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Department of Meteorology and Oceanography

Final Report

MESOSCALE WIND SYSTEMS AROUND THE GREAT LAKES

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ABSTRACT

An extensive observational study of the lake and land breeze climatology has been carried out near the eastern shore of Lake Michigan. Surface winds, temperatures, humidities, pressure, and solar radiation have been continuously measured at several stations for more than four years.

During periods of high lake breeze frequency, intensified studies of winds, temperatures, and humidities aloft and over the lake have augmented the climatological data. Case studies of well-developed lake breeze circulations have been published in technical papers and reports.

This report summarizes the field study program and the collected observational data. An inventory of the status and availability of the data are given in several tables. A short description of findings made on the basis of this field program is supplemented by abstracts of scientific papers based fully or partly on data pertinent to this study.

1. INTRODUCTION

The air pollution meteorologist is often faced with the problem of predicting the diffusion and transport of pollutants by the environmental wind field. While the geostrophic wind field, the gradient wind field or a wind field as determined from observed surface and upper air winds can provide some insight to these problems, local perturbations due to urban heat-island effects, terrain roughness, or water-land interface can cause wind field variations that range from negligible to very dominant. In cases when the Great Lakes region is being influenced by large slow-moving anticyclones with resulting weak gradient-winds, the land breeze and lake breeze circulations at the shoreline can produce wind speeds much larger than those due to the synoptic-scale pressure patterns. In such cases, these winds will be the dominant factor in determining the dispersion of air pollutants.

The air over a large lake often has stability characteristics that differ markedly from those of air over land. These differences in stability regimes can cause diffusion processes which require calculation methods quite different from those recommended for concentration calculations over land, Turner (1969). An extreme case of advection stability was measured over southern Lake Michigan on May 5, 1964 by Bellaire (1965). He showed that a temperature inversion of 0.7°C m^{-1} (40°F in 100 ft) developed in the lowest layer over the lake during southerly gradient-wind flow. Such an extreme inversion would effectively trap air pollution and minimize vertical diffusion.

The lake breeze circulation will set up stability regimes which are different from either those over a continental land mass or those found in an atmosphere in equilibrium with an underlying water surface. The descending air of a lake breeze circulation-cell may develop temperature inversions both over land and water, thus establishing rather stable situations with poor air pollution dispersion. When cool and stable lake air moves inland over heated soil, fumigation can occur as instability is induced into the air mass from below. Further inland, an unstable situation develops and air pollutants are readily diffused into larger volumes of the atmosphere so that pollutant concentrations become rather low.

The purpose of the research done under this grant was to investigate mesoscale wind systems around the Great Lakes with particular emphasis on the role played by the interface region at the shoreline. These local shoreline circulations; the lake and land breezes, occur generally under conditions of high pressure, low gradient wind, and pronounced temperature differences between lake and land surfaces. These are, in general, the same conditions that result in a stable atmosphere and poor dispersion of air pollutants.

The field study phase of the project was designed to measure the lake breeze parameters of wind, air temperature, water temperature, solar radiation, and humidity along a vertical cross section normal to the shoreline of one of the Great Lakes. Lake Michigan was chosen for the study because of its north-south orientation and the relative uniformity and smoothness of its shoreline along the Michigan side of the lower basin. It is also logistically convenient to The University of Michigan. The southern basin of Lake Michigan lends itself well to mathematical modeling as it can be described as either an infinitely long lake with parallel sides, Moroz (1965), a circular lake, or an elliptical lake.

The main field-study site was chosen near the eastern shore of Lake Michigan and along highway M-45, approximately 20 km south of Grand Haven, Michigan, Figure 1. At this location, the sand dunes which line the Lake Michigan shoreline are relatively small and the mean land surface is only 10 to 20 m above lake level. Furthermore, the slope of the land towards the lake is small and it can be assumed that no slope winds develop. Figure 1 shows the location of the field study sites. Routine lake breeze climatological measurements were taken over a period of several years with extensive measurements made during actual or anticipated periods of intensive lake breeze activity.

The abstraction and processing of data from the field studies were accomplished with the twin goals of producing a lake breeze climatology based on all available data and the determination of the detailed behavior of lake breezes on specific days. A paper on lake and land breeze characteristics, Cole (1967), presented some basic climatological factors while Olsson, Cole, and Hewson (1968a,b) presented one of the most detailed studies available of the genesis and decline of a well-developed lake breeze circulation on the Great Lakes.

Mathematical modeling of the lake breeze and the development of analytical methods for obtaining wind fields over Lake Michigan were the goals of the theoretical portion of this investigation. The lake breeze model developed by Moroz (1965), which was based on the sea breeze model of Estoque (1961,1962), was evaluated with data from the lake breeze on June 25, 1965 as reported by Olsson, Cole, and Hewson (1968a,b). These data agreed quite closely with the data used by Moroz in his original studies and the mathematical model produced results in general agreement with the observations. Further studies of this model are under way as a portion of the doctoral program of Mr. Arthur Tingle. He has found evidence that the Moroz-Estoque model may be very sensitive to the initial conditions and he is now testing a more generalized model.

The successive approximation technique of Cressman (1959) was modified to provide an analysis of sea-level pressure for the Lake Michigan area. With an increase in computer storage, the analysis region was later increased to include all five Great Lakes. From the computed grid point pressure analyses, Cole (1968), geostrophic winds were calculated to be used as first approximations to the wind fields responsible for air pollution transport.

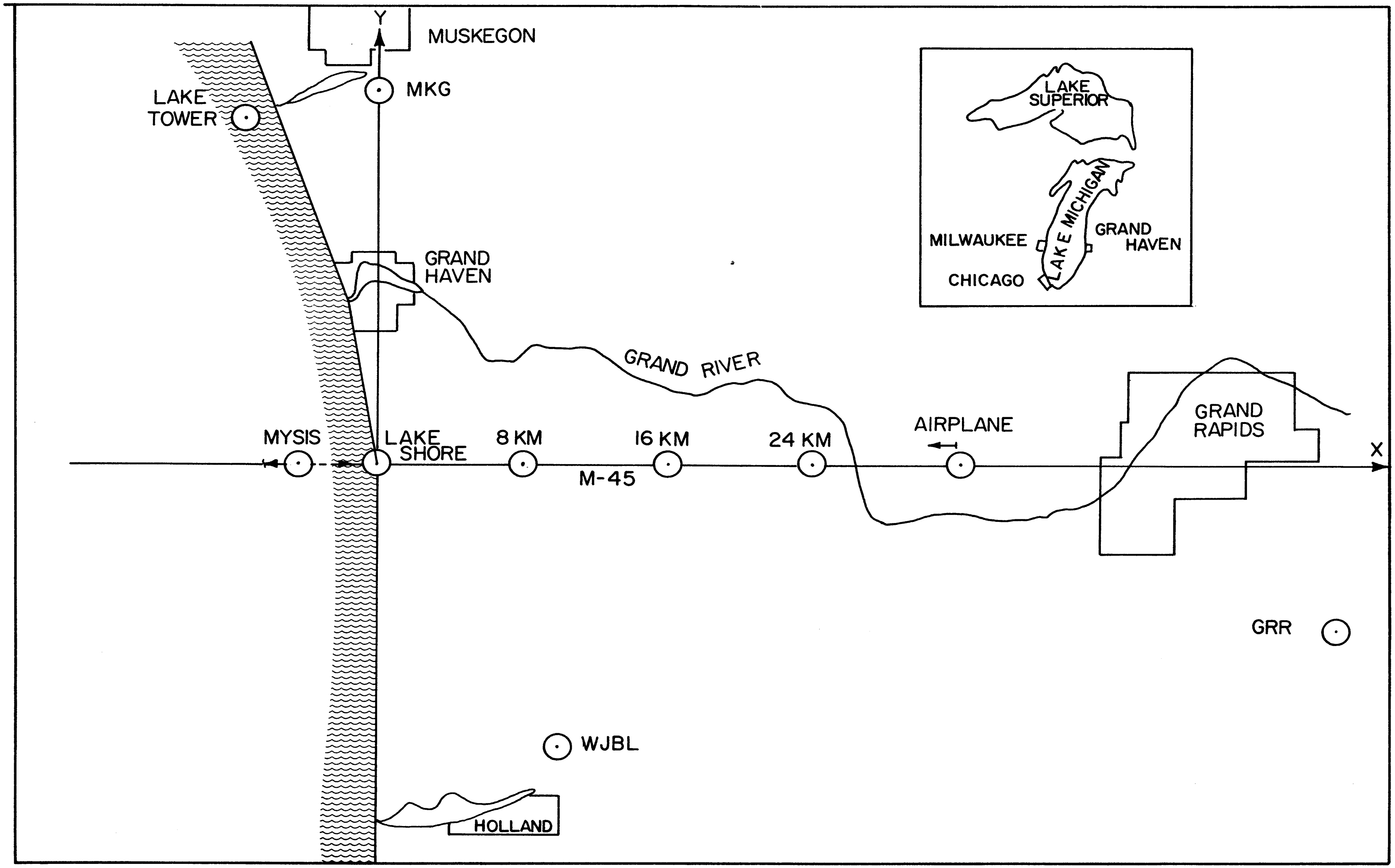

Figure 1. Location of observation stations near the eastern shore of Lake Michigan. Insert shows the location of the line of observations relative to Lake Michigan.

2. FIELD STUDIES

The field study portion of this investigation was designed to accumulate extensive long-term data for the determination of a lake breeze climatology for Lake Michigan and also to make intensive measurements of specific lake breeze circulations under various synoptic conditions. The lake breeze climatology phase of the study utilized the wind and temperature profile measurements from a tower at radio station WJBL in Holland, Michigan with the addition of temperatures, humidities, wind speeds, and wind directions measured at locations 0, 8, 16, and 24 km inland, along a line (Michigan highway M-45) normal to the shoreline (Table 1 and Figures 2-6). The sensors and recorders at these stations operated automatically from May 1965 through October 1965 and from May 1966 until sometime in 1968 or 1969, except when they were shut down due to mechanical failure. Specific lake breezes were studied by intensively measuring all possible lake breeze parameters on certain days when they occurred. For this purpose, manned observation sites were established at the four climatological sites along M-45 for surface land observations while aircraft and pilot balloons were used to make measurements in the upper air and a boat on Lake Michigan provided measurements in and over the water. Intensive studies were conducted during May and June of 1965 and 1966 with eight days of well-developed lake breeze circulations being observed. On other days measurements in varying detail were made, even though well-developed lake breezes did not occur. In 1967, a study of lake breeze circulations using tetroons was conducted along the shores in southern Lake Michigan, Olsson (1969).

2.1. THE CLIMATOLOGICAL PHASE

There have been a number of case studies of lake breeze circulations in recent years, Munn and Richards (1964), Moroz and Hewson (1966), Lyons (1966, 1967), Strong (1967), Moroz, Hewson, and Gill (1967, and Olsson, Cole, and Hewson (1968a,b); however, these studies treat one or a few days on which lake and land breezes occur but do not treat the climatology of those breezes. To obtain data adequate for a climatological description of lake and land breeze circulations, four instrumentation sites separated by 8 km (5 miles) each were established along a line perpendicular to the shore of Lake Michigan as shown in Figure 1. A detailed summary of the facilities at each of the stations is presented in Table 1 and the sites depicted in Figures 2-6. A summary of the data collected at these sites is given in Section 3 of this report. From the wind data such features as inland penetration characteristics, time of occurrence at various distances inland, and the intensities of the land and lake breezes are being determined. Temperatures and humidities as well as temperature profiles measured at the various stations, were collected for studies of air mass modification and changes of atmospheric stabilities near a lake shore.

2.2. THE INTENSIVE STUDY PHASE

The instrumentation used for the climatological phase was operated over periods of many months with weekly operational check visits. While the data from these sensors was adequate for a climatological study, much augmentation was needed during case studies of specific lake breeze circulations.

The climatological wind data were used as the surface wind during the intensive study periods. In addition, winds over the lake and winds aloft were measured during these periods. In 1965, the Research Vessel MYSIS, Figure 7, provided measurements of parameters over the lake. Pilot balloons were released from off shore and tracked both by a shipboard theodolite and by single or double theodolites located on the shore.

Double theodolite sites were established at each of the four observation points along M-45. As it was not possible to predict the occurrence of lake breezes with any certainty and as manpower limitations prevented extensive measurements at each site on each day, an escalating intensity of measurement program with single and double theodolite observations of winds aloft was used. As probable lake breeze situations were identified early in the morning, the intensity of pibal measurements was increased as the lake breeze developed. If, however, the lake breeze did not materialize, the pibal observations were reduced or eliminated. Theodolite readings at 30-sec intervals were used throughout the study with balloon releases at one-hour or half-hour intervals. This type of program produced a rather erratic appearing coverage of the sites as shown in Tables 8 and 9, Section 3, but it did allow several lake breeze days to be studied in more detail than if the personnel had been utilized in a uniform manner.

The temperature data from the hygrothermographs used in the climatological study became the surface air temperatures for the intensive study phase. The air temperature from the WJBL radio tower provided temperature profiles for the intensive study phase. Temperatures from further aloft were measured with instrumented aircraft during the intensive study periods in 1965 and 1966. The aircraft flew ascending and descending patterns from 300 m (1000 ft) to 2000 m (7000 ft) over the shore, inland at the test sites, and over the lake at various distances from shore. Two minutes were used in circling at each thousand-foot level to allow an equilibrium to be established in the sensing equipment. Details of collected data coverage are shown in Table 14, Section 3.

The humidity data from the hygrothermographs used for the climatological study provided surface humidity values for the intensive study period over the land stations. These data were augmented during the intensive study period by overwater humidity data from the R/V MYSIS and by humidity data from aloft measured with the humidity portion of the Friez Aerometeorgraph mounted on the aircraft, Figure 8.

Table 1. Summary and description of facilities used and measurements made during field studies near the eastern shore of Lake Michigan 1964-69. Numbers refer to comments on the following pages.

	1965							1966							1967-69				
	Lakeshore	8 km	16 km	24 km	Boat	Aircraft	WJBL	Lakeshore	8 km	16 km	24 km	Boat	Aircraft	WJBL	Lakeshore	8 km	16 km	24 km	WJBL
<u>Climatological phase</u>																			
12.2 m tower	1	2	3																
36.6 m tower								1	2	3	4				1	2	3	4	
91.5 m tower							5							5					
USWB-type shelter	1	2	3	4				1	2	3	4				1	2	3	4	
Surface wind	1	2	3		6			1	2	3	4				1	2	3	4	
Low wind profile							5							5	1				5
Surface temperature	1	2	3	4	6		5	1	2	3	4			5	1	2	3	4	5
Low lapse rate					6		5							5	1				5
Surface humidity	1	2	3	4	6			1	2	3	4				1	2	3	4	
Solar radiation	1				6			1							1				
Soil temperature							5							5					5
Surface pressure								1							1				
<u>Intensive-study phase</u>																			
CB radio	1				6			1											
Theodolites	1	2	3	4	6			1	2	3	4								
Balloon releases	1	2	3	4	6			1	2	3	4	6							
Aerometeorographs						7							7						
Wind aloft	1	2	3	4	6			1	2	3	4								
Temperature aloft						7							7						
Humidity aloft						7							7						
Water temperature					6							6							

Comments on Table 1

(1) Lakeshore station (0 km) was located on the City of Grand Rapids pumping station property on M-45 at the lakeshore. During the summer of 1965 a Climet Model Cl-9D wind speed and direction recording system was installed with sensors mounted at the top of a 12.2 m (40 ft) guyed steel tower, Figure 3. In June 1966 a 36.6 m (120 ft) tower was installed and equipped with top mounted Science Associates wind speed and direction sensors, #402 and #418, respectively. The wind data were recorded on an Esterline-Angus 20 pen event-recorder. During July 1967 two U-V-W-anemometers were mounted on the tower and winds were recorded on a Texas Instrument 3-channel strip chart recorder and an Ampex SP-300 tape recorder.

A Bendix Friez Model 594 recording hygrothermograph was located in a USWB-type instrument shelter at the station in May 1965 and exchanged for a barohygrothermograph in May 1966. In July 1967 copper-constantan thermocouples were installed in aspirated shields to measure lapse rates in the lowest 40 m near the lake shore. These sensors were located at the 5-, 10-, 15-, 20-, 25-, 30-, 35-, and 40-m levels and the temperatures were recorded on a Brown-Electronic Multipoint recorder. In November 1967 a new Leeds and Northrup, Speedomax multipoint recorder was installed. A Belfort recording pyrheliometer was located on the roof of the 10-m high pumping building at the station in May 1965. During the winter seasons this pyrheliometer was moved to the roof of a building at Consumers Power Company, approximately 15 km south of the Lakeshore station.

During the summers of 1965 and 1966 facilities for pilot balloon releases and tracking were located at the station. Field telephones and buzzers were used between the two theodolites (305 m N-S baseline) for coordination of double theodolite tracking of pilot balloons. A Messenger II, 5-W Citizen's Band radio-telephone using a top mounted antenna on the tower was used for communication with the other stations during the intensive-study phases.

(2) 8-km station was located on a farm in flat terrain. In May 1965, Science Associates wind speed and direction sensors, #402 and #418 respectively, were mounted at the 12.2-m level of a guyed steel tower. The wind data were recorded on an Esterline-Angus 20 pen event-recorder. In May 1966 the sensors were relocated and top mounted on a 36.6-m guyed steel tower, Figure 4.

A Bendix Friez Model 594 recording hygrothermograph was located in a USWB-type instrument shelter in May 1965.

During the intensive-study phases, facilities for pilot balloon releases and single or double theodolite tracking (305 m N-S baseline) of these balloons were located at the station. The tower was equipped with a top mounted antenna for CB radio communication.

(3) 16-km station was located on the lawn of a field station of the Michigan Department of Conservation during 1965 and moved to a site in open flat terrain in 1966, Figure 5. The facilities available at this station were the same as at the 8-km station.

(4) 24-km station was located in open slightly rolling farmland. The facilities available at this station were the same as at the 8- and 16-km stations except for surface wind instrument and tower. A 36.6-m tower with top mounted Science Associates wind speed and direction sensors, #402 and #418, respectively, and CB radio antenna was erected in June 1966, Figure 6.

(5) WJBL station was located on open farmland along US-31 and 5 km north of Holland, Michigan, Figure 2. Electric Speed Indicator 3-cup anemometers and wind vanes type F-420-C were mounted at the 19.5-, 39.0-, and 78.0-m levels of a 91.4-m high guyed steel radio tower in June 1964. Wind data were recorded on Esterline-Angus 0-1 ma dual strip-chart recorders. The top vane was lowered to the 61.0-m level in 1965 to reduce radio frequency pick-up.

Copper-constantan thermojunctions were mounted at the 2.4-, 4.9-, 9.8-, 19.5-, 39.0-, and 78.0-m levels for lapse rate measurements and thermojunctions at 0.01-, 0.10-, and 1.00-m depths in the ground sensed soil temperatures. These temperatures were recorded on a Honeywell-Brown multipoint recorder.

(6) Boats were used during the intensive study phases for over water meteorological measurements. In May and June 1965 a 50-ft, steel hulled research vessel MYSIS, Figure 7, belonging to the Great Lakes Research Division of the Institute of Science and Technology, The University of Michigan was used. An Electric Speed Indicator 3-cup anemometer and wind vane type F-240-C was mounted on the top of the ship's mast, 12.1 m above the water surface. Air temperature was measured with a Rosemont Engineering platinum resistance thermometer system with sensors mounted in Thornthwaite-type radiation shields at 11.8 and 5.1 m above the water surface. Water temperature was sensed 1.2 m under the water surface.

Humidity was sensed with a Honeywell lithium chloride dew probe on bow mounting at 5.0 m above the water surface and solar radiation was sensed by an Eppley solar radiation sensor mounted on top of the wheelhouse. Ship speed and heading were manually set, as was the date, while a digital clock produced time signals with 1 min resolution. Data from all the above instruments onboard the R/V MYSIS were recorded on an Information Instruments, Inc. data logger Model 641.

Releases of pilot balloons were made from the R/V MYSIS for either shipboard tracking with a marine theodolite or shoreline tracking with standard theodolites. A Messenger II, 5-W CB radio telephone was used for communication with lake shore and aircraft stations. During May and June

1966 a smaller boat was used for releases of pilot balloons off shore for shoreline tracking. No data were collected off shore during 1966.

(7) Aircraft (Cessna 172) were used for measurements aloft during the intensive-study phases in 1965 and 1966. Friez aerometeorographs were used for temperature and relative humidity recording, Figure 8. For calibration and checking of the aerometeorograph data, measurements were also made with a Yellow Springs Instrument Corporation Thermistor system in 1965. Both dry and wet bulb temperatures were measured. In 1966 a mercury thermometer and a psychrometer held in the cabin air scoop provided the supplementary temperature and humidity data.

A Hallicrafters, 5-W CB radio telephone was used for communication with ship and land stations.

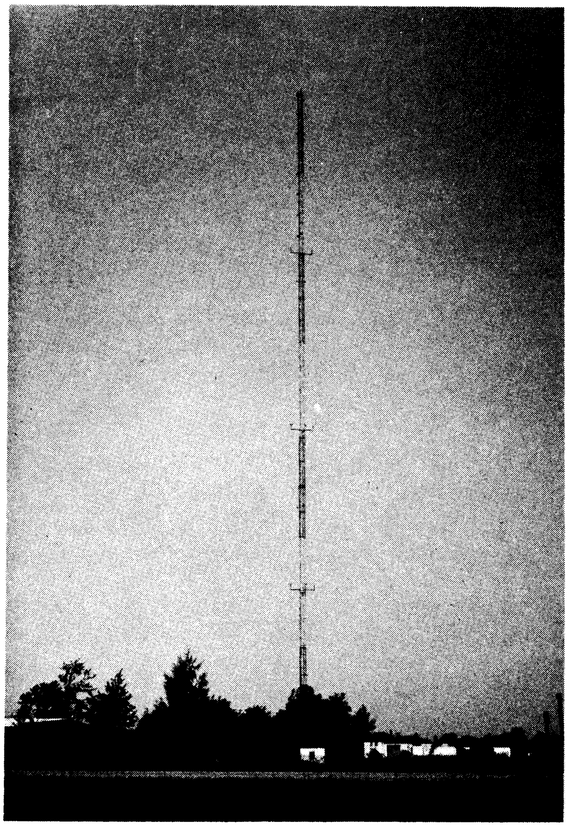

Figure 2. The WJBL, 91.4 m high, radio transmitting tower supporting wind and temperature sensors. The recorders are housed in the shelter at the foot of the tower.

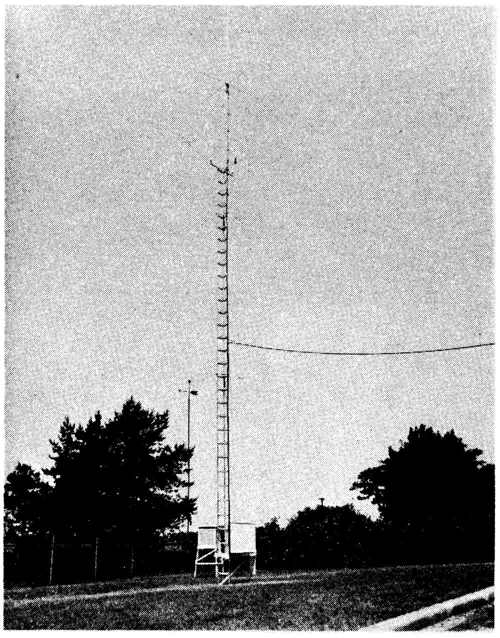

Figure 3. Lake shore station. An USWB-type instrument shelter at the foot of the 12.2-m meteorological tower, which supports wind sensors and a radio telephone antenna.

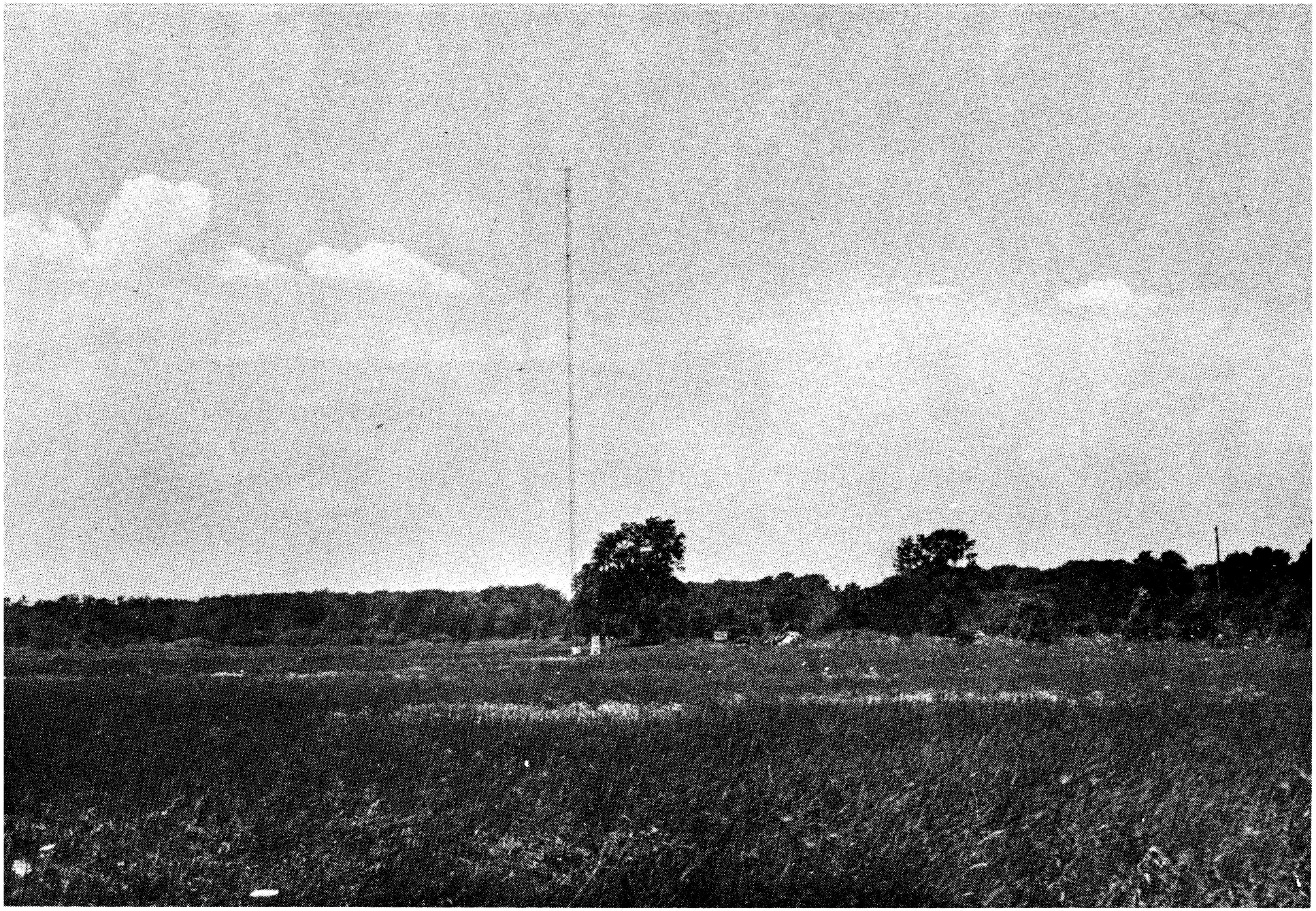

Figure 4. The meteorological tower and the USWB-type instrument shelter at the 8-km station viewed from the northeast.

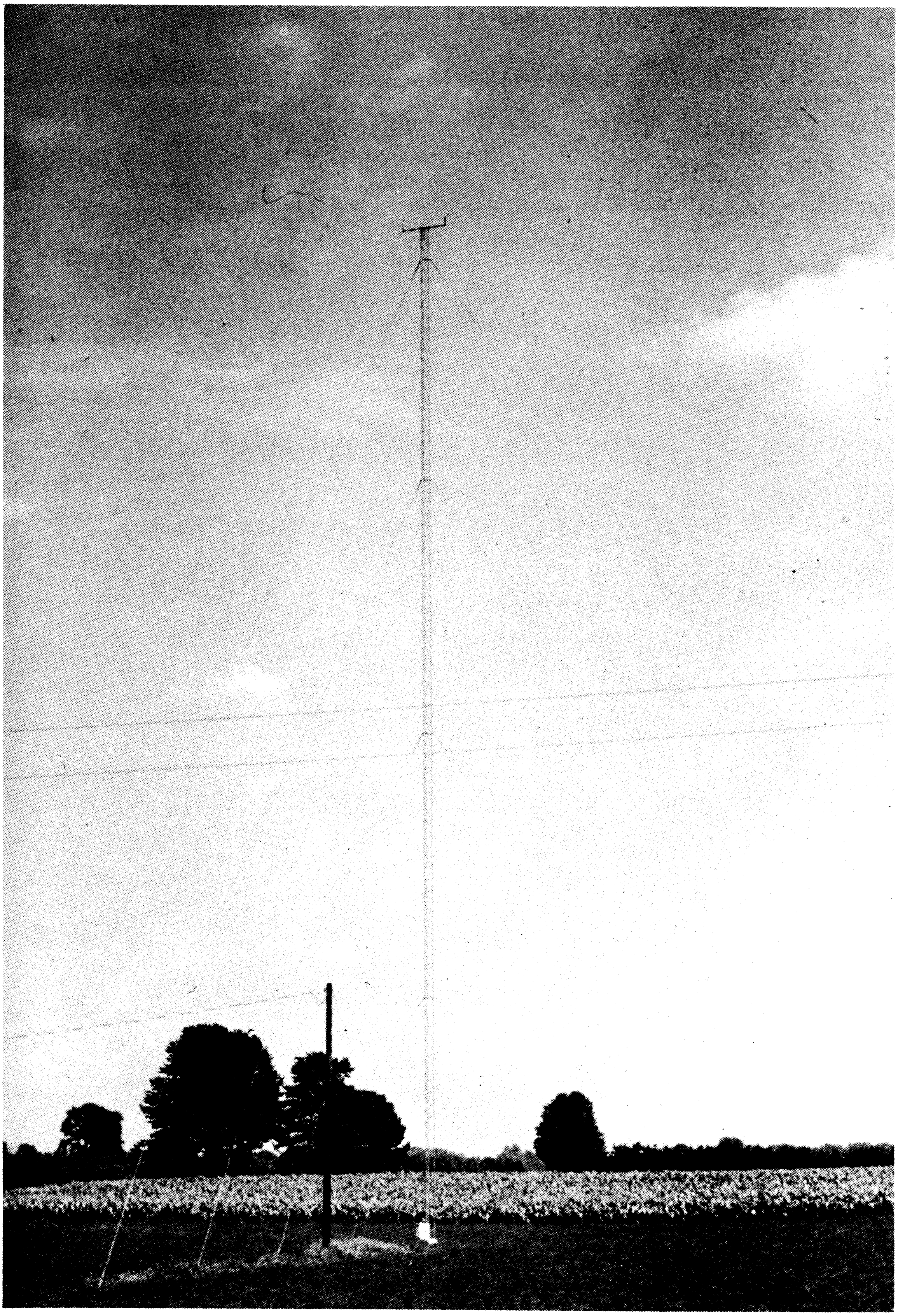

Figure 5. The meteorological tower and the USWB-type instrument shelter at the 16-km station viewed from the west.

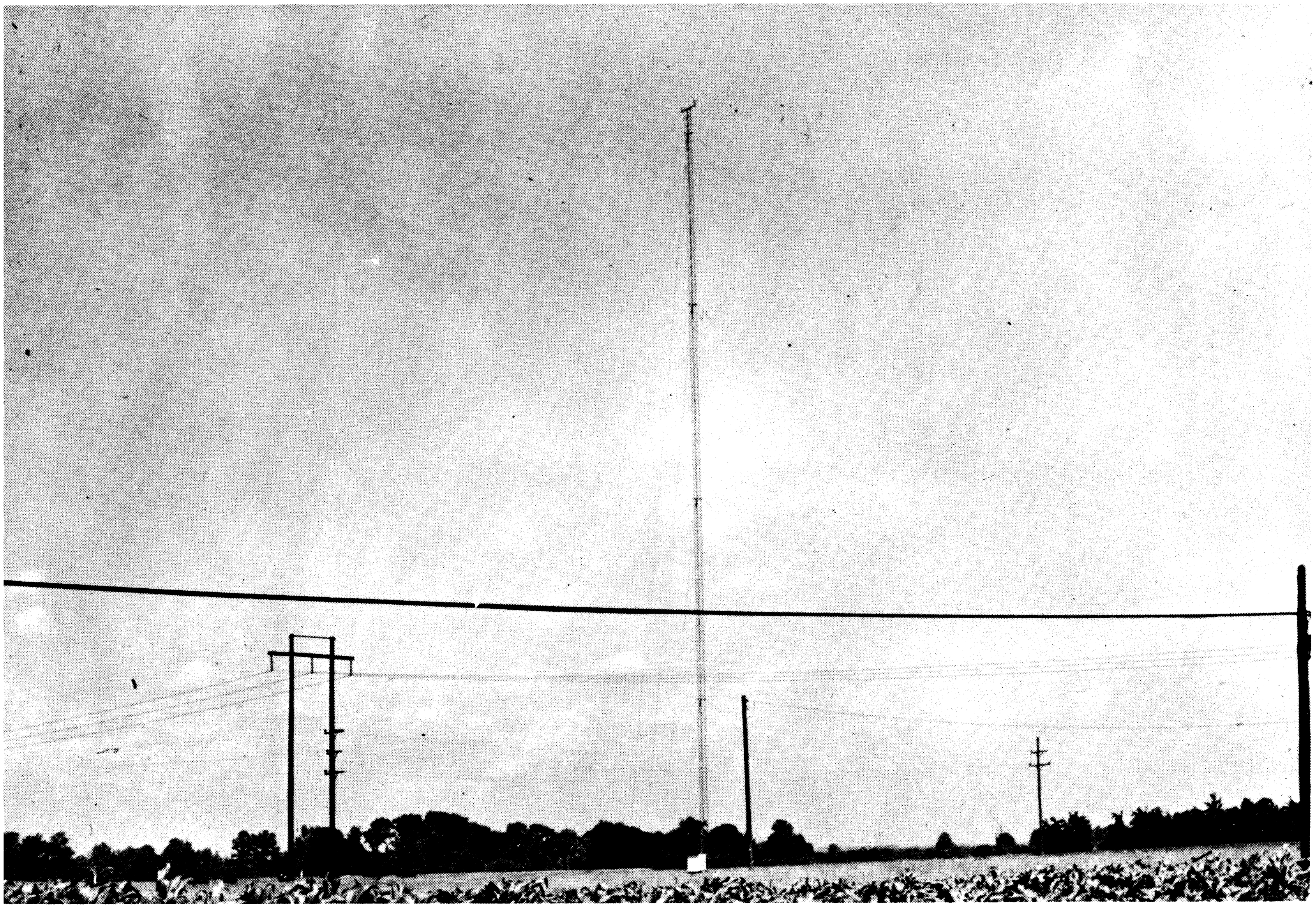

Figure 6. The meteorological tower and the USWB-type instrument shelter at the 24-km station viewed from the southwest.

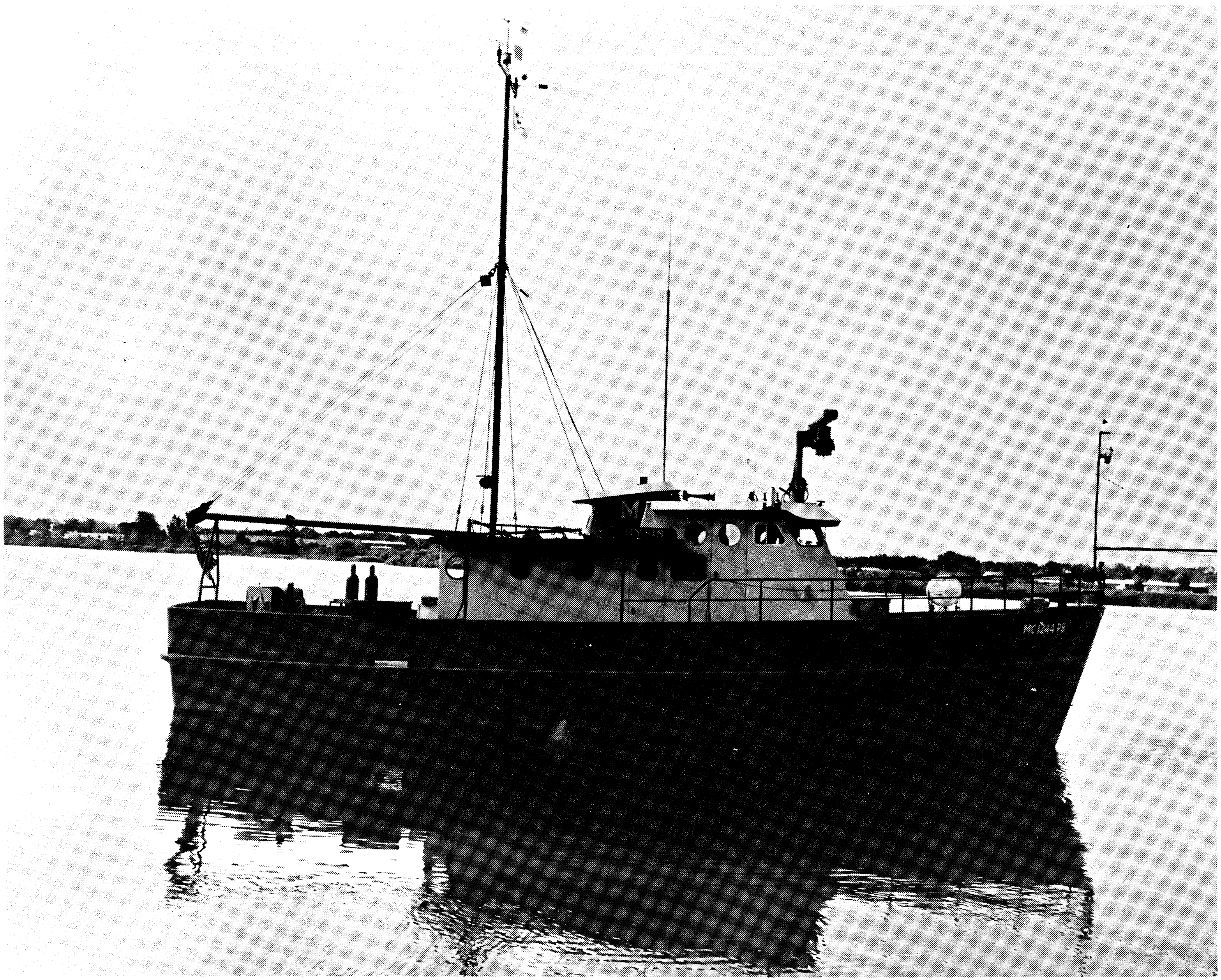

Figure 7. The R/V MYSIS equipped with temperature, humidity, radiation, and wind sensors.

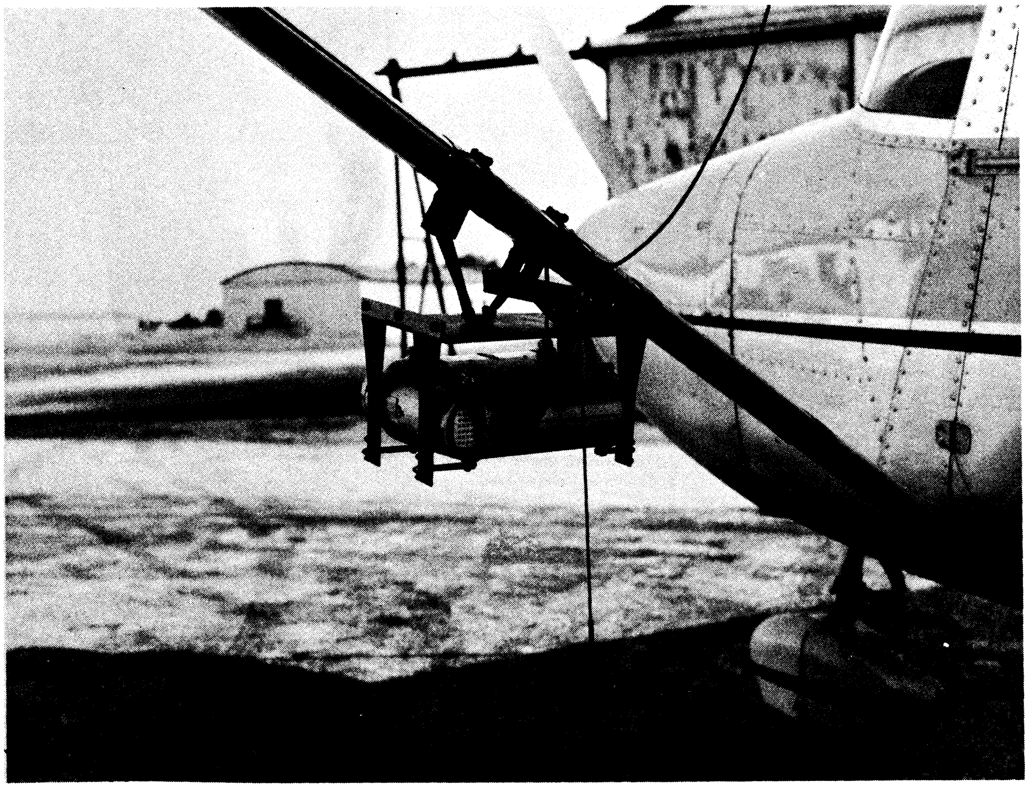

Figure 8. Friez aerometeorograph, mounted on left wing strut of a Cessna 172 aircraft.

3. AVAILABILITY AND STATUS OF DATA

All data collected during the field studies are stored at the Department of Meteorology and Oceanography, The University of Michigan except for some data collected onboard the R/V MYSIS, which is stored at the Great Lakes Research Division of the Institute of Science and Technology, The University of Michigan. A summary of available data is given in Table 2, while more detailed descriptions of the data from the various stations are presented in Tables 3-15. Raw data is in general available for the periods indicated in Table 2, except for periods when the facilities were shut down due to mechanical failure. As can be seen from Tables 3-15, many data have been abstracted and checked for consistency. Data collected in the period 1965-1967 have, to a great extent, been punched on IBM cards and stored on magnetic tape. Printouts of these tapes have been made. The wind aloft observations have been analyzed on a digital computer and print outs of these analyses are available.

Some of the data have been analyzed in detail and constitute the basis for several technical papers and reports. A listing of publications utilizing data from this project is given in Table 16 and respective abstracts appear in Appendix A.

TABLE 2. Summary of collected meteorological data near Grand Haven, Michigan, 1964-69. Dates indicate observation periods and numbers in brackets refer to tables where detailed information regarding respective data can be forund.

STATION	SURFACE WIND	WIND PROFILE	WIND ALOFT	TEMP. REL.HUM.	TEMP. PROFILE	PRESS.	SOLAR RADN.
LAKESHORE (0 KM)	Oct.-65 - July-69 (3)	July-67 [a]	May-June-65(8) May-June-66(9)	May-65 - July-69(10)	July-67 - July-69(10)	May-66 - July-69 (10)	May-65 - July-69 (10)
8 KM	May-65 - Mars-69 (4)	-	May-June-65(8) May-June-66(9)	May-65 - May-69 (11)	-	-	-
16 KM	June-65 - June-69 (5)	-	June-65(8) May-June-66(9)	May-65 - June-69(12)	-	-	-
24 KM	June-65 - June-69 (6)	-	June-65(8) June-66(9)	May-65 - June-69(13)	-	-	-
MYSIS	May-June 1965 [b]	-	June-65(8) [c] May-June-66(9)	May-June 1965 [b]	-	-	May-June 1965 [b]
AIRPLANES	-	-	-	June-65 May-June-66 (14)	June-65 May-June-66 (14)	-	-
WJBL	June-64 - Sept.-68 (7)	June-64 - Sept.-68 (7)	-	July-64 - [d] Sept.-68 (15)	July-64 - Sept.-68 (15)	-	-

a) Data not abstracted.
b) Data logged by Great Lakes Research Div., Institute of Science and Technology, The University of Michigan.
c) Small boat used for release of balloons and all tracking from shore in 1966.
d) No relative humidity observed.

TABLE 3. Lakeshore, 0 KM, station observation periods for wind speed and direction and status of data.

1965	10/9 - 12/18	Abstracted
1966	6/1 - 12/31	Abstracted
	6/7 - 12/31	On mag. tape
	11/28 - 12/12	No direction available
1967	1/1 - 12/31	Available
	1/1 - 4/17 and 5/7 - 10/31	Abstracted
	1/1 - 3/11 and 5/7 - 9/30	Checked
	5/7 - 9/30	On mag. tape
	2/6 - 5/1	No direction available
1968	1/15 - 1/29 and 2/12 - 12/31	Available
	1/15 - 3/10 and 4/1 - 6/16	No speed available
	2/12 - 2/26 and 3/11 - 3/25	Abstracted, but data questionable.
1969	1/1 - 7/31	Available

TABLE 4. 8 KM station observation periods for wind speed and direction and status of data.

1965	5/29 - 10/23	Checked
	5/29 - 9/30	On mag. tape
	5/29 - 9/11	On paper-tape and plotted
1966	6/28 - 12/31	On mag. tape
1967	1/1 - 7/10 and 7/17 - 12/31	Available
	1/1 - 7/10 and 7/17 - 10/31	Abstracted
	1/1 - 7/10 and 7/17 - 9/30	Checked
	6/6 - 7/10 and 7/17 - 9/30	On mag. tape
1968	1/1 - 12/31	Available
1969	1/1 - 3/24	Available

TABLE 5. 16 KM station observation periods for wind speed and direction and status of data.

1965	6/3 - 10/9	Abstracted
	6/3 - 9/30	Checked
	6/3 - 9/11 on papertape and plotted, but data questionable.	
1966	5/11 - 12/31	Available
	5/11 - 12/27	Abstracted
	5/16 - 5/31 and 6/2 - 12/27	On mag. tape
1967	1/1 - 1/31 and 5/7 - 12/31	Available
	1/1 - 1/31, and 5/8 - 10/31	Checked
	5/8 - 9/30	On mag. tape
1968	1/1 - 12/31	Available
	1/2 - 1/28	No speed available
	5/21 - 6/2	No direction available
1969	1/1 - 6/23	Available

TABLE 6. 24 KM station observation periods for wind speed and direction and status of data.

1966	6/1 - 12/31	Available
	6/1 - 12/27	Checked
	6/1 - 12/11	On mag. tape
1967	1/1 - 1/31 and 5/7 - 12/31	Available
	1/1 - 1/31 and 5/7 - 10/31	Checked
	5/7 - 9/30	On mag. tape
	1/23 - 1/31	No direction available
1968	1/1 - 3/11 and 3/25 - 12/31	Available
	2/12 - 2/26	Data questionable.
1969	1/1 - 6/23	Available

TABLE 7. WJBL station observation periods for wind speed, direction, and profile of wind and status of data.

1964	6/26 - 12/31	On mag. tape
1965	1/1 - 12/31	On mag. tape
1966	1/1 - 12/31	Abstracted
	1/1 - 11/25	Checked
	1/1 - 9/30	On mag. tape
1967	1/1 - 6/22 and 6/28 - 12/31	Available
	1/1 - 3/25	Abstracted
	11/22 - 12/31	No speed available at 61-m level
1968	1/1 - 9/14	Available
	1/1 - 3/15 and 7/5 - 9/14	No speed available at 61-m level
	1/20 - 3/15 and 7/7 - 9/14	No direction available at 39-m level

TABLE 8. Summary of available wind aloft observations made during field studies near the shores of the Southern basin of Lake Michigan, May and June 1965. Numbers indicate length of analyzed track in minutes. Underlining indicates that double theodolite tracking and analyses techniques have been used. Note that several tracks were analyzed both by double and single theodolite techniques. Dash (-) after number indicates that the balloon was released, not at the exact half hour, but within the subsequent half hour. Station notation = 0 = Lakeshore, 8 = 8 km station (8 km from lakeshore along M-45), etc., MYS = MYSIS, MKE = Milwaukee.

MONTH	MAY									JUNE																					MONTH
DATE	18	19	20	29	30		31			2	3			4	6	7	8		9				10			11					DATE
STATION	0	8	8	0	0	8	MYS	0	8	0	MYS	0	8	0	0	0	0	8	MYS	0	8	16	MYS	0	8	MYS	0	8	16	24	STATION
0500																															0500
0530																															0530
0600																															0600
0630																															0630
0700																															0700
0730																															0730
0800								18/19½																							0800
0830									20		6		20		18½		7½	10½													0830
0900								10½	12		12	20	20	20						14/22½	18		8½		14		17½	20	14		0900
0930	12½		20					19½/20	17½		13-	20	20	19½		12½				11½	15½	8½	7½7½/7		15		20	18	20	20	0930
1000			20				11	11½	15		13	17½	20	20					13	20		8½	6/20		14½	7	13	20	20	20	1000
1030	7½		20				13½	15½	13		4-		20	20		11	7½		13	10½	20	11½			17	5½	20/12½		20	20	1030
1100	5½		14			19½	12	12	17		17	8½/20	20	20					13	8½	10½	14	4/20½		15	13		12		20	1100
1130		16½	20		20	20		15	15½		8½-	8	9½	20			14			8½	9/18½	15½	7	12	19½		22½	20	20	20	1130
1200	15		20		20	18½		18½/19	15½		8½	19½	20			19	10		9½	19½		16½	11½-	15	20	13	8½/22½	13½	20	20	1200
1230	10½	8			20		11½				4			20						20	22½	16½			19½	13		20		20	1230
1300		12½	20		12		8½		17½		7½	18½		20		9	12½				22½	22		16	20		20	20			1300
1330	20		20	8½		20	9	11	10½		4½-	20	20	20		16			8	19½	20	16½		16	19½	13	18	20	20	20	1330
1400	10½	7½	20	7	20	20		15	14½		5½-	16½	20	20		20	12½		21	10/19½	7½/21		8½	17½			14½	20	20		1400
1430		6	20	7½	20	20		19½	6	9	5	9/20	20	20			13			18	20	22½	5	10½	20	13	20		20	20	1430
1500		4½	20	20	19	19½			20		5½-	9½	20	20			10½			13	20	11½		20	20		20½	20	20	20	1500
1530		20	19½	20	20	19½		18½	10½	6	5-	20	20	20						16½	18	12½	12	20	20	13		20	20	20	1530
1600		20	12½	20		18½			15	20	13	20	20	20		14				14					20					20	1600
1630	12				20					10½		10½/20		20						16	18½	22½									1630
1700										11½				20							17½	8½									1700
1730																					22½										1730
1800																															1800
1830																															1830
1900																															1900
1930																															1930
2000																															2000
2030																															2030

TABLE 8 (Concluded)

MONTH: JUNE

DATE / STATION	12 MYS	12 0	12 8	12 16	13 0	13 8	13 16	14 MYS	14 0	14 8	14 16	15 0	15 8	16 0	16 8	16 MIL
0500																
0530																
0600																
0630																
0700									20							
0730									20			7½/20		20		
0800									20	20		20		20		
0830		12½	20						20	20		20			20	
0900		14	16½	20	19½				19½	20		20	17½	20		5½
0930		13	16	20	20				19½	20		20	20	11		6½
1000	9-		16½	20	20				20	16		20	15	7½		
1030	10/6½-		9	20	20				10	20			6½	7½	9	
1100	10½/10		20	20	20	20			20	20		20	5		4½	
1130	4		20		20				20	20		6½				6½
1200	7½				20	20		13	20			5½	9			9
1230			18½		20	20		13	15	16½	20	7				4½
1300		18	20		20			13/20		20	20		8			7
1330		18	17½		20	20	11		20	20	20	5				7½
1400		20	20		20	20	20	10	20	20	20	4	5½			
1430			20		20		20			20	20	3	10			10½
1500			20		20	20	20		20	14½	10	10½	9			11
1530					20	20	20		17		13	14½	11			8½
1600					20	20	20			20	20	11	10			7
1630							20		20	20	10½	10				
1700								10½		20	9	9				
1730								17		11	8					
1800									20		13½/8					
1830									20	8½						
1900									20	11	20					
1930									20	20						
2000									20							
2030																

DATE / STATION	17 0	17 8	17 16	17 24	17 MIL	18 0	18 8	19 0	19 8	21 0
0500										
0530										
0600										
0630										
0700	20							14		
0730	20					20		20	20	
0800	20					20		20	12½	
0830	20					20		13½	20	
0900	20					20		20	13	
0930	20					20			10½/20	9
1000	3½/22½	20	22½			20	20	20	20	9/20
1030	20		22½			20	20			
1100	15		22½			20	20	8½	4½/20	20
1130		5½/21	22			20	20	20		
1200	22½	12				20	20		20	17½
1230	6½/16		8½			20				
1300	14	13½	19		20-			20	20	15
1330		16½	16½			20		20	20	
1400		6½	19½	5½	11			20	11½	12
1430		20	15	6	7/15½-	20		20	20	
1500		22	17	4/9½-	15					18½
1530		13½	7	9/11-	17					16
1600			12							
1630	10-	17½	18½		16½					
1700	17	22½	16							
1730	14	10½	18½		14					
1800	16	9½	8							
1830	11½	17½	12½		9½					
1900	20	13½								
1930	8½/9½-									
2000	8½/12½-									
2030	14½									

DATE / STATION	22 MYS	22 0	22 8	24 MYS	24 0	24 8	25 MYS	25 0	25 8	25 16	26 0	26 8
0500											20	
0530		20									7½	20
0600		20			14½	20		20			20	16½
0630		20			14	20	13		20		20	
0700		20			14½	18			20		20	20
0730		19½			13½	20			20		7½	20
0800		20			13½	20		20	20		20	20
0830					13½	20		20	20			3
0900		20	13½		14	20	12½/20		20		17½	17
0930		8½	20		16½	20		20	20			4½
1000		19½	14½		17	20		20	20		6½	13½
1030			20		17	20		20	20			17
1100		20	6½/20		12	18½	12½	13	20			
1130	7½	18	11½		12	4		19½	20			
1200		20	8½		11	20	12½/20		20			
1230			20	19½		15½		20	20			
1300		20	6		12½	17		20	20			
1330				20		20	12½-	20	20			
1400		15	9			20		20	18			
1430			10		20	20		20	17			
1500		9½	8		20	20		20	20			
1530						20		20	15			
1600		6	6/5-		20	19½		20	6/15			
1630		16+	4					20	15			
1700					20	20		20	15	15		
1730								20		15		
1800					20	20		9/20	15	7		
1830								20	11	8½		
1900						20		20	15	14½		
1930								20-		15		
2000								8½-	15			
2030								6½/20				

TABLE 9. Summary of available wind aloft observations made during field studies near the shores of the Southern basin of Lake Michigan, May and June 1966. Numbers indicate length of analyzed track in minutes, while, x, indicate that observations were made, but no complete analyses is available. Only single theodolite tracking was used during 1966. Dash (-) after number or x indicate that the balloon was released, not at the exact half hour, but within the subsequent half hour. Station notation = 0 = Lakeshore, 8 = 8 km station (8 km from lakeshore along M-45), etc., BT = Boat, MKG = Muskegon airport, NB = New Buffalo, GY = Gary, CLS = Chicago (Univ. of Chicago), MKE = Milwaukee.

MONTH	MAY																													JUNE						MONTH
DATE	14	17	21				22				24		25		26		28			29			30		31					1						DATE
STATION	0	0	BT	0	8	16	BT	0	8	16	0	8	0	8	0	8	0	8	24	0	8	24	0	8	BT	0	8	16	MKG	BT	0	8	16	24	MKG	STATION
0500																																				0500
0530																										x										0530
0600				15				7½																		x					x					0600
0630				15				10												15			x			x					x	x				0630
0700								13												15			x			x					x	x				0700
0730				15				10½												15			x			x					x	x	x			0730
0800		15		15				10½						15-						15			x			x				x		x	x			0800
0830				14½				7½					10½							12½			x	x		x					x	x	x			0830
0900		15		15			15	15	15	5½					14		15			14½			x	x		x	x			x	x	x	x			0900
0930		15	15	15	14	13½	15	15	15	15					15	12½	15			15			x	x	x	x	x				x	x	x			0930
1000		15	15		13	15	15	15	15	15	11½	4		15	15	13½	15	8½		15	x		x	x	x	x	x			x	x	x	x			1000
1030		15			11½	15	15	15	10	15			14½		15	14	15	15		15				x	x	x	x			x	x	x	x			1030
1100		15			12½	15	14/10-	10/10-	15	15	14	15	12½	15	15	15	15	7½		15		x	x	x	x	x	x			x	x	x	x			1100
1130		15			8	6½	10	7½/5-	6	15					15	15	15	13½		15	x	x					x			x	x	x				1130
1200		15		12½	15	10½	9-	10	10	15	15	13	8½	15	15	14	15	15		15			x			x	x			x	x	x			x	1200
1230				15	15	11½	10	15	15	15						8		15			x				x	x	x	x		x	x		x			1230
1300		9	15	15	15	15	15	11½		15	10	15	15	15	14½	13½	15				x	x	x		x	x	x	x		x	x	x	x			1300
1330		12½	15	15	15	15			15	15					10½	14½		15	15		x	x				x	x	x		x	x		x			1330
1400		12½	20	15	15	15	15	15	6½	15	15	15	15	15	15	14	15			15	x	x				x	x	x			x	x	x			1400
1430				15	15	15	15	9½	11½	13					12	8½	15	15	8-	15		x				x	x	x		x	x	x	x			1430
1500			15	15	15	15	15	11	15	15	15	15	15	15	14		15		12½-	13	x	x					x	x		x	x	x	x	x		1500
1530			15	15	15	15	15	15	15	14							15	15	13½-	x	x	x				x	x	x		x	x	x	x	x		1530
1600	15		15	15			7½		15	15							15		15-	x	x	x				x		x			x	x	x	x		1600
1630								15	15	15							15	15	11-	x	x	x				x	x	x			x	x	x	x		1630
1700	15							11	15	15							15		15-	x	x					x	x	x				x	x	x		1700
1730							15	10	15	15									9½-	x	x					x	x	x			x	x	x	x		1730
1800	15						15	15	14	15										x	x					x	x	x		x	x	x	x	x		1800
1830								14½	15	15										x	x					x	x	x		x	x	x	x	x		1830
1900	15							15	15	3½										x	x					x	x			x	x	x	x	x		1900
1930								15	15	15										x	x					x	x			x	x	x	x	x		1930
2000	15							15	15	15																x	x			x				x		2000
2030																																				2030
2100																																				2100
2130																																				2130
2200																																				2200
2230																																				2230
2300																																				2300
2330																																				2330
2400																													x						x	2400

TABLE 9 (Continued)

MONTH	JUNE																				
DATE	2				3	4			5			6			7			8			
STATION	BT	0	8	MKG	MKG	0	8	MKG	0	8	MKG	0	8	MKG	0	8	MKG	0	8	16	MKG
0500																					
0530		x																			
0600		x																			
0630		x																			
0700		x																			
0730		x																			
0800		x														x					
0830		x								x											
0900	x					x	x		x						x	x		x	x		
0930	x	x	x							x											
1000		x	x			x	x		x			x			x	x		x	x		
1030	x	x	x																		
1100		x	x			x	x		x			x	x		x	x		x	x		
1130		x	x																		
1200			x	x	x	x	x		x		x	x	x	x	x	x	x	x	x		x
1230	x	x	x																		
1300						x	x		x-			x	x		x	x		x	x		
1330			x																		
1400			x			x	x		x				x		x	x		x	x		
1430																		x	x		
1500												x						x	x		
1530																		x	x		
1600																		x	x	x	
1630																		x	x	x	
1700																		x	x	x	
1730																		x	x	x	
1800																		x	x	x	
1830																					
1900																					
1930																					
2000																					
2030																					
2100																					
2130																					
2200																					
2230																					
2300																					
2330																					
2400				x	x			x			x			x			x				x

MONTH	JUNE																					MONTH
DATE	9		11			12		14			15			16			17					DATE
STATION	0	MKG	0	8	MKG	0	MKG	0	8	MKG	0	8	MKG	0	8	MKG	BT	0	8	16	24	MKG	STATION
0500																							0500
0530																							0530
0600																		x	x	x			0600
0630																	x						0630
0700																			x	x	x		0700
0730																							0730
0800				x										x	x		x	x	x	x	x		0800
0830																							0830
0900	x			x							x	x		x	x		x	x	x	x	x		0900
0930			x														x						0930
1000	x		x	x				x	x		x	x		x	x		x	x	x	x			1000
1030																							1030
1100			x	x				x	x		x	x		x	x		x	x	x	x			1100
1130																							1130
1200	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	1200
1230																							1230
1300	x		x	x				x	x		x	x		x	x			x	x				1300
1330																							1330
1400	x			x		x		x	x		x	x		x	x		x	x	x		x		1400
1430																							1430
1500	x							x	x					x	x			x	x		x		1500
1530																							1530
1600														x				x	x		x		1600
1630																							1630
1700																							1700
1730																							1730
1800																							1800
1830																							1830
1900																							1900
1930																							1930
2000																							2000
2030																							2030
2100																							2100
2130																							2130
2200																							2200
2230																							2230
2300																							2300
2330																							2330
2400					x								x			x						x	2400

TABLE 9 (Concluded)

MONTH	JUNE																													MONTH
DATE	18				19			20		21						22			23						24	27				DATE
STATION	BT	0	8	MKG	0	8	MKG	8	MKG	BT	0	8	16	24	MKG	0	8	MKG	0	MKG	NB	GY	CLS	MKE	0	0	8	16	32	STATION
0500																											x	x		0500
0530																										x	x	x		0530
0600		x																	11½		15	12		11		x	x	x		0600
0630																										x				0630
0700	x		x																10½		11½	13	12½	11			x	x		0700
0730																														0730
0800	x	x	x			x		x									x		10		11½	9	10	10½	x	x	x	x		0800
0830																														0830
0900	x	x	x		x	x		x			x					x	x		9½		8½	9	9½	8½	x	x	x	x		0900
0930		x																								x	x	x		0930
1000	x		x		x	x		x			x	x				x	x		8		11	11	6½	7½	x	x	x	x		1000
1030											x													12½		x	x	x		1030
1100			x		x	x				x	x	x	x	x		x	x		5½		10½	4½	11½	7½		x	x	x		1100
1130																			6		3½	10½	5	4		x	x	x-		1130
1200				x	x	x			x	x	x	x	x	x	x	x	x	x	11½	x	10½	15	6½	8½	x	x	x			1200
1230																x-			14		14½	12½	10½	15		x	x	x		1230
1300					x	x				x	x	x	x	x		x	x		14		11	11½	9	4	x	x	x	x		1300
1330																x			12		12½		8	10		x	x	x		1330
1400					x	x				x	x	x	x	x		x	x		15		13	10½	8	10	x	x		x		1400
1430																										x	x	x		1430
1500										x	x	x	x	x												x	x	x		1500
1530																												x		1530
1600																			13½			14	8½	10		x		x	x	1600
1630																														1630
1700																			12½		15	15	7½	7½		x		x	x	1700
1730																					15			9½				x-		1730
1800																			15		11½	10½	7½	15		x			x	1800
1830																			15		8	15	8½	10				x	x	1830
1900																			15		9	11½	10½	15		x		x-	x	1900
1930																			11½		9	10½	10	11½		x		x	x	1930
2000																			12		13½	12	9	12		x		x	x	2000
2030																										x		x	x	2030
2100																										x		x	x	2100
2130																										x			x	2130
2200																										x		x		2200
2230																										x	x	x		2230
2300																										x	x	x		2300
2330																										x	x			2330
2400				x			x		x						x			x		x						x	x			2400

TABLE 10. Lakeshore, 0 KM, station observation periods for temperature profile, relative humidity, pressure and solar radiation and status of data.

1965	5/5 - 6/30 .... solar radn	Abstracted
	5/26 - 12/11 .... temp. & rel. hum...	Abstracted
	5/26 - 12/10 temp. & rel. hum. plotted.	
1966	5/3 - 12/31 ... temp., rel. hum., & press...........	Available
	5/3 - 12/19.. temp., rel. hum., & press	Available
	5/22 - 12/31 ..... solar radn	Available
1967	1/1 - 12/31 .... all	Available
	1/3 - 1/16 ... temp., rel. hum., & press	Abstracted
	1/1 - 7/17 and 8/1 - 9/13 No temp.	Profile Available
1968	1/1 - 12/31 .... all	Available
	6/1 - 6/3 and 6/8 - 6/24 No pressure data available	
1969	1/1 - 7/31 .... all ...	Available

TABLE 11. 8 KM station observation periods for temperature and relative humidity and status of data.

1965	5/26 - 12/11	Abstracted
	5/26 - 12/10 temp. & rel. hum. plotted.	
1966	5/3 - 12/31	Available
	5/3 - 12/19	Abstracted
1967	1/1 - 12/1	Available
	1/3 - 1/16	Abstracted
1968	1/1 - 12/31	Available
	6/19 - 6/23 data questionable	
1969	1/1 - 5/26	Available

TABLE 12. 16 KM station observation periods for temperature and relative humidity and status of data.

1965	5/26 - 12/11	Abstracted
	5/26 - 12/11 temp. & rel. hum. plotted	
1966	5/3 - 12/31	Available
	5/3 - 12/19	Abstracted
1967	1/1 - 12/31	Available
	1/3 - 1/16	Abstracted
1968	1/1 - 12/31	Available
1969	1/1 - 6/23	Available

TABLE 13. 24 KM station observation periods for temperature and relative humidity and status of data.

1965	5/26 - 12/11	....	Abstracted
	5/26 - 12/10 temp. & rel. hum. plotted		
1966	5/3 - 12/31	....	Available
	5/3 - 12/19	....	Abstracted
1967	1/1 - 12/31	....	Available
	1/3 - 1/16	....	Abstracted
1968	1/1 - 12/31	....	Available
1969	1/1 - 6/23	....	Available

TABLE 14. Summary of periods of airplane soundings of temperature and humidity made near Grand Haven, Michigan, 1965 and 1966. Times indicated are EST. For 1966 only time for beginning flight period is indicated.

Month, Year	Day	Flight Period (EST)	Remarks
June 1965	6	0934 - 1058	
	10	1316 - 1441, 1527 - 1706	
	11	0915 - 1036, 1319 - 1445	
	12	0814 - 0944, 1024 - 1143, 1326 - 1457, 1545 - 1702	
	14	1314 - 1444, 1528 - 1651	
	15	0826 - 0951, 1038 - 1206, 1314 - 1434	
	16	0833 - 0951	
	17	0813 - 0935, 1045 - 1214, 1314 - 1430, 1448 - 1626	Note deviating flight path.
	22	1346 - 1507	
	24	0818 - 0940, 1023 - 1151, 1316 - 1448, 1529 - 1657	
	25	0737 - 0907, 0953 - 1121, 1231 - 1404	
	26	0824 - 0959, 1039 - 1207	
	27	0746 - 0923, 1006 - 1139	
	29	1341 - 1514, 1559 - 1730	
May 1966	30	1345, 1530	No wetbulb temperature
June 1966	1	0950, 1045, 1400, 1435	No wetbulb temperature
	2	0900, 1105, 1400, 1638	
	5	1345, 1545	
	6	1345, 1622	
	7	1401, 1604	
	16	1550	
	17	0930, 1415	
	18	1400	
	19	1400	
	20	1358	
	21	0925, 1415	
	22	0915	
	23	1045, 1445, 1630	
	24	1350	

TABLE 15. WJBL station observation periods for temperature profiles and status of data.

1964	7/4 - 12/19	Available
1965	4/22 - 12/31	Abstracted
	5/15 - 12/31	Checked
	5/19 - 12/31	On mag. tape
1966	1/1 - 8/6 and 12/15 - 12/31	Available
	1/1 - 7/6	On mag. tape
1967	1/1 - 7/22	Available
1968	3/29 - 9/14	Available

TABLE 16. Technical papers and reports supported fully or partially by this grant or based fully or partly on data collected during the field studies. Number in front of title refers to publication number of the Department of Meteorology and Oceanography, The University of Michigan.

07143-1-T	THE LAKE BREEZE CIRCULATION ALONG THE SHORELINE OF A LARGE LAKE by Moroz, 1965. Technical report and Ph.D. thesis from Department of Meteorology and Oceanography, The University of Michigan; 120 pp.
93	THE MESOSCALE INTERACTION OF A LAKE BREEZE AND LOW LEVEL OUTFLOW FROM A THUNDERSTORM by Moroz and Hewson, 1966. Paper published in J. Appl. Met., 2; 148-155.
—	CHARACTERISTICS OF LAKE AND LAND BREEZES OF THE SOUTHERN BASIN OF LAKE MICHIGAN by Cole, 1967. Paper presented at Conference on Fair-Weather Meteorology of the Am. Met. Soc., Santa Barbara, Calif., February 28-March 2, 1967.
129	AN EVALUATION OF WIND ANALYSIS AND WAVE HINDCASTING METHODS AS APPLIED TO THE GREAT LAKES by Cole, 1967. Paper presented at Tenth Conference on Great Lakes Research and published in the conference proceedings; 186-196.
—	VARIATION OF A LAKE BREEZE WIND WITH TIME NEAR THE LAKESHORE by Moroz, Hewson, and Gill, 1967. Paper presented at Tenth Conference on Great Lakes Research and published in the Conference proceedings; 221-230.
126	LAKE EFFECTS ON AIR POLLUTION DISPERSION by Hewson and Olsson, 1967. Paper presented at the Sixth Annual Sanitary and Water Resources Engineering Conference sponsored by Vanderbilt University and the Tennessee Department of Public Health, June 1-2, 1967, Nashville, Tennessee. The paper is published in the conference proceedings; 134-145. A revised version of this paper was published in J. Air Poll. Cont. Assoc., 17; 757-761.
08650-1-T	INVESTIGATION WITH A MATHEMATICAL MODEL OF THE LAKE BREEZE by Wilson, 1967. Technical report from Department of Meteorology and Oceanography, The University of Michigan; 32 pp.
100	A LAKE BREEZE ON THE EASTERN SHORE OF LAKE MICHIGAN: OBSERVATIONS AND MODEL by Moroz, 1967. Paper published in J. Atm. Sci., 24; 337-355.
137	OBJECTIVE MESOSCALE ANALYSES OF THE SURFACE PRESSURE AND GEOSTROPHIC WIND FIELDS OF THE GREAT LAKES AREA by Cole, 1968. Paper presented at Eleventh Conference on Great Lakes Research and published in conference proceedings; 298-312.

TABLE 16 (Concluded)

138	AN OBSERVATIONAL STUDY OF THE LAKE BREEZE ON THE EASTERN SHORE OF LAKE MICHIGAN, 25 JUNE 1965 by Olsson, Cole, and Hewson, 1968. Paper presented at Eleventh Conference on Great Lakes Research and published in conference proceedings; 313-325.
—	USE OF THEODOLITE TRACKED TETROONS AND PHOTOGRAPHIC TECHNIQUES IN STUDYING LAKE SHORE CIRCULATIONS by Lyons and Olsson, 1968. Paper presented at Eleventh Conference on Great Lakes Research.
08650-2-T	OBSERVED LAND AND LAKE BREEZE CIRCULATION ON THE EASTERN SHORE OF LAKE MICHIGAN, 25 JUNE 1965 by Olsson, Cole, and Hewson, 1968. Technical report from Department of Meteorology and Oceanography, The University of Michigan; 159 pp.
08650-3-T	OBSERVED TEMPERATURE PROFILES NEAR THE LAKE MICHIGAN SHORELINE by Herkhof, 1969. Technical report from Department of Meteorology and Oceanography, The University of Michigan; 37 pp.
02621-1-T	LAKE EFFECTS ON AIR POLLUTION DISPERSION by Olsson, 1969. Technical report and Ph.D. thesis from Department of Meteorology and Oceanography, The University of Michigan; 216 pp.
—	AIR POLLUTION DISPERSION IN A LAKE BREEZE REGIME: TRAJECTORY STUDY USING TETROONS, SMOKE PHOTOGRAPHY, AND AIRCRAFT MEASUREMENT OF AEROSOLS by Olsson and Lyons, 1969. Paper presented at 62nd Annual Meeting of the Air Pollution Control Association.

4. CONCLUDING REMARKS

The Great Lakes basin of the United States and Canada is one of the highly industrialized regions of the North American continent. However, the distribution of industry varies greatly from the high density regions of Chicago-Gary, Detroit, Cleveland, Buffalo, and Toronto to the sparsely settled areas on Lake Superior, northern Lake Michigan, and northern Lake Huron. With the relative abundance of fresh water in the Great Lakes and the actual or eminent shortage of water supplies elsewhere, the industrialization and population of the region will increase markedly in the future, and air pollution considerations may require new industry to locate in those areas that are now relatively unsettled.

Air and water pollution are currently serious problems in certain portions of the Great Lakes Basin, i.e., the environs of southern Lake Michigan and Lake Erie are the horrible examples. These air pollution problems will increase in direct proportion, or more rapidly, with increasing industrialization and population. Holding the line or decreasing air pollution concentration levels can be achieved only by a multi-faceted approach encompassing source emission control, location of industry and meteorological control of industrial operations, transportation, trash disposal, etc.

There is no doubt that the best way to reduce the concentration of pollutants in the atmosphere is to prevent the emission of polluting material from the source, either local or distant. Desirable as this approach may be, the complete elimination of all pollutants can usually be achieved only by the elimination of the processes that produce the polluting materials. While the complete elimination of air pollution sources is physically possible, it is socially and economically impossible and a certain residue will continue to get into the air. The diffusion and transport of that residual of air pollution that gets into the atmosphere despite all source control measures must be evaluated at the present and predicted for the future.

An air pollution model of the Great Lakes region is a mechanism whereby such evaluations and predictions can be made. With the model the air pollution concentration at any location can be computed from an inventory of pollution sources and a knowledge of the diffusion parameters and the environmental wind field. Computations with such a model allow evaluations to be made of the effect of perturbations or alterations in the utilization of the Great Lakes region. Specifically, the effect of the introduction of new industries can be evaluated from an air pollution view prior to construction and locations can be identified that will cause minimal additions to overall environmental air pollution concentrations. With the air pollution model, a new process designed to suppress a pollution source can be studied in relation to its cost effectiveness prior to installation.

It is entirely conceivable in the not too distant future that industrial operations will be programmed to produce the optimal amount of goods with a minimum of atmospheric pollution. On the afternoons of those days with good atmospheric dispersion conditions, all industry could operate and everyone could drive his automobile wherever he wished. On the other hand, meteorological conditions of a stagnant anti-cyclone with very poor diffusion under a low level inversion would require the shutdown of all but the most essential industry and transportation. Between these extremes there would be many classes of allowable emissions whose implementation would be very dependent on the air pollution diffusion and transport capabilities of the atmosphere. A Great Lakes air pollution model will be vital to the operation of an optimized system that will utilize the waste disposal capability of the atmosphere to its utmost without causing undo harm to the population.

At this time, experienced meteorological forecasters in the Great Lakes basin can predict pollution levels in a broad general sense, but the accurate detailed forecasts necessary to an operational control system are not obtainable. The data obtained by the field studies conducted under this grant and the analytical investigations will contribute to the development of a better understanding of the meteorology of the Great Lakes basin with special emphasis on the water-land interface. Also, it will provide basic information for the development of a Great Lakes air pollution model.

The extensive field measurement programs have produced a large body of data documenting the local mesoscale air movements at the shoreline of a Great Lake. Olsson (1969) and Olsson, Cole, and Hewson (1968) have described a well developed lake breeze circulation based on this data. This description serves as the experimental data for theoreticians to explain. Tingle (1969) has modified the lake breeze model of Moroz (1965) to include more relaistic relationships among the lake breeze parameters. His modeling conclusions will be very important to the development of a Great Lakes air pollution model.

A Great Lakes air pollution model in its simplest configuration will consist of a knowledge of pollution emission sources, the height of the mixing layer, an estimate of horizontal diffusion, and a determination of the mean wind in the mixing layer. As pollution inventories have been and are being made by various governmental agencies, the knowledge of pollution sources can be documented for many regions and estimated with fair accuracy for the remainder.

The height of the mixing layer can be determined from rawinsonde observations made by ESSA. However, the coverage is much too sparse to produce mesoscale details for the Great Lakes region. The aircraft data taken during the 1965 and 1966 field studies will help fill this data gap.

The objective surface-pressure analysis program, Cole (1968) and the resulting geostrophic wind calculations should provide the basis for determining a mean wind through the mixing layer. Modifications based on real surface-wind observations and surface layer stability factors will have to be determined in order that a meaningful mixing-layer wind can be calculated. The pibal wind measurements taken during the field studies of 1965 and 1966 constitute data to be used in a study of the mean wind in the mixing layer. The temperature profiles from the shoreline tower and radio station WJBL are significant data for stability studies.

Field studies, data processing, and analyses as conducted under this grant provide an excellent opportunity for graduate and undergraduate students, see Appendix B, to broaden their training experience by participation in actual research programs. In particular, graduate students receiving support from the National Air Pollution Control Administration as air pollution trainees were able, personally, to experience air pollution research in the field. These trainees had the opportunity to take responsibility for some aspects of the investigations and thus develop and exercise their planning and management abilities. Wilson (1967) and Herkhof (1969) published reports based on their contributions.

One Ph.D. dissertation, Olsson (1969), has been written based on data obtained in the field studies. A second Ph.D. dissertation by Tingle will be a theoretical study of mathematical modeling of lake and land breezes. He was influenced to investigate this problem because of his association with the field studies of 1965 and 1966. Although the published reports present analyses only of specific cases or aspects of the measured parameters, subjective analyses of all the data have led to some more general conclusions, see e.g., Hewson and Olsson (1967), Herkhof (1969), and Olsson (1969).

In addition to Olsson and Tingle, three other graduate students, who are now air pollution trainees, received field study experience because of this grant. Each of these students is now writing his Ph.D. dissertation in a phase of air pollution meteorology.

Many undergraduate students assisted in the field studies or in data processing and analyses under the direction of faculty, staff members, or graduate students. These associations have broadened their perspective of air pollution meteorology and related their academic studies to real problems of the world. At least two of these undergraduate students have taken employment in air pollution control agencies of state and federal government.

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APPENDIX A

ABSTRACTS OF SCIENTIFIC PAPERS AND REPORTS SUPPORTED

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THE MESOSCALE INTERACTION OF A LAKE BREEZE AND LOW LEVEL OUTFLOW FROM A THUNDERSTORM

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ABSTRACT

In the summer of 1964 a program was initiated to observe physical and dynamical characteristics of the lake breeze at a site on the eastern side of Lake Michigan. Lake breeze development and progress inland was observed by periodic pilot balloon measurements in a vertical plane perpendicular to the lakeshore.

During the afternoon of 22 July, while the lake breeze was still intensifying, a thunderstorm crossed the line of observing stations. Low level outflow from the thunderstorm displaced the lake breeze and dominated the local flow regime for more than two hours after outflow was first observed. The development and interaction of the lake breeze and thunderstorm flow patterns are shown through an analysis of the wind component normal to the shoreline.

A significant feature of this lake breeze system, as of others to be reported on more fully later, is the occurrence of a pronounced return current aloft. Such strong return currents are not often found above sea breezes.

THE LAKE BREEZE CIRCULATION ALONG THE SHORELINE OF A LARGE LAKE

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ABSTRACT

This study was conducted to determine the physical features of a lake breeze wind system occurring at the shoreline of a large deep lake. In the first part of the study an observed lake breeze in the vertical plane normal to the shoreline is described at hourly intervals. The observed thermal structure of the atmosphere on a day when a clearly defined lake breeze occurred is also presented. In the second part a numerical model for a symmetric lake breeze is constructed and found to produce results in good agreement with the observations presented in part one.

The observations of the lake breeze circulation system were made at a location on the eastern side of Lake Michigan under circumstances when prevailing external meteorological conditions would exert minimum influence on the local thermal circulation. Over the land the depth of the layer of onshore flow is approximately 750 m and a maximum velocity of 5 to 7 m sec^{-1} is observed within 250 m of the surface directly over the lakeshore. Above the lake breeze current a well defined return flow is apparent by mid-afternoon. The layer of return flow is about twice as deep as the lake breeze and velocities in the return flow are proportionately lower. The local wind system affects large scale atmospheric flow patterns through a depth exceeding 2500 m above the surface.

The simultaneous existence of a lake breeze on opposite side of the lake is demonstrated, at least near the surface, using climatological records. Homogeneity of the lake breeze along the shoreline and the orderly progress of the lake breeze front to a distance exceeding 16 km inland are clearly apparent in the data presented.

Turning of the local wind in response to the Coriolis force is also demonstrated by the observations.

In the second part of the study a mathematical model of the lake breeze is presented starting with the differential equations for motion and heating in the atmosphere, the hydrostatic equation and the equation of continuity. The finite dimension of the lake is incorporated into the model which is termed semi-bounded in contrast to the sea breeze model which has no horizontal restriction. The flow deviations attributable to differential heating over land and water are obtained using the techniques developed by Estoque for the unbounded sea breeze. The differential equations are represented by finite difference approximations and a solution for the lake breeze flow patterns is obtained using an IBM 7090 digital computer. Features of the development of the lake breeze in both model and observations are in good agreement.

LAKE EFFECTS ON AIR POLLUTION DISPERSION

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ABSTRACT

Local wind regimes induced by a lake or a shoreline may have a major influence on air pollution dispersion. Pressure differences due to differential heating of the air, e.g., that due to differences in surface characteristics, are the driving forces of lake and land breeze circulations and slope and valley winds. Differences in roughness between land and lake surfaces will cause wind shear and aerodynamic downwash effects at a shoreline. Stability changes in the air result from differences in surface temperature and roughness between land and lake, e.g., when warm unstable air moves out over a cool lake a temperature inversion will develop near the surface giving very poor dispersion conditions in this lower layer. Pollution released in this stable layer may be carried in high concentrations for many miles and cause severe damage as the air moves across a down wind shoreline and advances inland. The information presented is designed to permit an assessment of the probable complexity of the dispersion patterns near a shoreline so that possible requirements for additional meteorological and dispersion information may be determined. Brief descriptions of two actual lakeside sites, one on Lake Erie and the other on Lake Michigan, are given and their relevant characteristics are presented. Natural ventilation was above average at both sites.

CHARACTERISTICS OF LAKE AND LAND BREEZES OF THE SOUTHERN BASIN OF LAKE MICHIGAN

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ABSTRACT

From five years of U. S. Weather Bureau hourly observations, time resolved wind roses and hourly mean winds have been computed for each month at Muskegon and Grand Rapids, Michigan, and Milwaukee, Wisconsin. A second computation was made using only the data from fair weather days. Fair weather days were determined by visual inspection of the USWB daily weather map series.

From these data, lake and land breezes have been classified and the characteristics of each class determined. The "normal" or "mean" lake breeze and the associated synoptic weather pattern have been computed for each month or season.

AN EVALUATION OF WIND ANALYSIS AND WAVE HINDCASTING METHODS AS APPLIED TO THE GREAT LAKES

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ABSTRACT

The specification of an appropriate wind field over the Great Lakes is one of the more serious limitations to successful wave hindcasting. Available data consist of wind or pressure measurements along with temperature, humidity, etc. Wind charts may be prepared from the former; however, wind reports from the lakes are rather scarce while those from land stations are often not representative of over-water conditions. The geostrophic and gradient wind approximations consititute standard methods for calculating winds from a pressure field. However, reducing these winds to an anemometer height wind suitable for use in a wave hindcast scheme is a process not well understood at this time. To evaluate the methods now in use, wind and wave hindcasts were made for selected time intervals during 1965 and 1966. For Muskegon, Michigan comparisons have been made between hindcast and observed winds and waves.

The surface winds were determined from the geostrophic and gradient winds by empirical methods utilizing atmospheric stability and wind field curvature. A surface wind field was also deduced from upwind land station reports using empirical results based on stability and fetch. Wave hindcasts were obtained by the semi-empirical techniques of the significant wave height and wave spectra. The surface winds obtained from the geostrophic wind analysis and wave determined by the significant wave height technique correlated best with observed data; however, the correlation coefficients were not highly significant.

VARIATION OF A LAKE BREEZE WIND WITH TIME NEAR THE LAKESHORE

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ABSTRACT

A series of observations of the local lake breeze thermal circulation has been made using pilot balloons at a location on the eastern shore of Lake Michigan under circumstances where external factors influencing the development of the local wind system were minimal. The variations of the across-shore and alongshore components of the wind with time are presented for several levels above an observation site at the lake shore. A lake breeze return current above the layer of onshore flow is clearly evident in the data. The layer of return flow is deeper than that of the lake breeze, and velocities in the return current are less than those in the layer of onshore flow. Turning of the lake breeze wind with Time in response to Coriolis force is apparent in the observations presented. The existence of a simultaneous lake breeze blowing in opposite directions on opposite sides of the lake is also demonstrated using climatological records.

INVESTIGATIONS WITH A MATHEMATICAL MODEL OF THE LAKE BREEZE

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ABSTRACT

Although the lake breeze is considered an important mesometeorological phenomenon, there has not been much work done to mathematically describe it. Many studies of sea breezes have been carried out; some of the results are applicable to the lake breeze, but others are not. Moroz in 1965 modelled the lake breeze using modifications of some of the sea breeze ideas, and a computer program is now available to serve as the model.

This study perturbs this model in three ways, each different in concept. The first perturbation is simply a data change: the maximum temperature of the land is increased by 3.2°C. The model correctly predicts the increase of the lake breeze circulation. The next modification involves trying to model a land breeze, as yet not attempted with the model. No circulation characteristic of a land breeze is produced, but reasons are presented to possibly explain why. In the last case the model itself is changed by substituting an eddy diffusivity profile which decreases from the top of the boundary layer to the top of the model as the square of the height, instead of linearly as previously used. The movement of the lake breeze is slowed, but its strength remains as in the unperturbed model.

A LAKE BREEZE ON THE EASTERN SHORE OF LAKE MICHIGAN: OBSERVATIONS AND MODEL[1]

William J. Moroz
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ABSTRACT

This study was undertaken to determine the physical and dynamical characteristics of the lake breeze wind system at a site on the eastern shore of Lake Michigan. Lake breeze development and progress inland were observed by hourly pilot balloon ascents in a vertical plane perpendicular to the lake shore. The fields of moisture and temperature in this vertical plane on a day when a clearly defined lake breeze occurred were obtained using an instrumented aircraft. Observations were made during periods when prevailing external meteorological conditions would exert minimum influence on the local thermal circulation.

Over the land the depth of the layer of onshore flow is approximately 750 m and a maximum velocity of 5-7 m sec^{-1} is observed within 250 m of the surface directly over the lake shore.

Above the lake breeze current a well defined return flow is apparent by midafternoon. The layer of return flow is about twice as deep as the lake breeze and velocities in the return flow are proportionately lower. The local wind system extends through a depth exceeding 2500 m.

Using climatological records it is demonstrated that flow can be in opposite directions on opposite sides of the lake, at least near the surface. Homogeneity of the lake breeze along the shoreline and the orderly progress of the lake breeze front to a distance exceeding 16 km inland are clearly apparent in the data. Evidence suggests that the structure and dimensions of the lake breeze wind system over the water are similar to those over the land. Turning of the local wind in response to the Coriolis force is also demonstrated by the observations.

One cell of symmetric lake breeze has been modelled numerically using the techniques developed by Estoque for the sea breeze with appropriate boundary condition modifications to account for the finite extent of the water surface. The

temperature wave over the land was specified in accordance with observed temperatures on days when a lake breeze did occur. Results of the numerical forecast after 6 hr and after 9 hr of meteorological time are compared with the observed lake breeze at corresponding times.

OBJECTIVE MESOSCALE ANALYSES OF THE SURFACE PRESSURE AND GEOSTROPHIC WIND FIELDS OF THE GREAT LAKES AREA

Alan L. Cole
Department of Meteorology and Oceanography, The University of Michigan

ABSTRACT

Surface wave hindcasting and forecasting, lake current studies, air pollution problems, ice movement investigations and many other areas of research in the Great Lakes region require a knowledge of the surface wind field. The production of such a wind field by an objective pressure analysis and the application of the geostrophic wind assumption is discussed and evaluated. The successive approximation technique (SAT) using a 17 by 18 grid with 75 km grid spacing and about 110 input pressures is used to calculate grid point.pressures. The orthogonal components of the geostrophic wind are then readily calculated. The pressures analysis technique was evaluated by comparing measured pressures with those obtained by interpolation from the SAT analysis. Both data used in the analysis and some that were withheld from the analysis were tested with the former showing an error of a few tenths of a millibar and the latter having errors from a half to two millibars. A second evaluation was made by comparing the pressures obtained from the SAT analysis with mean values of several hand analyses performed by students at The University of Michigan and by experienced forecasters at ESSA Weather Bureau and USAF Air Weather Service stations. The objective analysis at the grid points was usually within one standard deviation of the mean values of the hand analyses.

AN OBSERVATIONAL STUDY OF THE LAKE BREEZE ON THE EASTERN SHORE OF LAKE MICHIGAN, 25 JUNE 1965

Lars E. Olsson, Alan L. Cole, and E. Wendell Hewson
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ABSTRACT

An observational study carried out near Grand Haven, Michigan on 25 June 1965 has produced the most extensive measurements available of a nearly idealized lake breeze circulation. The complete cycle of nocturnal land breeze to lake breeze during the day with a return to land breeze at night was observed and measured. The field measurements will guide theoretical studies and experimental evaluations of proposed lake breeze models.

The synoptic situation is documented and mesoscale analyses presented. Graphs describing winds and temperatures as functions of time and space are included, as is a graph indicating moisture change at various stations. The penetration of the lake breeze front is measured by wind, temperature and moisture changes. Temperature lapse rates and their variations are presented.

USE OF TEODOLITE TRACKED TETROONS AND PHOTOGRAPHIC TECHNIQUES IN STUDYING LAKE SHORE CIRCULATIONS.

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ABSTRACT

Constant level balloons, tetroons, made of 2-mil Mylar and with a nominal volume of one cubic meter, were used in studying lake breeze circulations near the University of Chicago, south of downtown Chicago, on August 11-13, 1967. These balloons when inflated and balanced properly will, in the absence of strong vertical currents, float on a predetermined density level. The relatively large surface areas and low inertia of the balloons will cause them to respond to horizontal and vertical air motions, and it can be assumed that the balloon trajectory closely describes the trajectory of a parcel of air. Five tetroon release were made from the shore in predominantly anticyclonic conditions with weak northwesterly gradient flow. The tetroons were tracked by two optical theodolites located on high buildings near the shore, Standard double theodolite analysis techniques were used for data reduction.

Temperature and wind observations were obtained from standard meteorological instrumentation at several surface stations and serial single theodolite pibal observations were made along a line normal to the lake breeze front. Time lapse movies, standard speed movies and panoramic pictures indicating the movement of smoke and haze were taken during the course of the tetroon flights, both from surface locations and from an aircraft.

Three balloon flight trajectories will be presented and comparisons will be made with surface and pibal observations and with simultaneous movies and pictures. Two balloons released before noon, on different days, were carried inland by the onshore component of the lake breeze circulation, ascending slowly in response to convective updrafts. In the neighborhood of the lake breeze front, (the convergence zone), which in one case was located 3 km inland and in the other 1 km inland, the balloons were lifted up to the return flow level, approximately 1000 m and 600 m respectively. The offshore component of the

lake breeze circulation carried the balloons out over the lake at approximately constant levels. Subsidence of the air over the cooler lake surface in conjunction with the ceasing of convective updrafts caused the balloons to descend. The balloon that moved offshore at a height of 1000 m was picked up by the onshore flow 1.5 km off shore. The balloon had then fallen to a height of approximately 600 m. This balloon again moved inland reaching its lowest level of flight, approximately 200 m, close to the shore. A subsequent ascent was observed before the balloon was lost by the tracking crew. Thus the balloon was followed through the entire lake breeze circulation cell. A third balloon, released in the late afternoon, when the lake breeze front was more than 20 km inland, was never observed to return. The trajectory is however interesting in that the balloon moved inland in a shouthwesterly direction and at a height of about 300 m while winds aloft were from north to northwest.

OBSERVED LAND AND LAKE BREEZE CIRCULATION ON THE EASTERN SHORE OF LAKE MICHIGAN, 25 JUNE, 1965

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ABSTRACT

An observational study carried out near Grand Haven, Michigan on 25 June, 1965 has produced probably the most extensive measurements available of a nearly idealized land and lake breeze circulation. The complete cycle of nocturnal land breeze to lake breeze during the day with a return to land breeze at night was observed and measured. These data constitute field measurements that are available for the guidance of theoretical studies and for the experimental evaluation of proposed lake breeze models.

The synoptic situation is documented and several mesoscale analyses presented. Several graphs describing winds and temperatures as functions of time and space are included as is a graph indicating moisture change at various stations. The penetration of the lake breeze front is measured by wind, temperature, and moisture changes. Temperature lapse rates, wind profiles, and their variations are presented.

A comprehensive summary of previously reported observational studies of land, lake, and sea breeze circulations is reported.

OBSERVED TEMPERATURE PROFILES NEAR THE LAKE MICHIGAN SHORELINE

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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.

LAKE EFFECTS ON AIR POLLUTION DISPERSION

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ABSTRACT

Local wind regimes induced by a lake or a shoreline have a major influence on air pollution dispersion. Pressure differences due to differential heating of the air, e.g. those due to differences in surface characteristics between land and lake, are the driving forces of lake and land breeze circulations. Differences in roughness between land and lake surfaces will cause wind shear and aerodynamic downwash effects at a shoreline. Stability changes in the air result from differences in surface temperature and roughness between land and lake, e.g. when warm unstable air moves out over a cool lake a temperature inversion will develop near the surface, thus creating poor dispersion and trapping of pollutants. Fumigation will occur as this stable layer is broken up when the air moves across a shoreline and advances inland. A number of these lake influences have been examined in detail on two separate occasions.

The first observational study was carried out near the eastern shore of Lake Michigan on 25 June, 1965 and produced the most extensive measurements yet made of pure lake and land breeze circulations. Almost ideal anticyclonic conditions with clear skies and light winds prevailed.

In the second investigation constant level balloons, tetroons, were used to study air trajectories in lake breeze circulations near the highly urbanized and industrialized southwestern shore of Lake Michigan on 12 - 13 August, 1967. The tetroons were tracked by two optical theodolites and in one case a tetroon was observed to describe a complete lake breeze circulation loop. Extensive measurements of temperatures, humidities, aerosol concentrations, and winds were made both at the surface and aloft and photographs and time lapse movies of clouds, haze, and smoke were taken.

Based on these observational studies and an extensive literature review, the role of local wind systems near a large lake in dispersing atmospheric pollutants is explored in depth.

AIR POLLUTION DISPERSION IN A LAKE BREEZE REGIME: TRAJECTORY STUDY USING TETROONS, SMOKE PHOTOGRAPHY, AND AIRCRAFT MEASUREMENTS OF AREOSOLS

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ABSTRACT

Constant level balloons, tetroons, were used to study air trajectories in lake breeze circulations near the highly urbanized southwestern shore of Lake Michigan on 12-13 August, 1967. The tetroons were tracked by two optical theodolites and in one case a tetroon trajectory described a complete lake breeze circulation loop. Extensive measurements of temperatures, humidities, aerosol concentrations, and winds were made both at the surface and aloft and several photographs were taken of clouds, haze, and smoke. Good correlations were found between tetroon-derived winds and winds measured with conventional techniques. Detailed descriptions of the observed meteorological characteristics of the lake breeze circulations and associated transports of moisture and aerosols are presented.

APPENDIX B

PERSONNEL WHO HAVE CONTRIBUTED TO OR RECEIVED BENEFITS FROM THE RESEARCH CONDUCTED UNDER GRANTS NOS. AP-00380-01,02,03

1. Faculty

Hewson, E. Wendell	Professor of Meteorology Project Director 1965-1967
Wiin-Nielsen, Aksel C.	Professor of Meteorology Project Director 1968-1969
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