Muskegon on the east lake shore. The influence of the two cold fronts on 4 and 5 July is also seen on the figure. The first front obviously passed through Newport about 10 pm, and Milwaukee and Muskegon about 4 am.

CONCLUSIONS

This analysis illustrates that, in temperate climates with frequent fronts and rainfall, it is necessary to use routine weather observations in order to better understand observed variations in ozone concentrations in time and space.

A typical multi-day ozone episode in the region begins on a day with light southerly winds, high pressure, clear skies, and high temperatures. Ozone concentrations are moderately high around the source regions. On the second day, ozone and its precursors are advected up the center of Lake Michigan, causing impacts mainly on the western shoreline. On the third and fourth days, as a front approaches from the northwest the winds generally strengthen and turn more westerly. The broad ozone plume veers so that it passes over the eastern shore of the Lake and into Michigan. Superimposed on these broad regional plume patterns are mesoscale perturbations due to the persistent stable surface boundary layer over Lake Michigan and due to the effects of land and lake breezes along the shorelines. The pattern can also be significantly perturbed by weak fronts, clouds, and thunderstorms. The episode usually ends when a front brings clouds into the region.

ACKNOWLEDGEMENTS

This research was sponsored by the Lake Michigan Air Directors Consortium (LADCO) and was conducted under a subcontract from Sonoma Technologies, Inc., with Dr. Paul Roberts as the project manager.

REFERENCES

1. S.R. Hanna, "Characteristics of Ozone Episodes during SCCCAMP 1985," J. Appl. Meteorol. 30: 534-550 (1991).

2. J. Haney, et al., Ozone Air Quality Scoping Study for the Lower Lake Michigan Air Quality Region, Report No. SYSAPP-89/113 Prepared by SAI for US EPA, 1989.

3. Murray and Trettel, Inc., LMOS Weather and Forecasts (1991), Final Report by Murray and Trettel, Inc. for LADCO, Des Plaines, IL 60018, 1991.

4. P.T. Roberts, T.S. Dye, S.R. Hanna, and C.M. Haga, Preliminary Data Analysis for the Lake Michigan Ozone Study, Report STI-90212-1157-DR, Prepared for LADCO, Des Plaines, IL 60018, 1991.

5. N. Bowne and D. Shearer, 1990 Field Measurements Program, Summary Report No. 4133-001-300 Prepared by ENSR for LADCO, Des Plaines, IL 60018, 1991.

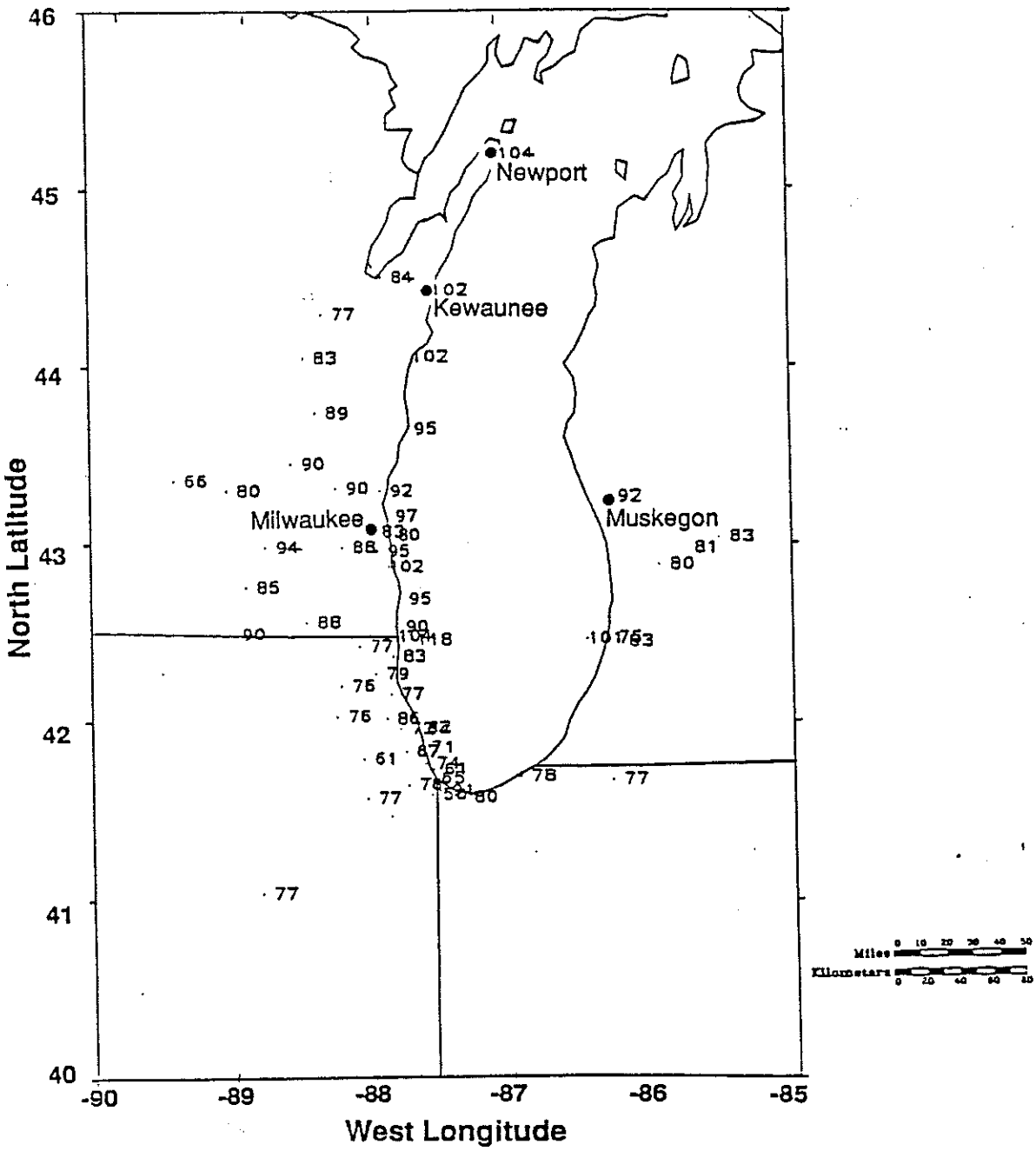

Figure 1. Map of Lake Michigan region, showing locations of four monitoring sites analyzed in Figures 3 and 5. Ozone concentrations (ppb) at 1500 CDT on July 3, 1990, are shown[4].

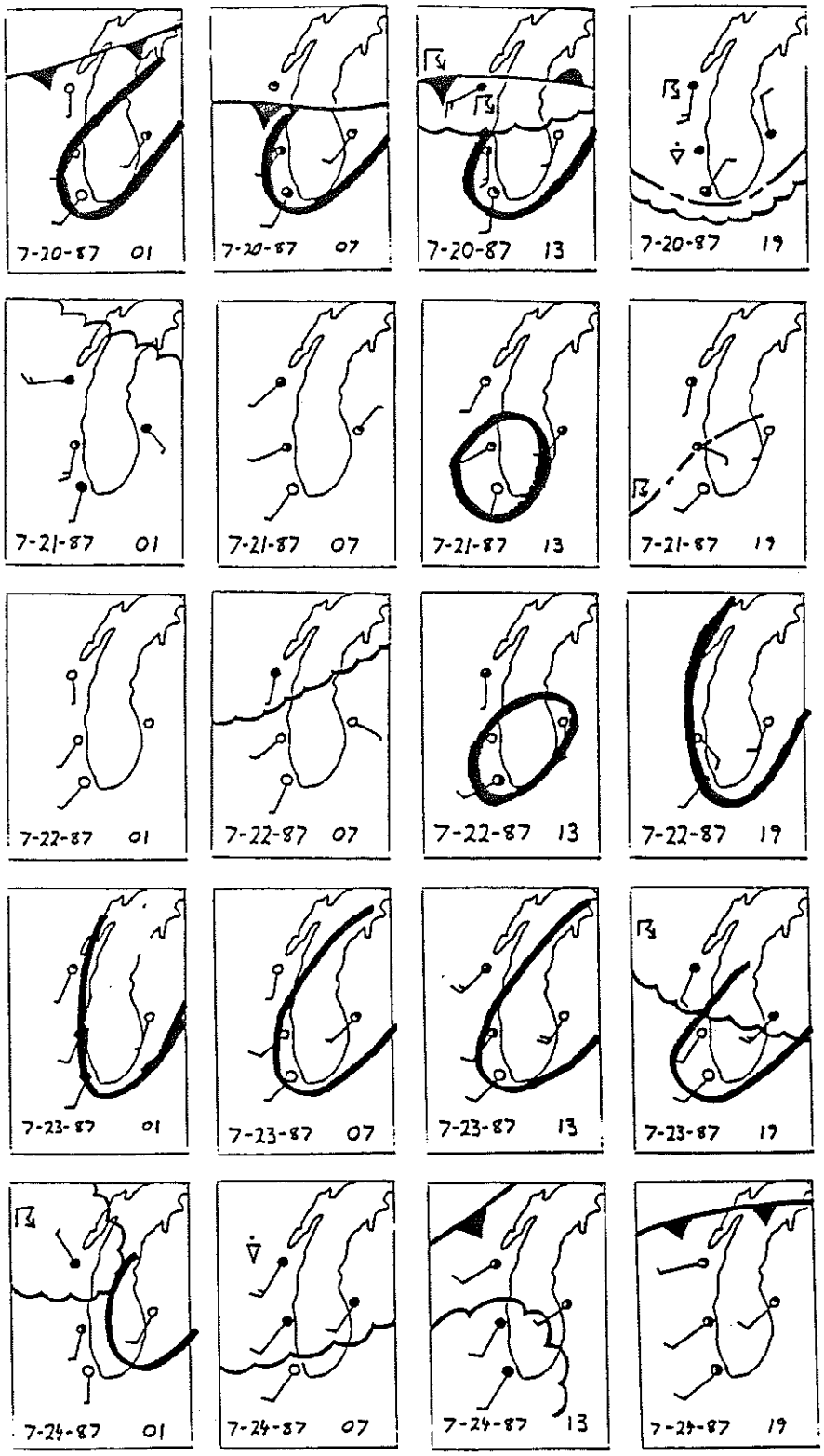

Figure 2. Series of surface weather maps, with boundary of regional ozone plume shown as thick line, for Lake Michigan area on July 20 through July 24, 1987. The amount of shading in the weather station circle is proportional to the amount of cloud cover, and each long barb on the arrow represents a wind speed of about 10 mph.

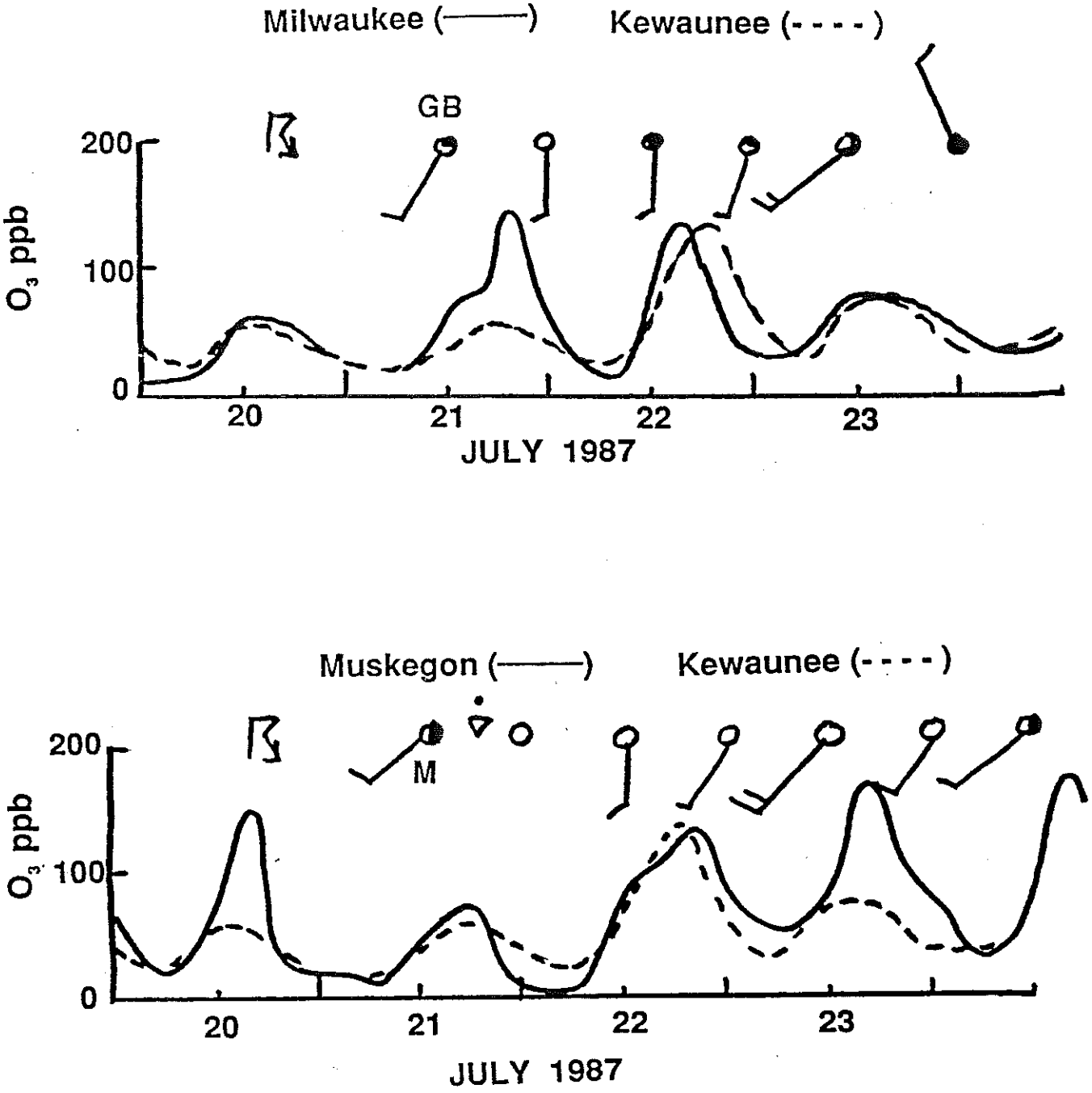

Figure 3. Time series of ozone concentrations on July 20 through 24, 1987, with surface weather conditions at Green Bay (GB) and Muskegon (M) shown. The top figure shows stations on the southern (Milwaukee) and northern (Kewaunee) parts of the west shore of the lake, and the bottom figure shows stations on the eastern (Muskegon) and western (Kewaunee) shores.

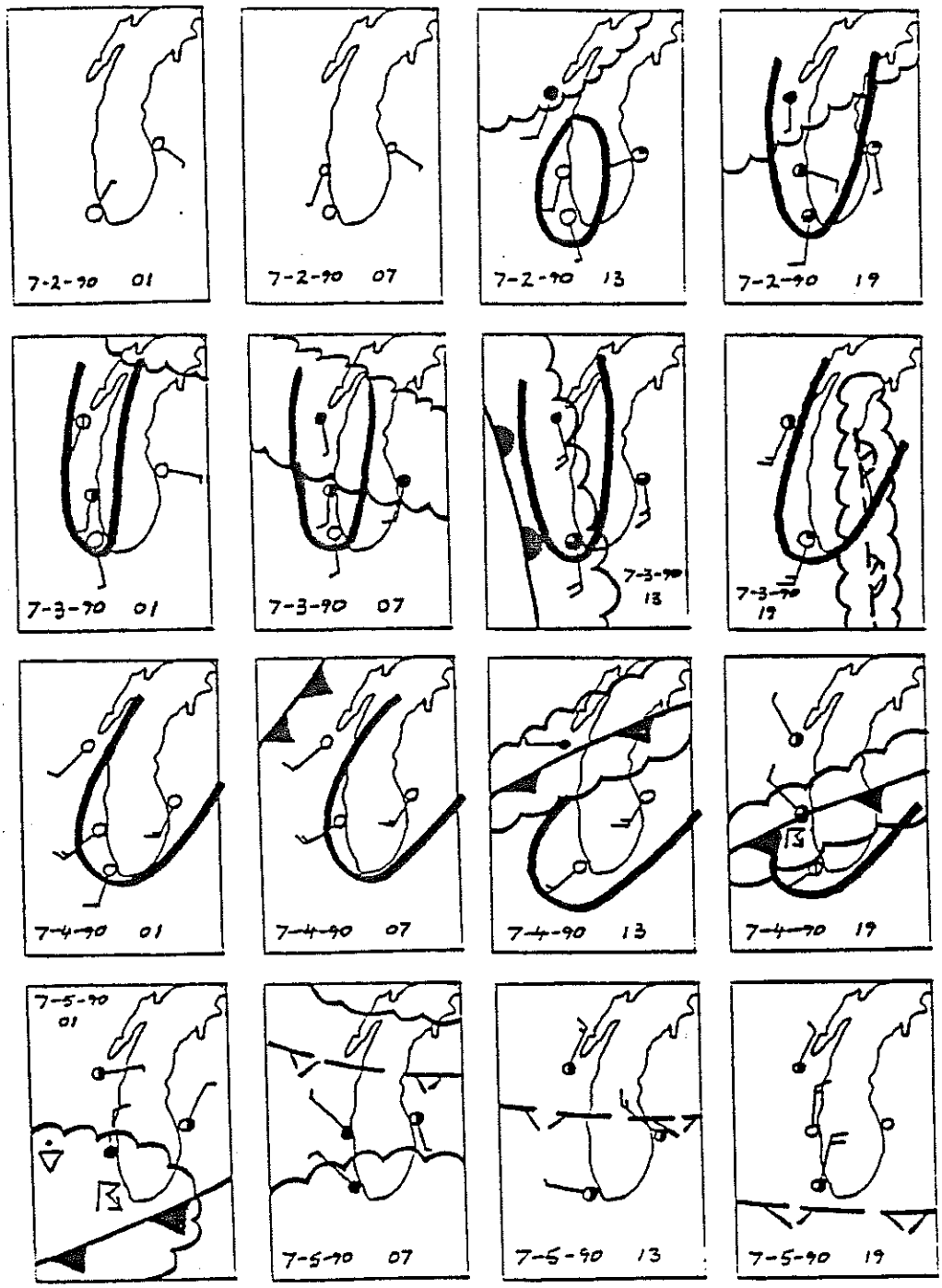

Figure 4. Series of surface weather maps, with boundary of regional ozone plume shown as thick line, for Lake Michigan area on July 2 through July 5, 1990. The amount of shading in the weather station circle is proportional to the amount of cloud cover, and each long barb on the arrow represents a wind speed of about 10 mph.

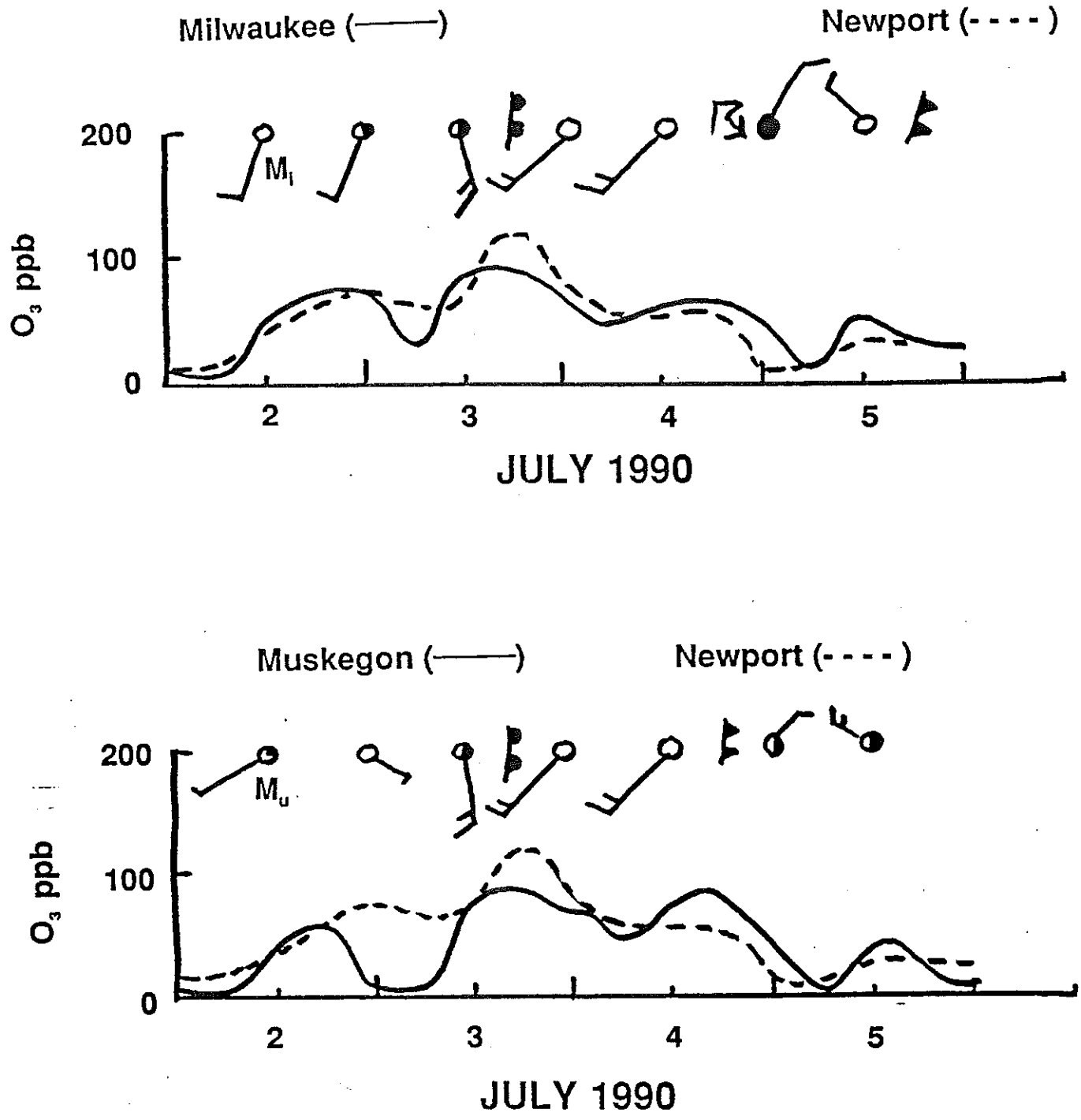

Figure 5. Time series of ozone concentrations on July 2 through 5 1990, with surface weather conditions at Milwaukee (Mi) and Muskegon (Mu) shown. The top figure shows stations on the southern (Milwaukee) and northern (Newport) parts of the west shore of the lake and the bottom figure shows stations on the eastern (Muskegon) and western (Newport) shores.