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A STUDY OF OZONE AIR QUALITY ON THE WESTERN SHORE OF LAKE MICHIGAN

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INTRODUCTION

One of the most difficult air pollution problems facing the nation and Illinois today is the persistently high levels of ozone, sometimes referred to as "smog" or photochemical oxidants, that occur in many urban areas. Nationally, nearly eighty million people currently live in urban areas that from time to time experience ozone concentrations in excess of the National Ambient Air Quality Standards (NAAQS) for ozone. In Illinois, nearly 7.4 million people (more than 60 percent of the State's population) are currently exposed to ozone concentrations exceeding the ozone NAAQS. Exposure to such elevated ambient ozone levels puts some of these people's health at risk and may also cause damage to crops, forests, and other types of vegetation.

Ozone (O_3) is a secondary pollutant and is not emitted from tailpipes or smokestacks like carbon monoxide or other pollutants. Rather it is formed by a complex series of chemical reactions in the atmosphere in the presence of sunlight. When reactive non-methane hydrocarbons (NMHC) and nitrogen oxides (NO_x) accumulate in the atmosphere and are exposed to the ultraviolet component of sunlight, ozone and peroxyacetylnitrate (PAN), an irritating oxidizing agent, are formed. Nitrogen oxides and NMHC are therefore called ozone precursors.

The actual mechanism of ozone formation begins with the absorption of ultraviolet light energy by nitrogen dioxide (NO_2) which results in its disassociation into nitric oxide (NO) and an oxygen atom. Most of these oxygen atoms react with atmospheric molecular oxygen (O_2) to form ozone (O_3). Nitric oxide will then react with ozone to re-form nitrogen dioxide to complete the cycle. Ozone is used up as fast as it is formed, and ambient ozone levels remain low. A build-up of ozone above the equilibrium concentration of these reactions occurs when nitric oxide reacts with non-methane hydrocarbons rather than ozone. Oxygen atoms from hydrocarbon radicals oxidize nitric oxide to nitrogen dioxide without using ozone. Ambient ozone is not depleted but can build up quickly.

The effects of elevated levels of ozone and photochemical oxidants on man and vegetation are well documented. Ozone is a pulmonary irritant that affects the respiratory mucous membranes, other lung tissues, and respiratory functions. Clinical and epidemiological studies have demonstrated that ozone impairs the normal mechanical function of the lung, causing alterations in respiration, the most characteristic of which are shallow, rapid breathing and a decrease in pulmonary compliance.[1,2,3,4] Exposure to ozone results in clinical symptoms such as chest tightness, coughing, and wheezing. Alterations in airway resistance can occur, especially to those with respiratory diseases (asthma, bronchitis, emphysema).[5,6,7] These effects may occur in sensitive individuals, as well as in healthy persons undergoing exercise, at short-term ozone concentrations between 0.15 and 0.25 ppm.

Ozone itself is a primary cause of most of the health effects reported in toxicological and experimental human studies, and the evidence for attributing many health effects to this substance alone is very compelling. In addition, a number of atmospheric photochemical substances are known to produce health effects, some of which are not attributable to pure ozone but may be caused by other photochemical substances in combination with ozone. For example, peroxyacetylinitrate (PAN) is a known eye irritant with effects that often occur in conjunction with those of ozone.

Since ozone formation is dependent on temperature and sunlight, ozone is a seasonal pollutant, reaching its highest concentrations on warm, sunny summer afternoons. The officially designated ozone season in Illinois extends from April through October, with the highest concentrations being observed in June, July and August.

The National Ambient Air Quality Standard (NAAQS) for ozone is 0.12 parts per million (ppm) averaged over 1-hour period.[8] The United States Environmental Protection Agency (USEPA) states that an ambient air monitoring site is in compliance with the standard when the expected number of days per calendar year having a 1-hour concentration above 0.12 ppm is less than or equal to 1.[9]

The State of Illinois has made considerable progress in reducing ozone air pollution since the passage of the federal Clean Air Act (CAA) in 1970. There are two areas of the State, however, where ozone remains a concern. Of the two areas, the Chicago urban area is the larger, has a much greater population, and has had more exceedances and higher ozone levels than the Metro-East St. Louis area. This paper will address only the Chicago area and the influence that Lake Michigan has on ozone levels in this region.

GEOGRAPHIC BACKGROUND OF CHICAGO

Chicago is located along the southwest shore of Lake Michigan. The Chicago area, with nearly eight million people in the Illinois portion of the Consolidated Metropolitan Statistical Area[10] (CMSA), has the largest population of any metropolitan area in the interior of the United States and is one of the country's most important transportation, manufacturing, and commercial centers. The City proper is roughly 8 to 10 miles wide and extends from south to north for about 25 miles along the lakeshore.

The entire area around the southern end of Lake Michigan is essentially a level plain averaging only tens of feet higher than the surface of Lake Michigan, which is 580 feet above mean sea level. The natural surface features of the area do not have a significant affect on air movement in or near the City and do not cause any noticeable drainage or channelling of winds, although the reduced frictional drag over Lake Michigan frequently allows winds to be stronger along the lakeshore. The City's buildings are important landscape features, more so than the natural relief. Air flow is often channeled between buildings, producing stronger winds at street level than would otherwise be the case. This is particularly true in the central business area (the "Loop"), where there are many tall buildings. There are 32 buildings taller than 500 feet in the Loop, including three of the five tallest in the world (the Sears Tower, 1454 ft.; the Standard Oil Building, 1136 ft.; and the John Hancock Building, 1127 ft.). However, the nickname of Chicago as the "Windy City" is a misnomer, as the average wind speed here is not greater than that in many other parts of the United States.

CLIMATOLOGY OF CHICAGO

The climate of Chicago is predominantly continental in character because of the City's central location inside the North American Continent. Chicago has cold winters, warm summers, and only moderate precipitation, though Lake Michigan tempers the extremes of heat or cold. Also, because Chicago is in the Central Plains, a region in which interaction between cold air from the north and warm air from the south takes place, the very cold periods of winter and hot humid conditions of summer are frequently interrupted by milder weather. The amount of measured sunshine is moderate in summer, quite low in winter. During the ozone season, winds are generally light or moderate.

The prevailing winds in the Chicago area are from the west over the course of a year but are from the south-southwest during the ozone season. During the summer, the stagnant high pressure system (the "Bermuda High") which frequently lies to the southeast of Illinois is responsible for the southerly component of the wind flow. During the ozone season the monthly resultant wind direction varies from southerly to westerly, with an average of southwesterly flow occurring for this period of the year. The annual average wind speed is a little over 10 miles per hour (mph). However, the average speed during July and August is only about 8 miles per hour, reflecting the more stagnant nature of the air masses over Chicago in the summertime.

The amount of ozone measured during the summer months is related to the amount of sunshine observed. During the ozone season the average sky coverage is 6.0 tenths, ranging from 5.5 tenths in July to 6.8 tenths in April. The percent of possible sunshine ranges from 48 percent in October to 69 percent in July, with an average of 59 percent for the ozone season, which is slightly above the annual average (53 percent).

An important parameter regarding the potential for air pollution in Chicago is the average mixing height. Mixing heights vary from hour to hour on a daily as well as a seasonal basis. The average annual morning mixing height is 360 meters; the average afternoon mixing height is nearly 1200 meters. Mixing heights are typically higher in summer than in winter, but both seasons have a high potential for air pollution episodes. In winter, low mixing heights can cause trapping of pollutants at the surface causing air pollution problems for short periods of time. However, weather patterns are much more vigorous and frontal passages are more frequent in winter than in summer, allowing the pollutants to disperse in the atmosphere. In summer, extended periods of strong subsidence under widespread high pressure are likely to give rise to air pollution episodes even though the mixing heights are greater.

The proximity of Chicago to Lake Michigan has a significant effect on the City's climatology. In particular, temperature differences between Lake Michigan and the adjacent land area affect local winds. The lesser frictional drag over the lake causes winds to be frequently stronger along the lakeshore than farther inland and often permits air masses from the north to reach the shore areas before they reach the rest of the region. Special wind effects occurring at the shoreline have a bearing on local air pollution. These winds are referred to as lake effect winds or lake breeze.

Often on summer afternoons the area of the City near the lakeshore is cooled by an easterly breeze from Lake Michigan, which may lower temperatures by as much as 10° to 15° below those on the west side of the City. The breeze usually extends only a mile or so inland, but sometimes reaches several miles from the shore, and more rarely, into western suburbs. On some summer days, however, the prevailing wind from the west or southwest is strong enough to overcome the lake breeze, and on those days the temperature along the lake shore becomes as high as elsewhere in the City. On the average, summer temperatures near the lake shore are lower in the daytime and higher at night than those temperatures away from the lake.

OZONE AIR QUALITY

For many years, the Illinois Environmental Protection Agency (IEPA) has operated a statewide air quality monitoring network in Illinois to measure ozone levels. In 1986, the IEPA operated 39 ozone monitoring sites in the State and 17 of these were in the northeastern Illinois area. The Wisconsin Department of Natural Resources (WDNR) operated 19 ozone monitoring sites in the eastern Wisconsin area in 1986. Figure 1 identifies the location of these ozone monitors in the Lake Michigan area.

Historically, ozone has been the most pervasive pollutant monitored in Illinois. Violations of the current 0.12 ppm standard have been recorded statewide in the past. However, the greatest number of occurrences of ozone concentrations above the NAAQS have occurred in the Chicago area. This is primarily due to the large number of stationary, area, and mobile emission sources in this area. Ozone concentrations in Illinois and Eastern Wisconsin have generally been decreasing since 1979. In 1986, northeastern Illinois sites recorded 2 exceedances of the 0.12 ppm standard, whereas in 1979 sites recorded 33 exceedances of the standard. For eastern (E) Wisconsin monitoring sites in 1986, there were 17 exceedances of the standard, while in 1979 there were 42 exceedances. This data is summarized in Table I.

In 1983, there was an increase of measured ozone concentrations due to atypical meteorological conditions which were highly conducive to the formation of ozone. The Chicago area experienced 1-1/2 times as many ozone conducive days in 1983 as in the preceding and three following years. The years 1984 through 1986 have been more typical in terms of meteorological conditions. Each year has also seen a decrease in both the highest and second-highest ozone concentrations observed in the State, as well as a decrease in the number of monitors exceeding the ozone standard and the number of days when the standard was exceeded in Illinois.[11,12,13]

FIGURE 1

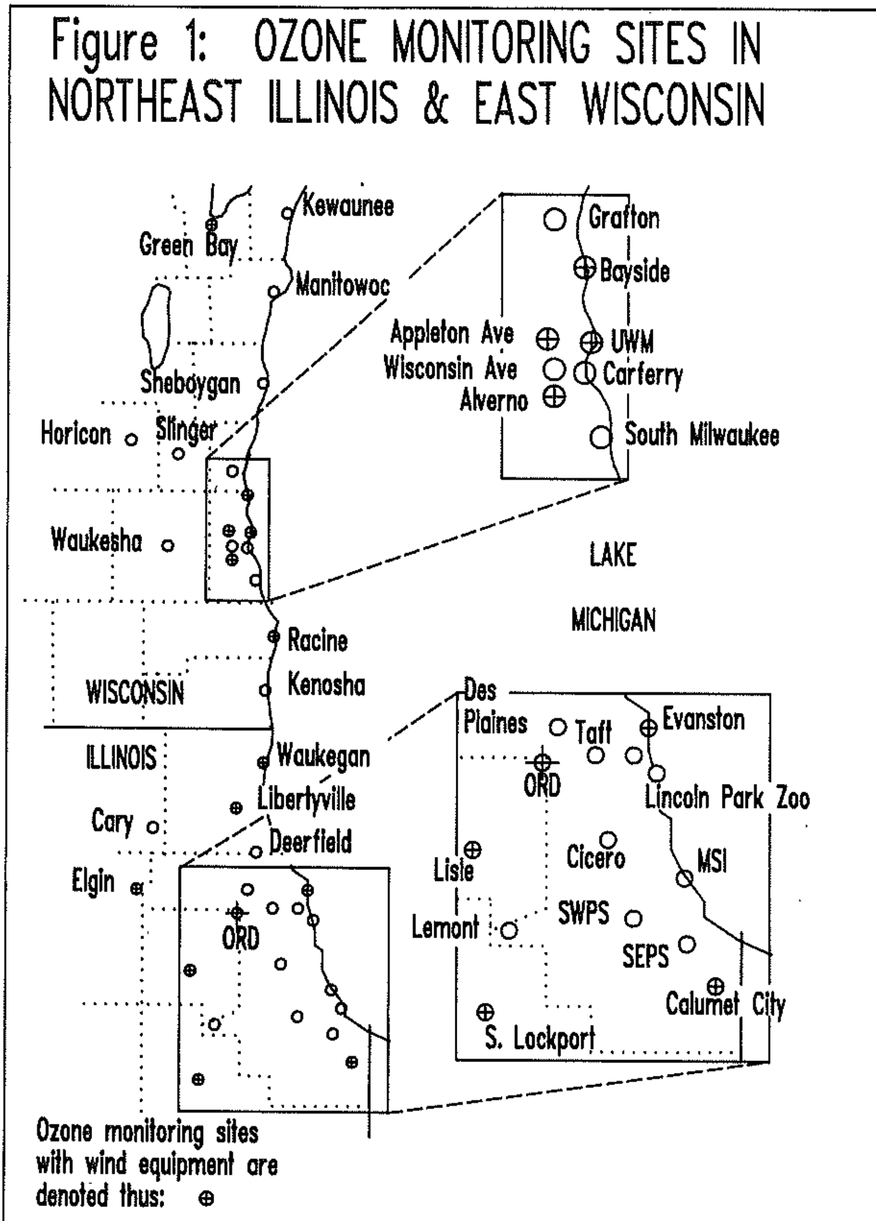


Figure 1: OZONE MONITORING SITES IN NORTHEAST ILLINOIS & EAST WISCONSIN
Kewaunee
Green Bay
Manitowoc
Sheboygan
Horicon
Slinger
Waukesha
Racine
Kenosha
WISCONSIN
ILLINOIS
Waukegan
Libertyville
Cary
Deerfield
Elgin
ORD
Grafton
Bayside
Appleton Ave
UWM
Wisconsin Ave
Carferry
Alverno
South Milwaukee
LAKE
MICHIGAN
Des Plaines
Taft
Evanston
ORD
Lincoln Park Zoo
Lisle
Cicero
MSI
Lemont
SWPS
SEPS
Calumet City
S. Lockport
Ozone monitoring sites with wind equipment are denoted thus: ⊕

TABLE I

NUMBER OF OZONE EXCEEDANCES ABOVE 0.12 PPM AT NE ILLINOIS AND E WISCONSIN MONITORING SITES

Monitoring Site	1986	1985	1984	1983	1982	1981	1980	1979
ILLINOIS:								
Waukegan	0	3	4	5	0	4	5	9
Libertyville	0	1	1	4	1	2	4	2
Cary	0	0	0	2	1	1	0	--
Deerfield	0	2	1	3	0	2	1	5
Arlington Heights	--	--	--	--	0	1	0	0
Elgin	0	0	0	2	0	1	0	2
Des Plaines	0	0	2	2	--	--	--	--
Evanston	0	4	4	6	1	2	5	5
Skokie	--	--	--	--	0	3	3	3
Chicago/Taft	1	1	--	--	--	2	1	1
Chicago/Edgewater	0	0	--	--	--	--	--	0
Chicago/Lincoln Pk Zoo	--	0	1	1	0	0	--	--
Glen Ellyn	--	--	--	2	0	0	--	--
Cicero	0	0	1	4	--	--	--	--
North Riverside	--	--	--	--	0	1	2	0
Lisle	0	0	1	--	--	--	--	--
Chicago/Museum S&I	1	0	0	3	--	1	--	--
Chicago/Stevenson	--	--	--	--	0	1	0	--
Chicago/SW Pump	0	0	1	4	--	--	--	--
Chicago/SE Police	0	0	0	2	0	--	--	--
Lemont	0	0	--	2	--	--	--	--
Calumet City	0	1	0	2	0	0	4	3
South Lockport	0	0	0	3	--	0	0	0
Braidwood	--	0	0	1	1	0	1	0
Total Exceedances	2	12	16	48	4	23	27	33
WISCONSIN:								
Kewanee	0	0	--	--	--	--	--	--
Manitowoc	0	2	6	--	--	--	--	--
Sheboygan	0	0	6	11	2	0	9	10
Slinger	0	1	1	1	1	1	2	--
Grafton	2	2	2	9	1	4	4	2
Bayside	2	1	3	--	--	--	--	--
Waukesha	2	1	1	3	4	2	0	3
Milwaukee:								
UWM (Kenwood)	5	4	4	10	2	8	4	6
Appleton Ave	0	2	1	3	0	3	0	0
Alverno	1	3	3	7	1	4	2	4
S. Milwaukee	0	2	--	--	--	--	--	--
Racine	4	4	5	13	1	10	5	6
Kenosha	1	3	4	6	0	7	3	11
Total Exceedances	17	25	36	63	12	39	29	42

Notes: 1. Sources of data - IEPA data files, including Annual Air Quality Reports,
- Wisconsin DNR annual reports, including exceedance reports
2. A dash (-) means that that site was not operating that year.

LAKE CIRCULATION PATTERNS

Illinois shares the southern tip of Lake Michigan with Indiana and Michigan and its western coastline with Wisconsin. Movement and dispersal of pollutants in this area are influenced by the following meteorological and physical factors:

- the orientation of Lake Michigan;
- differences in the physical properties of land/lake;
- synoptic scale migrating high pressure systems with their accompanying subsidence inversion;
- lake/land breezes.

These factors influence the coastal meteorology, and each may act on a different spatial and temporal scale. The lake/land circulation system along the western coastline of Lake Michigan is complex and subject to the natural variability of the weather as well as to the interaction of the meteorological and physical factors that characterize this area of the country. It is the interaction of these different factors at several scales that introduces the complexity that is characteristic of lakeshore meteorology.

Orientation of Lake Michigan

Lake Michigan has an average depth of 279 feet and a surface area of approximately 22,300 square miles. Unlike the other Great Lakes, the major axis of Lake Michigan runs nearly north and south. This means that it is roughly perpendicular to the mean westerly flow over this region. Differences in temperature, pressure, and density are often largest in a direction which has great influence on the development of the lake/land breezes that develop along the shoreline.

Physical Property Differences

The physical contrast between the lands bordering the lake and the lake itself often act to influence the meteorology of the narrow corridors bordering Lake Michigan. For example, the lake acts as a source of moisture, adding water to the air over its surface, while this happens to only a limited extent over land. This physical contrast in air mass densities causes abrupt temperature differences near the shoreline as well.

When such contrasts in density are associated with air mass differences, such as those occurring during severe weather, they are often called "dry lines" in recognition of the fact that dry air is more dense than moist air at the same temperature. The density differences of the air along the lakeshore can also act as a natural aid to the development of a dry line along the coast. A line of sharp density differences at the land/lake interface can also act to accelerate winds horizontally.

On differing time scales land/water differences play an important role. Marked differences in sources of pollutants, the heat content, and the moisture content of the air give rise to both diurnal and seasonal variations. The relatively rapid heat transfer of land as compared to that of water causes the water to act as a moderating influence to provide milder summers along the coast. It also acts to drive the air offshore at night when the land cools faster than the water. Faster heating of the land during the day also means that the cool summer breezes off the lake will lose some of their force as the summer progresses.

The drag of the lake's surface on the air above it is less than the drag over the land's surface, and in urban areas the protrusion of vegetation and buildings above the surface act to impede the flow over the surface. This impediment slows the wind coming off the lake so that winds near the surface tend to increase in speed vertically. Surface friction, acting in opposition to the wind, reduces wind speed and turns it to the left (or inland for southerly flow), since the balancing coriolis force is diminished at low wind speeds. Aloft, in the absence of friction, the wind continues on its course unaffected. A line of vertical wind shear is set up with the winds at higher levels being both faster and more westerly, i.e., toward the lake. This vertical wind shear can then lead to a distorted spiral type of flow as the air moves out over the lake.

Synoptic scale

While the general atmospheric flow over the Midwest is west to east, during the summer months this westerly flow is often disturbed on a smaller scale by the migrating high pressure centers. These large synoptic scale features often dominate the weather over large areas of the Midwest as they stagnate and accumulate pollutants from the surface and trap them under a wide spread upper-level inversion that acts as a lid to limit mixing. The large-scale anticyclones that often dominate the southeastern part of the continent can act as large scale conveyors to transport precursors and pollutants over long distances, even from rural areas.

When the anticyclones influence the Lake Michigan area, they may influence the local meteorology in a more direct way. For instance, the subsidence associated with these high pressure systems leads to increased stability of the air aloft and is often aided at the lower levels by radiational cooling of the air near the ground during the night. The persistence of the subsidence aloft during the day, however, contrasts with warming at the surface. During the summer afternoon, lower levels of the urban atmosphere may become unstable under the upper level subsidence inversion. Over the urban area the mixing height tends to reach its maximum about 8 to 10 AM. Over the lake, however, the marine inversion will remain more constant and typically lower. This gives rise to the development of a thermal interior boundary layer (TIBL), which increases rapidly in height over land as one moves inland from the lake. While the height of the urban boundary layer over Chicago is known to reach up to 1500 meters, the height over the lake is less certain but is believed to be only a few hundred meters high. A shallow stable layer frequently occurs over water when the air temperature is higher than the water temperature and this broad, stable layer can act to decouple winds aloft from winds near the lake surface.

Lake Breezes

Much of the understanding of lake/land breezes comes from studies that considered the diurnal patterns of winds along sea coasts.[14] Although lake/land breezes occur on a smaller scale than the sea/land breezes, they can have a large impact on lakeshore meteorology. This type of flow exhibits a diurnal cycle in response to solar heating. The lake breeze has its earliest onset and longest duration during summer while the land breeze will tend to dominate during winter.

The lake breeze is driven by the daily solar heating of the land (see Figure 2). As the land warms during the day, the overlying air begins to rise as it becomes warmed by the ground. A vertical flow develops over land while the air aloft over the lake begins to warm. The air near the lake's surface remains relatively cool because the surface of the water does not warm up as fast as the land. As the air over land warms it becomes more bouyant, rises, and sets up a pressure gradient aloft under the large scale subsidence inversion. A pressure gradient is thus established aloft which provides the driving force for outflow of air aloft over the lake. A cool surface over the lake allows the air to sink and the pressure to build so that the horizontal surface pressure gradient forms opposite to that aloft; the surface air flows from the surface high over the lake to the surface low over the land. The simple thermal circulation once established provides a surface flow that goes from lake to land. The land breeze is essentially the reverse of this type of flow, which occurs due to the reversal of horizontal temperature gradients after sundown.

This discussion presents a general picture of flow near the lake and treats only the flow perpendicular to the shoreline. Given the variability of daily weather, this flow is likely to be complicated by interaction with the larger synoptic-scale flow which often has a component parallel to the coast. The simple east-west circular cell of the lake/land breeze may be distorted by a large scale flow imposed on it.

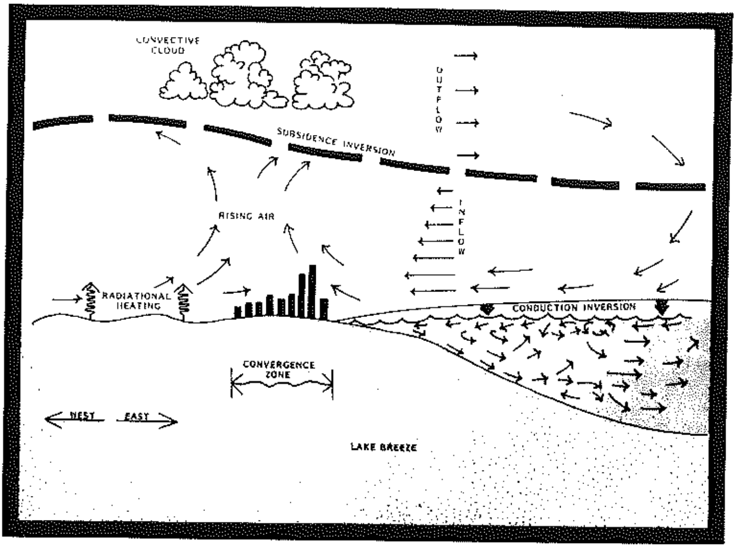
Lake-shore flow has been found difficult to predict and quantify. However, one measure of the likelihood of the formation of the lake breeze is "lake breeze index", represented by the equation:

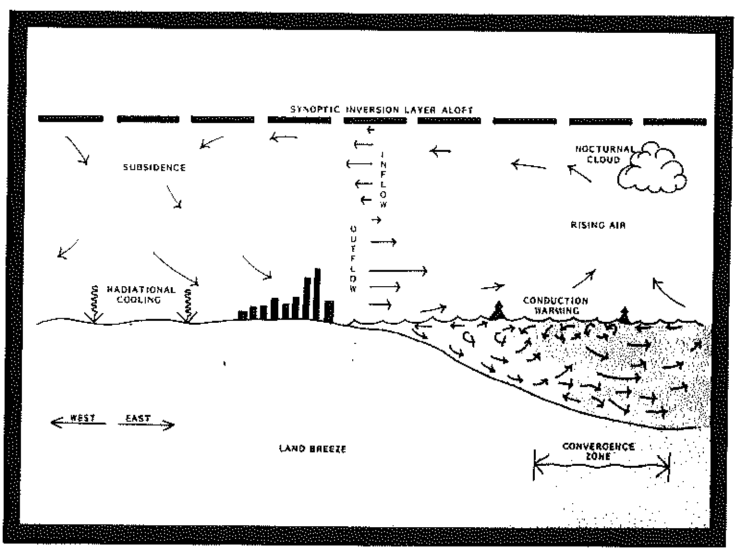
$$\sigma = \frac{(Vg)^2}{Cp\ \Delta T}$$

where Cp is the specific heat of dry air, Vg is the geostrophic wind and ΔT is the temperature difference between the land and the lake.[15] The equation is a comparison between the energy content of the inertial (general flow) and thermal (land-lake temperature differences) forces. For a given wind speed, σ becomes smaller for a higher temperature difference showing that thermal

FIGURE 2

TYPICAL LAKE/LAND BREEZE PATTERNS





forces may overwhelm inertial forces when temperature gradients across a lakeshore become large and the geostrophic wind is light. When the pressure gradient parallel to the coast becomes large, the geostrophic wind increases and temperature differences are less important to lake breeze formation. It has been found that for σ <10, the occurrance of a lake breeze is highly likely. Unfortunately, σ gives us little information about flow parallel to the shoreline as will be seen in the analysis of two high ozone days which follows.

ANALYSIS OF TWO REPRESENTATIVE HIGH OZONE DAYS

From the population of days with high ozone, two days have been chosen as examples of the two distinct types of days with elevated ozone values in the area west of Lake Michigan. Two distinct patterns have been identified--one in which the Chicago and Milwaukee areas appear to have little effect on one another's high ozone, and a second in which the entire area acts as a continuum. The two types of days generally appear to be similar from a meteorological point of view, with southwesterly wind flow inland and a lake breeze along the shoreline; but the development of ozone in the area is quite different.

Hourly ozone information was collected from the Illinois and Wisconsin ozone air monitoring networks (see Table II). Wind information was obtained from National Weather Service (NWS) observations at O'Hare Airport in Chicago and from hourly wind data at those ozone monitoring sites in Wisconsin and Illinois that had colocated ozone and wind equipment.

Pattern A--Tuesday, August 28, 1984 (See Figure 3)

At 0600 CST, a surface ridge extended along the east coast of the United States. A weak trough extended from western Ontario through Minnesota to Texas. Surface flow over Illinois was light (less than 10 kts), southerly and anticyclonic. This situation changed little over the next 24 hours. The weather in the Chicago area and along the western shore of Lake Michigan was hot and hazy. The maximum temperature at O'Hare Airport was 94°F.

As shown in Figure 2, at 1200 CST, ozone levels along the western shore of Lake Michigan were still below the level of the NAAQS. Hourly averages were just below 120 parts per billion (ppb) in Racine, and had not yet reached 100 ppb in either Milwaukee or Chicago. Low level flow in the Chicago area was southerly to southwesterly inland, and southerly along the lake. In Milwaukee, winds were light and from the north.

Between 1200 CST and 1300 CST, ozone levels in Racine jumped to above 170 ppb, while other lakefront monitoring sites from north of Milwaukee to Chicago registered less extreme rises. Most of the Chicago area and inland Milwaukee remained comparatively low, with no sites in Chicago or Milwaukee exceeding 100 ppb. Flow remained south or west of south in the Chicago area, but winds in Milwaukee were from the southeast (i.e., off the lake). The sharp rise in ozone at Racine and other sites was generally coincident with the onset of the lake breeze.

FIGURE 3

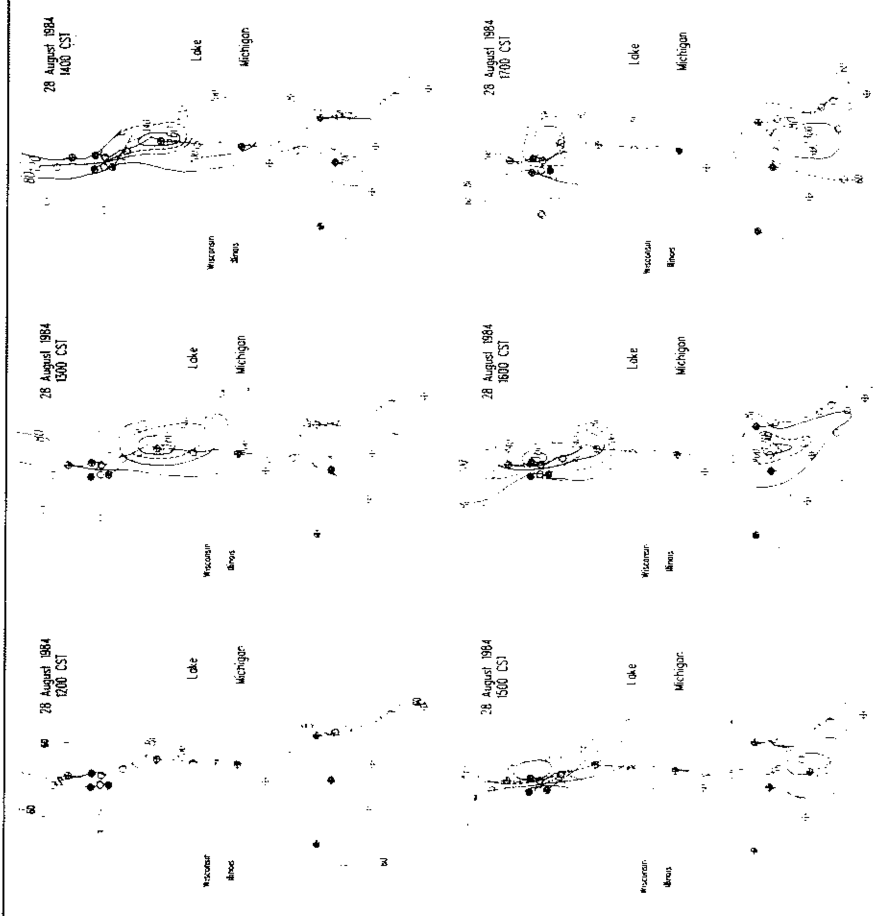


Figure 3
Ozone concentrations in northeastern Illinois and southeastern Wisconsin on the afternoon of 28 August 1984. Isopleths are in ppb of ozone, and areas exceeding the NAAQS are shaded.

TABLE II

ILLINOIS-WISCONSIN OZONE STUDY

Hourly Ozone Values on June 8, 1985 at CST Hours Indicated

Monitor	11	12	13	14	15	16	17	18	19
WISCONSIN									
Manitowoc	64	71	75	95	98	93	91	96	98
Sheboygan	45	58	74	65	62	63	75	89	94
Slinger	--	--	--	--	--	--	--	--	--
Grafton	62	83	71	76	80	127	148	121	97
Bayside	--	--	--	--	--	--	--	--	--
Milwaukee/Appleton	50	60	69	79	87	121	129	103	67
Milwaukee/UWM	84	79	81	81	102	160	147	111	50
Milwaukee/Wisc. Ave	--	--	--	--	--	--	--	--	--
Milwaukee/Carferry	--	--	--	--	--	--	--	--	--
Waukesha	51	60	67	54	54	57	55	56	50
Milwaukee/Alverno	62	65	79	85	113	151	130	106	69
South Milwaukee	64	70	73	80	135	153	130	102	70
Racine	73	76	86	108	132	135	112	57	64
Kenosha	72	80	103	137	146	141	108	74	45
ILLINOIS									
Waukegan	77	88	130	144	148	127	97	52	50
Libertyville	68	70	58	54	49	48	47	55	55
Cary	45	43	40	37	36	37	39	42	41
Deerfield	87	91	145	136	60	53	53	52	55
Elgin	58	53	46	45	--	44	53	53	49
Des Plaines	67	64	62	53	48	47	48	45	49
Evanston	97	112	139	140	143	103	48	47	40
Taft	66	64	50	34	38	55	52	53	47
Edgewater	--	--	--	--	--	--	--	--	--
Lincoln Park Zoo	44	68	94	107	112	89	39	38	38
Cicero	58	60	61	50	49	45	43	42	37
Lisle	59	48	44	47	--	45	44	38	29
Museum of Sci & Ind	14	17	28	30	30	29	25	27	20
Southwest Pump Stn	55	66	65	56	48	43	50	52	44
Southeast Police Stn	58	58	57	50	41	40	41	41	37
Calumet City	51	60	65	57	44	39	45	40	35

Hourly Ozone Values on August 28, 1984 at CST Hours Indicated

Monitor	11	12	13	14	15	16	17	18	19	20
WISCONSIN										
Manitowoc	54	37	46	84	91	89	76	79	63	54
Sheboygan	58	75	79	81	84	81	106	157	133	113
Slinger	49	54	62	69	79	74	54	33	55	64
Grafton	--	--	--	--	--	--	--	--	--	--
Bayside	--	--	--	--	--	--	--	--	--	--
Milwaukee/Appleton	55	68	73	81	66	53	69	43	30	45
Milwaukee/UWM	62	67	94	131	173	161	128	74	28	41
Milwaukee/Wisc. Ave	57	56	73	80	62	72	88	58	25	37
Milwaukee/Carferry	59	69	91	145	147	148	101	60	36	39
Waukesha	54	61	66	64	64	61	60	43	39	30
Milwaukee/Alverno	62	64	80	74	62	91	93	48	24	32
South Milwaukee	--	--	--	--	--	--	--	--	--	--
Racine	75	117	173	172	146	124	82	67	43	41
Kenosha	62	100	132	108	98	71	73	48	40	34
ILLINOIS										
Waukegan	72	70	99	113	91	63	54	23	4	12
Libertyville	75	71	60	57	66	65	48	39	35	28
Cary	61	61	62	60	--	--	--	--	--	--
Deerfield	80	76	78	68	64	74	50	27	28	20
Elgin	68	64	63	61	64	59	55	40	33	12
Des Plaines	13	10	9	4	3	1	0	0	--	--
Evanston	85	91	114	106	92	91	78	57	46	44
Taft	--	--	--	--	--	--	--	--	--	--
Edgewater	--	--	--	--	--	--	--	--	--	--
Lincoln Park Zoo	52	54	74	80	68	79	66	56	49	39
Cicero	50	83	96	97	121	117	102	92	74	63
Lisle	78	76	65	57	57	65	51	35	15	28
Museum of Sci & Ind	48	66	71	69	67	69	60	52	37	29
Southwest Pump Stn	58	75	75	78	82	80	73	65	50	44
Southeast Police Stn	48	74	75	76	76	80	70	65	27	11
Calumet City	52	61	63	65	68	72	64	59	46	41

Notes: 1. A dash (-) means that the site was not operating that year.
2. Ozone values are given in parts per billion.

Ozone levels continued to rise along the lakeshore at Racine and north into Milwaukee at 1400 CST, but levels decreased from Kenosha south, with a few exceptions. Racine was still above 170 ppb, but in Milwaukee, only the monitoring sites near the lakeshore recorded levels above the NAAQS. Flow over most of Chicago remained southwesterly; but a lake breeze had begun in the Chicago area, and winds along the lakeshore were southerly to south-southeasterly from Chicago north. In Milwaukee, the lake breeze was stronger and winds there were from east-southeast to southeast.

By 1500 CST, maximum ozone levels were north of the Milwaukee lakeshore area. The Near West Side of Chicago had higher ozone levels (still below the NAAQS) than elsewhere in the city since early afternoon. At 1500 CST the Cicero monitor exceeded the NAAQS. Note that flow over most of Chicago was still southwesterly, but the lake breeze continued to dominate the flow in Milwaukee and along the lake.

At 1600 CST, there were two separate ozone maxima along Lake Michigan--one in Chicago and its western suburbs with a maximum of about 120 ppb and another along the lakeshore of Milwaukee with its maximum about 160 ppb. The area from Waukegan to Kenosha between the two maxima had low levels (70-80 ppb) of ozone similar to those which prevailed before noon. At this time, surface flow in the Chicago area was from the southwest even along the lakeshore, since the synoptic flow had overpowered the lake breeze. In Milwaukee, however, the lake breeze persisted longer, although winds inland were returning to synoptic flow and were from the south or slightly west of south.

By 1700 CST, ozone levels in the Milwaukee area were falling rapidly and were only slightly above 120 ppb at the maximum. High levels of ozone continued at later hours further north along the lakeshore in Sheboygan, but Manitowoc never exceeded the NAAQS. In Chicago, the maximum concentration remained generally constant, and the overall flow showed little change which by this time was somewhat more southerly in Chicago.

By 1800 CST, high ozone levels had almost disappeared, though levels exceeding the standard persisted in Sheboygan (north of Milwaukee) until past 1900 CST. Ozone concentrations were well below 100 ppb in both the Chicago and Milwaukee areas but were higher in Chicago than in Milwaukee. Surface flow in Chicago was southerly, but Milwaukee's surface flow still had a lake-breeze component from the southeast. By 1900 CST, winds along the western shore of Lake Michigan were southerly to southwesterly as the lake breeze collapsed.

This day has been classified for this study as typical of Pattern A. High ozone levels formed independently in eastern Wisconsin and in northeastern Illinois. The mass of ozone in Wisconsin appeared to move north in the synoptic flow, but the mass did not appear to originate in Chicago. The lake breeze did not penetrate far inland. The highest ozone levels were observed near the convergence zone where the lake breeze circulation and the southwesterly synoptic flow came together. Chicago's elevated levels did not appear to move northward, and they were lower than the levels observed in Milwaukee. The ozone that day did not originate in air over the lake.

There was little change in the synoptic situation between August 28 and August 29. Ozone levels exceeding the NAAQS, and similar to those of August 28 occurred somewhat further inland on August 29 in Illinois north of Chicago and in Milwaukee, Racine, and Kenosha. Late on August 29, however, a cold front passed through the area. The arrival of a cooler, cleaner air mass meant no further elevated ozone levels.

Pattern B--Saturday, June 8, 1985 (See Figure 4)

At 0600 CST, a ridge extended from a high pressure area in northeast Arkansas northward through Illinois and Wisconsin to western Ontario. The ridge was west of lake Michigan in the morning but moved east of the lake during the day. A strong frontal system associated with a low in Saskatchewan extended through the Dakotas and back toward Wyoming; this system moved rapidly east and was past Lake Michigan by June 9. Flow over Illinois was predominately light (less than 10 kts) southwesterly. This flow increased during the day but was not so markedly anticyclonic as in the previous example. Weather in Chicago and along the western shore of Lake Michigan was fair and hot (95°F at O'Hare Airport, the month's maximum) with no haze reported.

As shown in Figure 4, flow over Chicago and Milwaukee was southwesterly except right along the lakeshore, where a weak southeasterly lake-breeze was already present by 1200 CST. Ozone levels north of the city of Chicago along the lakeshore were near 120 ppb, and there was an area north of Milwaukee with levels just over 80 ppb. Most other monitors were measuring below 70 ppb.

Ozone levels rose sharply between 1200 CST and 1300 CST in the area north of Chicago into Lake County and were well above the NAAQS at Evanston, Deerfield, and Waukegan. Milwaukee had levels in the 70-80 ppb range; however, and inland sites in the Chicago area were also low. The synoptic flow in the Chicago area was still southwesterly, but the entire Milwaukee area now had winds from the southeast off the Lake.

By 1400 CST, the area with ozone levels above the NAAQS extended from extreme north Chicago almost to Racine. Once again the highest levels (in the 140 ppb range) were in a narrow band along the lakeshore and a few miles inland. The synoptic flow continued southwesterly in the Chicago area, and Milwaukee's winds remained southeasterly. Winds along Chicago's shoreline were southerly with a slight easterly component off the Lake.

Little change occurred between 1400 CST and 1500 CST, except that the area of high ozone moved northward. The NAAQS was exceeded along the lakeshore from Evanston to South Milwaukee, but the area did not extend as far inland as it had at 1400 CST. Deerfield was above 130 ppb at 1400 CST but decreased to 60 ppb at 1500 CST. The winds along the lakeshore in Illinois were from the south, with almost no easterly component; Milwaukee winds were still southeasterly. The synoptic flow from the southwest started to overcome the lake breeze in the Chicago area.

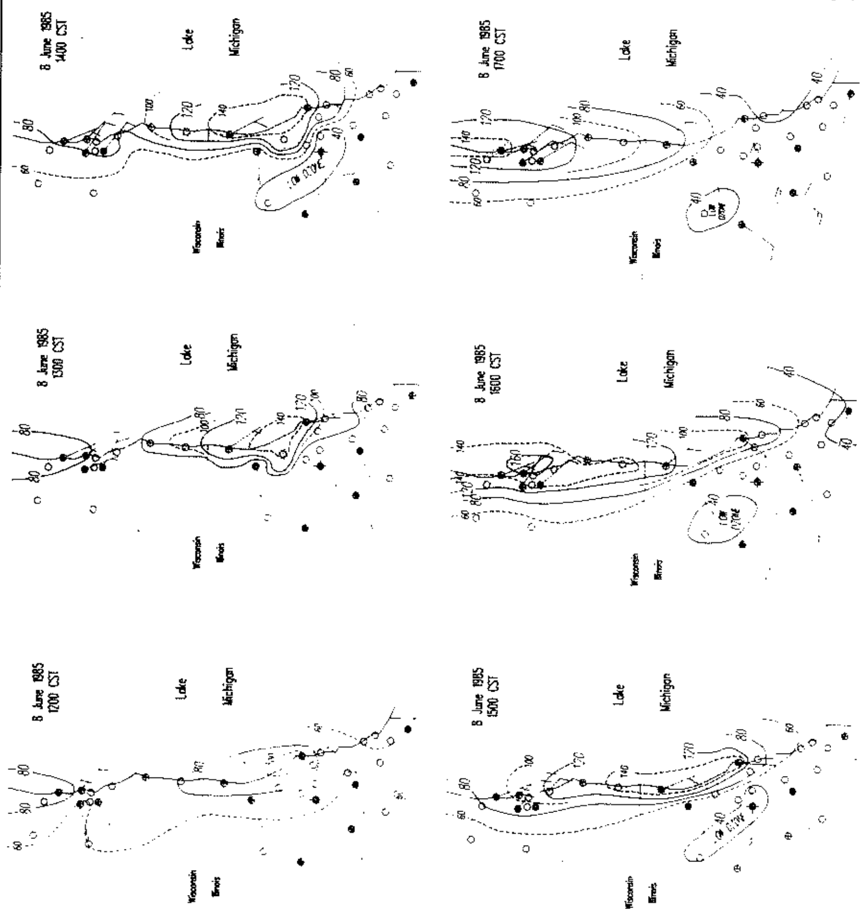


Figure 4

Ozone concentrations in northeastern Illinois and southeastern Wisconsin on the afternoon of 8 June 1984. Isopleths are in ppb of ozone, and areas exceeding the NAAQS are shaded.

At 1600 CST, winds throughout the Chicago area were southwesterly, even along the lakeshore, though winds remained southeasterly in Milwaukee. The area of high ozone continued to move northward; the entire Milwaukee area was well above the NAAQS at this hour. By contrast, levels in Illinois were dropping off, and barely exceeded 100 ppb anywhere in the Chicago area except at Waukegan, the northernmost Illinois monitoring site. In Milwaukee, the highest levels (about 160 ppb) were measured along the lakeshore north of the city; inland sites were considerably lower, though still above the NAAQS.

At 1700 CST, the area of high ozone was continuing northward from Milwaukee, but rapidly decreased later in the afternoon. Neither Sheboygan nor Manitowoc exceeded 100 ppb on this day. Levels south of Milwaukee dropped as they had in Illinois the hour before; both Racine and Kenosha were below the NAAQS by this time. Wind flow continued southwesterly over Chicago and was stronger (up to 15 kts) than it had been earlier. Milwaukee area winds remained southeasterly.

On this day (Pattern B), high ozone levels were generally elevated along the entire west coast of the lake and appeared to move northward along the shoreline. As in the previous pattern, the highest ozone levels were observed along and near the lakeshore, within a convergence zone where the lake breeze circulation from the east or southeast and the synoptic flow from the southwest come together.

On this day, a precursor-rich "plume" moved along the lakeshore, giving rise to high ozone levels as it moved northward. The highest levels observed in the Chicago area and north toward Milwaukee were in the range of 140 ppb, while the highest levels (160 ppb) were observed downwind of downtown Milwaukee. This suggests that the ozone and precursors from Chicago moved northward during the day. As they began to decrease in intensity, the Milwaukee plume and, to a lesser degree the plumes from other urbanized areas, were continuously injected into the air mass. Elevated ozone levels from Chicago to Sheboygan resulted from continuous replenishing of the stagnant air mass with additional ozone and ozone precursors as the air moved through each urbanized area.

EVALUATION OF THE TWO PATTERNS

During periods when Pattern A was noted, the ozone formed in discrete pockets around the urban areas. On August 28, 1984, ozone levels became elevated in the Chicago and Milwaukee areas independently of one another, even though the synoptic flow was from the south to southwest. Maximum levels were reached at about the same time. On June 8, 1985, however, Milwaukee reached its maximum levels well after Chicago, indicating an ozone "continuum." This day illustrates Pattern B during which the ozone formed and continued to increase as it moved northward and more precursors were added along the way.

On both of these days, however, the presence of a lake breeze had a very strong effect on where the highest ozone levels were observed. In general, the highest levels were observed near the convergence zone where the lake breeze and the synoptic flow met. This was found to be 3 to 5 miles inland, depending on the meteorological conditions. Only on comparatively rare occasions was ozone observed outside of the lake breeze circulation along the shores of Lake Michigan.

To evaluate the strength of the lake breeze during periods when each pattern was noted, the lake breeze index (σ) was computed. The value of σ was determined for both the Chicago and Milwaukee areas using the "modified lake breeze" index[15]:

$$\sigma = (Vg)^2/Cp\Delta T = 1.271 \times 10^7/[\Delta N^2(T_1 - T_W)]$$

where Vg is the geostrophic wind speed (m/s), ΔN the 4-mb isobar spacing (Km) taken from National Weather Surface maps, Cp the specific heat of dry air at constant pressure (1004J/Kg-°K), and ΔT the temperature difference (°K) between the lake surface water temperature (Tw) and the average of maximum air temperatures reached inland during the day (T_1). For Chicago, T_1 was taken as the average of the 10 northeastern Illinois climatological stations[16]; those for Milwaukee were taken from National Weather Service maximum temperature charts. T_W for the Chicago and Milwaukee areas were taken as 21.1°C and 20.6°C for August 28, 1984, while for June 8, 1985 the respective values used were 14.4°C and 13.3°C (representing the mean surface water temperature offshore at Chicago and Muskegon[15]).

The values of σ for these two days were much less than the critical value of 10, so that for both days lake breeze development would be expected in both areas.[15] Values of σ were 1.94 and 0.40 on August 28, 1984, and June 8, 1985, respectively, for the Chicago area. For the Milwaukee area σ values for these two days were 4.67 and 0.52. The lower magnitudes of σ at Chicago for both days suggest that lake breeze effects were greater here than at Milwaukee, although such effects might be expected in both areas. The very low values of σ in both areas on June 8, 1985 (Pattern B), show that conditions for the formation of a well-developed lake breeze were present along a considerable stretch of the lakeshore. This finding suggests that when a well-developed lake breeze is expected along the coastline, conditions may become conducive to elevated ozone levels along the entire western shore of Lake Michigan.

During the Pattern B conditions, the entire western Lake Michigan coastline experienced elevated levels, with the highest values being near the major urbanized areas (i.e., Chicago and Milwaukee).

Conversely, when a less well-developed lake breeze was expected (Pattern A), the ozone developed in discrete pockets near the urbanized areas. During periods with Pattern A, there appears to be very little (or no) interaction between the two areas.

CONCLUSION

Development of elevated ozone levels along the Lake Michigan coastline appear to be dominated by two distinct patterns, both of which develop when the synoptic flow is south to southwesterly. This flow near the Lake Michigan coast is substantially disturbed by development of a well-defined lake breeze. In Pattern A, the lake breeze is weaker and a continuum of elevated ozone levels along the western lakeshore is not found. Rather, in this pattern, ozone levels develop in discrete pockets around the major urbanized areas of Chicago and Milwaukee.

In the second pattern (B), the strength of the lake breeze is measurably greater and acts to aid the development of elevated ozone levels along a considerable length of shoreline. While only two typical examples have been provided here, preliminary results suggest that the lake breeze and its strength relative to that of the synoptic flow play a crucial role in the development of elevated levels of ozone along the western Lake Michigan coastline.

These preliminary results also suggest that the modified lake breeze index (σ) might be a useful tool to delineate days with expected development of hot spots versus those in which larger scale episodes might occur. It remains for future analyses to better quantify the relationship between σ and the extent of ozone development along the western Lake Michigan coastline.

Ozone continues to be a major concern for all of the urban areas across the country. However, understanding the causes of elevated ozone levels near Lake Michigan is made even more complex by the presence of the land/lake interface. Results of this study demonstrate that at least two unique scenarios exist in which land/lake breezes affect the degree that ozone transport occurs on the western shore of Lake Michigan.

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