FOREST AND LAKE BREEZE PATTERNS AND THE LA PORTE, INDIANA, RAINFALL ANOMALY

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ABSTRACT

FOREST AND LAKE BREEZE PATTERNS AND THE
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By

Wallace M. Elton

A thirty-year pattern of anomalously high warm-season precipitation centered on La Porte, Indiana, has recently been attributed to atmospheric pollution by the industrial complex in the vicinity of Gary, Indiana. The purpose of the present study is to attempt to evaluate possible phyto-geographic evidence that the La Porte anomaly pre-dates the development of the industrial complex and to make a preliminary test of an alternative hypothesis regarding the cause of the anomaly. It is postulated that a lake breeze front frequently lies near La Porte during summer days when the regional surface flow has a westerly component. Convergence associated with the front may lead to isolated or augmented precipitation and produce greater seasonal rainfall totals near the mean frontal position.

A forest composition survey was conducted during August and September, 1969, along the Valparaiso morainic system which trends northeast-southwest through La Porte,

Porter, and Lake Counties, Indiana, and passes through the described rainfall anomaly. Mesophytic species, particularly Fagus grandifolia (beech) and Acer saccharum (sugar maple) were found to predominate in forest stands in La Porte and eastern Porter Counties, the area subject to the greater precipitation. In western Porter and Lake Counties, more xerophytic species, including Quercus velutina (black oak), Q. alba (white oak), Q. macrocarpa (bur oak) and Carya glabra (pignut hickory) dominated. Previous studies compiled from historical records have verified the existence of this pattern in the presettlement vegetation. These findings suggest the presence of a long-term environmental gradient.

A pilot survey of soil texture along the moraine was also conducted. Samples collected from the B horizon and from a depth of four feet indicated an increase in clay content from east to west with a corresponding decrease in the percentage of sand. It is believed that the greater clay content to the west could reduce readily available water capacity sufficiently to account for the absence of mesophytic tree species. Therefore, it is concluded that the forest contrast cannot be cited as strong evidence for the presence of a long-term climatic gradient.

Wind data were collected from June 11 through August 31, 1969, at six stations in northwestern Indiana and northeastern Illinois in order to test the hypothesis.

Analysis of wind direction records revealed twenty-two days on which lake breezes apparently developed along the southeastern shore of Lake Michigan under regional winds from westerly azimuths, in spite of the general subnormal temperatures of the 1969 summer season. During these days, the lake breeze frequently penetrated to the vicinity of La Porte, particularly when the regional flow was westerly or northwesterly. Neither the number of observation stations nor the length of the study period was sufficient to define precisely the mean position of the lake breeze front. These findings tentatively suggest that the lake breeze may be a factor in the regional precipitation pattern, particularly during periods of positive temperature departure.

Determination of whether the La Porte anomaly is in fact related to lake breeze convergence would require detailed examination of wind patterns on days of excess precipitation at La Porte over a longer period. It is doubtful whether such an examination can be carried out through examination of past records because these exist for only three of the six stations available for the present study.

FOREST AND LAKE BREEZE PATTERNS AND THE

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Among the people who aided in various phases of this project are: Mr. Robert A. Ward of the U. S. Weather Bureau, Purdue University; Mr. H. Moses of Argonne National Laboratory; Mr. D. L. Brubeck of Purdue University's North Central Campus, Westville, Indiana; officials of the Michigan City station of the Northern Indiana Public Service Company; Dr. R. I. Dideriksen and Mr. F. W. Sanders of the U. S. Soil Conservation Service, Indianapolis; and Mr. B. Schrand, Service Forester, Indiana Department of Natural Resources. Final drafting of the maps and diagrams was done by Mr. J. D. Root. Many other individuals, too numerous to mention, gave assistance which is gratefully acknowledged.

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CHAPTER I

INTRODUCTION

Recently an anomalous pattern in the spatial distribution of average warm-season precipitation in northwestern Indiana has been described by Changnon (1). This pattern, the La Porte rainfall anomaly, consists of an island of relatively high precipitation centered on the city of La Porte, Indiana (Figure 1). During the period 1956-1960 the average summer (June - August) rainfall at La Porte exceeded 17 inches; over the same period precipitation at South Bend, twenty-five miles to the northeast, averaged 10 inches, while at Valparaiso, twenty miles to the southwest, mean rainfall was approximately 13 inches. Similar patterns of average annual number of thunderstorms and hail days were also described. Changnon attributed these patterns, which his data indicated have developed since 1925, to the addition of atmospheric pollutants by the industrial complex near Gary, Indiana. There has been considerable discussion as to whether the apparent precipitation anomaly is real or is the result of measurement error (2,3,4). For the purposes of the present study, the greater rainfall at La Porte is assumed to be a real phenomenon.

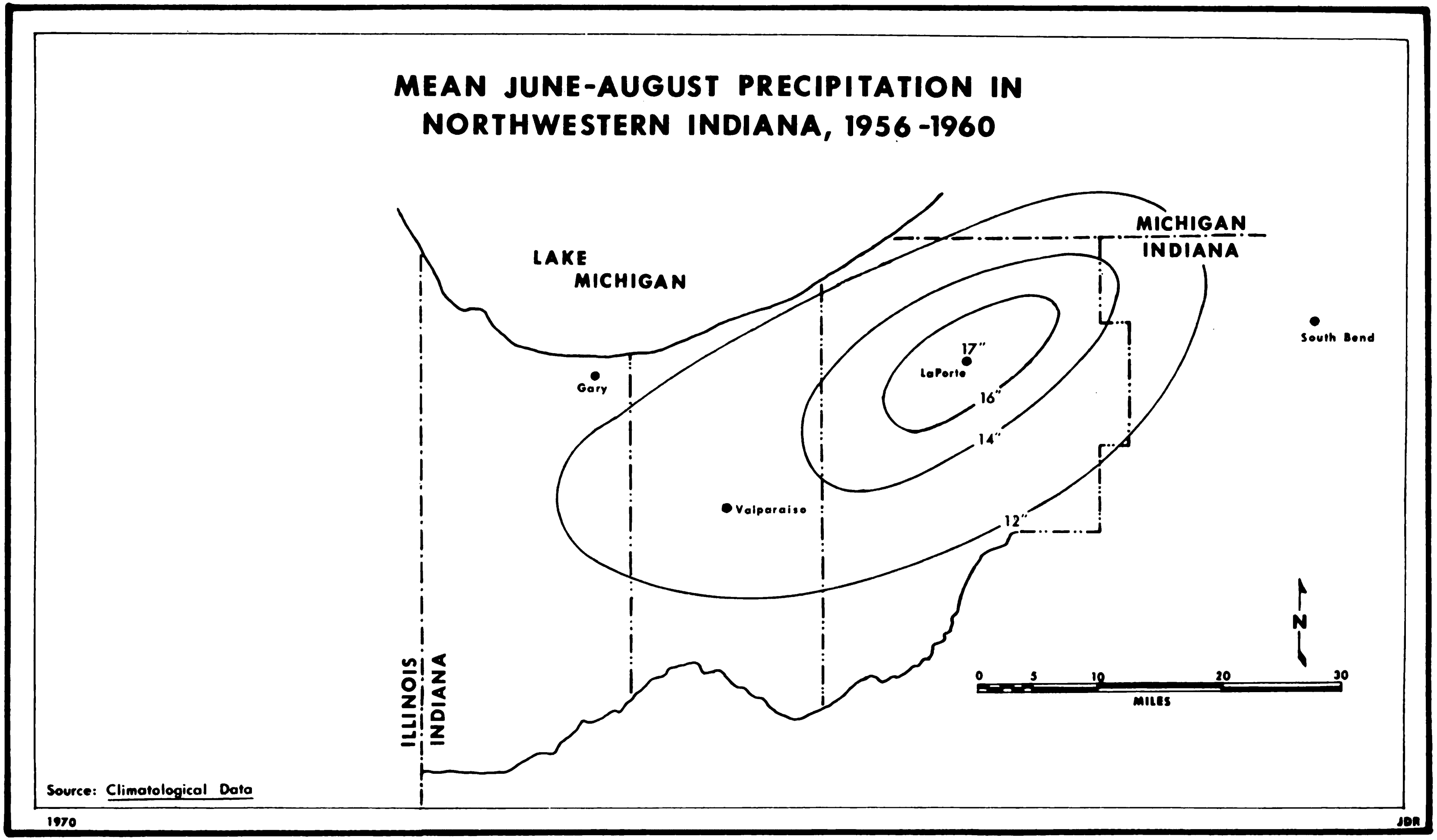
MEAN JUNE-AUGUST PRECIPITATION IN
NORTHWESTERN INDIANA, 1956-1960
LAKE
MICHIGAN
MICHIGAN
INDIANA
ILLINOIS
INDIANA
Gary
Valparaiso
LaPorte
South Bend
17"
16"
14"
12"
N
0
5
10
20
30
MILES
Source: Climatological Data
1970
JDR

FIGURE 1

Contrasting forest types along the Valparaiso moraine in the vicinity of the described rainfall anomaly, however, suggest the long-term presence of an environmental gradient predating heavy industrial air pollution. This moraine, which approximately parallels the shore of Lake Michigan, extends almost through the center of the La Porte rainfall anomaly as mapped by Changnon (Figure 2). The forests at the eastern end of the Indiana portion of the moraine are composed of mesophytic species, predominantly beech (*Fagus grandifolia*) and sugar maple (*Acer saccharum*); those at the western extremity are primarily black oak (*Quercus velutina*), white oak (*Q. alba*), and hickory (*Carya* spp.). In the vicinity of Valparaiso, a sharp transition from one type to the other occurs. Because beech in Indiana is an excellent indicator of mesic conditions while the black oak normally indicates a drier site (5,6), the forest contrast suggests the possible presence of a moisture gradient due to either climatic or edaphic factors. Analysis of the records from the original U. S. land surveys has indicated that this forest contrast existed at the time of European settlement of the area (7,8).

This study has three principal aims. The first of these is to present the results of a forest survey designed to describe the distribution of tree species within the area of the Valparaiso moraine and hence confirm the existence of the contrasting forest types.

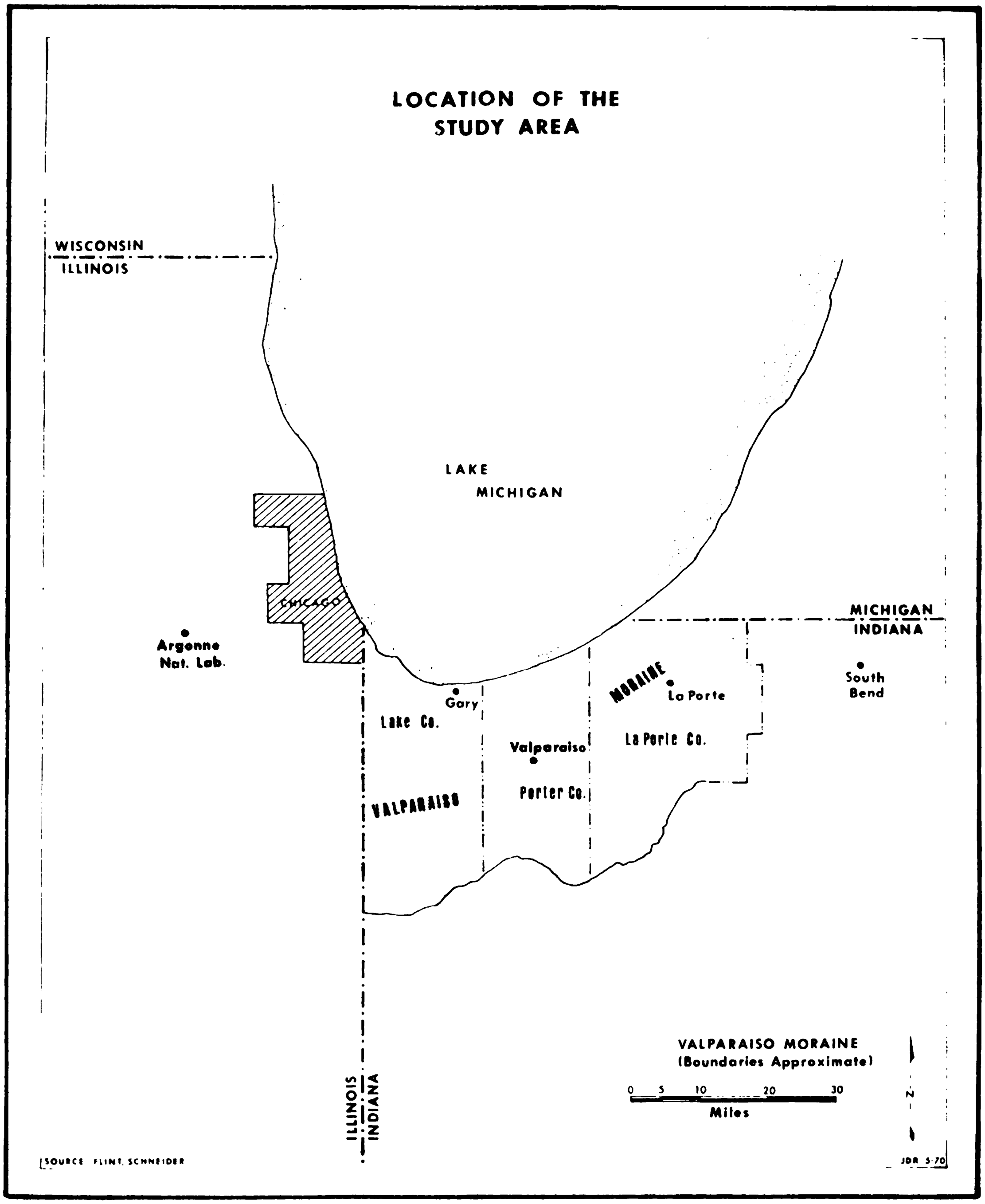
LOCATION OF THE
STUDY AREA
WISCONSIN
ILLINOIS
LAKE
MICHIGAN
CHICAGO
Argonne
Nat. Lab.
MICHIGAN
INDIANA
South
Bend
Gary
Lake Co.
MORAINE
La Porte
La Porte Co.
Valparaiso
Porter Co.
VALPARAISO
ILLINOIS
INDIANA
VALPARAISO MORAINE
(Boundaries Approximate)
0 5 10 20 30
Miles
N
SOURCE FLINT, SCHNEIDER
JDR 5-70

FIGURE 2

Second, the results of a pilot survey of selected subsoil characteristics along the moraine will be presented. The purpose of this part of the investigation is to determine whether variations in the chosen parameters correlate spatially with the forest composition differences and therefore might be causally related to them. The absence of any apparent soil-forest correlations would strengthen the suggestion that some kind of climatic gradient is present.

The third aim is to develop a climatic hypothesis which could help explain the long-term environmental gradient suggested by the observed forest contrast and might shed new light on the La Porte rainfall anomaly, and to assess a research method designed to offer a preliminary test of that hypothesis. The hypothesis is that the La Porte anomaly results in part from spatial variation in the degree of influence exerted upon the local climatology by lake breeze flow from Lake Michigan. Specifically, it is suggested that when the regional wind has a westerly component, a situation which appears to be common in the area during the summer months (9), interaction between the lake breeze and the regional air flow produces a zone of convergence which frequently coincides spatially with both that portion of the Valparaiso moraine supporting a mesophytic forest and the La Porte anomaly. It is believed that augmented vertical air motion within this convergence zone can result in locally increased cloud formation and precipitation.

A preliminary attempt will be made to evaluate the hypothesis using data for wind direction and speed collected at six sites in northwestern Indiana and northeastern Illinois. It is believed that such data will permit detection of the presence of a lake breeze at each station. The data were gathered during the months of June, July, and August, 1969.

The influence of Lake Michigan and the other Great Lakes upon regional and local climatology has long been a subject of investigation. Most early studies focused on the more obvious and easily detectable aspects of lake modification and were primarily descriptive in nature. In particular, lake-induced snowfall and moderation of temperatures received considerable attention.

Brooks (10), in perhaps the earliest study of the snowfall climatology of the region, discussed at length the zones of higher snowfall in the vicinity of the lakes. Dole (11) described the regional pressure gradients which seemed to favor lake snows. More recently, Thomas (12) has reviewed the lake snow literature and the synoptic conditions which are conducive to them, while Changnon (13) has attempted to analyze and map the influence of southern Lake Michigan upon snowfall.

The control exerted by the Lakes on local temperature regimes has received considerable attention because of its economic importance with regard to the location of fruit-growing districts. Odell (14) stated that higher winter minimum temperatures on the lee side of Lake Michigan, which reduce the likelihood of damage to fruit trees, are a major reason for the success of orchards in the area. Olmstead (15) reached a similar conclusion and noted that the lake delays warming of the region in the spring, thus apparently retarding blossoming until the danger of a severe frost is lessened. Leighly (16) described and mapped the impact of the Great Lakes on the annual march of temperatures.

Lake modification of other climatic elements, including cloudiness, frequency of fog, and humidity, has been observed by Odell (14) and Visher (17).

In recent years investigators have become increasingly concerned with the dynamic interaction between the Great Lakes and atmospheric processes that influence the climate over adjacent areas. Particular attention has been given to the warm-season lake breeze circulation.

Studies have shown that the arrival of a lake breeze over an area usually brings a reduction in air temperature, an increase in relative humidity, and supression of convective activity and cumulus formation (18,19). The processes which occur near the inland margin of a lake breeze are quite different, however. Observational and theoretical studies of sea breeze situations have revealed the presence of large vertical velocities resulting from convergence with non-sea breeze air just ahead of these fronts (20,21). Olsson (22) found similar strong upward motion in convergence zones associated with lake breezes in western Michigan. Under certain conditions, such lake breeze convergence zones can produce bands of cumulus clouds and local thunderstorms in the vicinity of southern Lake Michigan. Lyons (23) observed that towering cumuli can form parallel to the Lake's southwestern shore during northwesterly geostrophic winds. Estoque (21), using a mathematical model of sea breeze conditions, found that vertical air movement near a sea breeze front may be especially strong when the geostrophic flow is parallel to the coast with low pressure over the water. Since summer prevailing winds in northern Indiana are southwesterly (9), it appears that the above situation would be relatively common along Lake Michigan's southeastern shore. Thus there is evidence that lake breeze convergence can increase local precipitation and thunderstorm activity and that such convergence could be an important process in the vicinity of the La Porte rainfall anomaly.

Relatively few vegetation studies concerned with northwestern Indiana have been conducted and no known investigations of the forest contrast along the Valparaiso moraine have been made. Shelford (24) considered the area to be ecotonal between beech-maple, maple-basswood, oak-hickory forest types. Braun (25) described the area as a tension zone between the beech-maple and oak-hickory forest regions to the east and west of the study area, respectively, and noted the absence of beech from extreme northwestern Indiana. Cowles (26) concluded that the oak-hickory forests on morainic uplands near Chicago would ultimately be replaced by the beech-maple association which he observed to the north and east near Lake Michigan. However, Diller (27) believed that soil moisture deficiencies in June, resulting from higher temperatures and lower precipitation, restrict the westward extension of beech and sugar maple in northern Indiana. Potzger and Keller (7), using records of the original U. S. land surveys, mapped the occurrence of beech in the presettlement forest cover of northwestern Indiana. Their map indicates that the percentage of beech declined abruptly from east to west in central Porter County within the area of the Valparaiso moraine. Lindsey (28), also working from land survey records, found a tongue of beech-maple forest projecting into La Porte County from southwestern Michigan surrounded by oak-hickory and prairie vegetation.

Few attempts have been made to relate vegetation patterns to climatic modification by Lake Michigan. Quick (29) and Kenoyer (30) observed that certain northern species extend their ranges farther south in Michigan along the Lake Michigan shore than they do farther inland. Potzger and Keller (7) noted that the line of prevailing winds crossing southern Lake Michigan seemed to correspond to the occurrence of beech and other mesophytic species in northwestern Indiana. Finally, Harman (31) examined forest and climatic gradients resulting from lake modification within the zone of sand dunes in southern Michigan and Indiana.

The present study is an initial attempt at evaluation of a possible spatial association between lake breeze flow, the La Porte rainfall anomaly, and forest contrasts along the Valparaiso moraine. It is hoped that it will contribute to further understanding of the climatology and plant geography of the southern Lake Michigan region.

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CHAPTER II

METHODOLOGY

The study area for this project can be generally identified as Lake, Porter, and La Porte Counties, the three Indiana counties which border on Lake Michigan. It is for these counties that the climatic hypothesis was developed and evaluated. With regard to the forest and soil surveys, however, the study area can be more narrowly defined as that portion of the above counties which lies within the Valparaiso morainic system (Figure 3). In the field, published county soil survey maps were used to delimit the morainic area (1,2,3). These maps were completed between 1918 and 1944 and therefore are highly generalized. It was believed, however, that they would be adequate for outlining the area of soils developed from glacial till.

In order to document the forest gradient, a field survey of forested tracts within the Valparaiso morainic area was conducted during August and September of 1969. Since the objective of the survey was to provide data on forest composition and species distribution over a large area rather than to permit complete phytosociological analysis, the detailed sampling techniques commonly used in

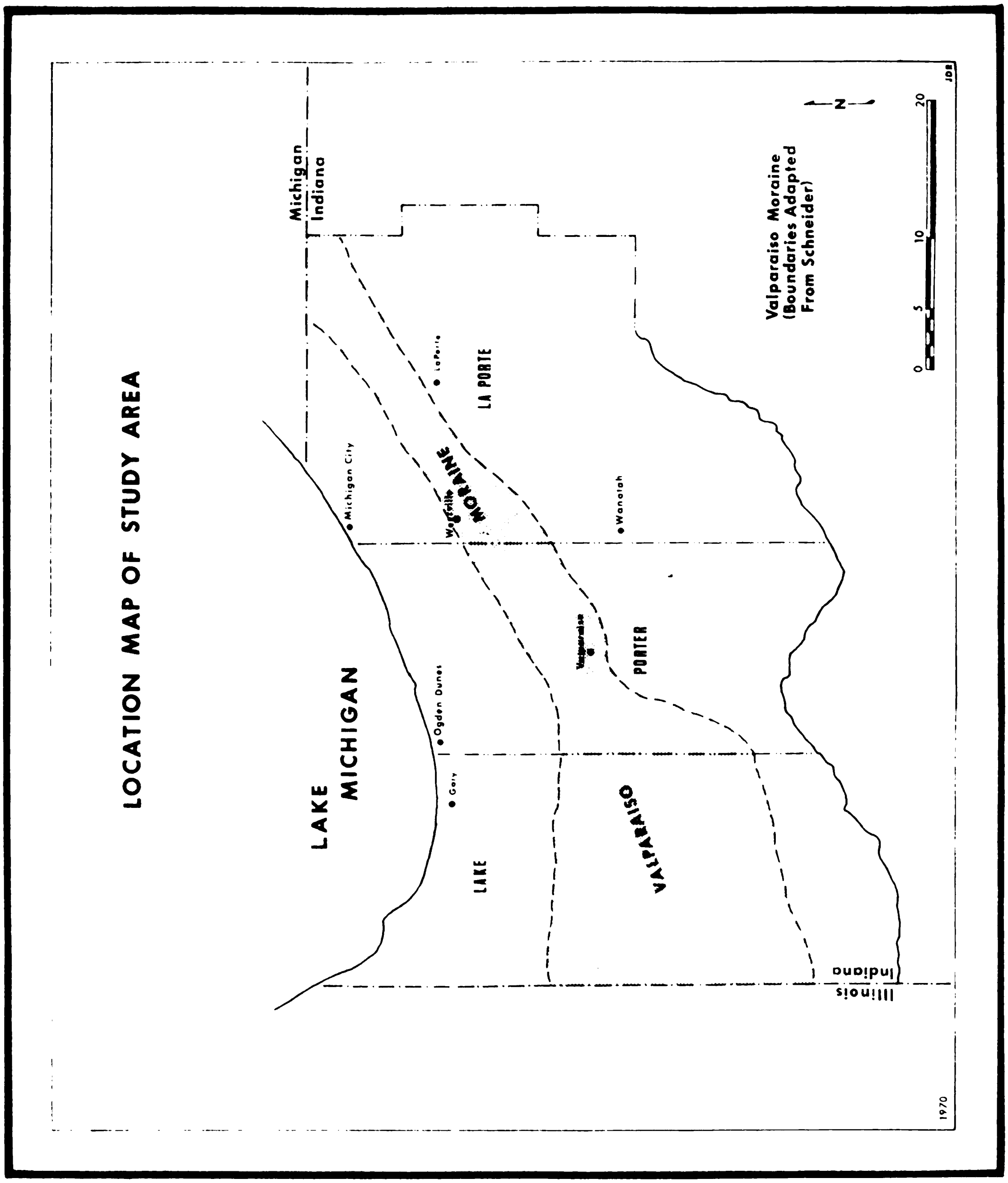
LOCATION MAP OF STUDY AREA
LAKE MICHIGAN
Michigan
Indiana
Michigan City
LaPorte
LA PORTE
MORAINE
Wanatah
PORTER
Ogden Dunes
Gary
LAKE
VALPARAISO
Illinois
Indiana
Valparaiso Moraine
(Boundaries Adapted
From Schneider)
N
0
5
10
20
JDB
1970

FIGURE 3

ecological research were not followed. Instead, a simpler design similar to that employed by Braun (4) and Whittaker (5) was selected.

Within each stand selected for study two square one-half acre plots were marked out. It was found that plots of this size could be established and examined by the investigator without great difficulty. Plots were placed on the most level portions of their respective woodlots at least ten yards from any margin of the stand. Within each plot all living woody stems three inches or more in diameter were counted and recorded by species in order to obtain data on present canopy composition. Cruising of several stands revealed that analysis of two plots, giving a total sample area of one acre, yielded a good estimate of stand composition. In addition, shrub species observed throughout the stand were recorded, as were tree species noted in the stand which did not occur within the study plots. Emphasis was placed on tree species because they are less likely to be influenced by minor degrees of human disturbance than are understory species (6). This method admittedly yields less information than the more frequently used techniques, but it allowed the investigator to survey a large number of woodlots so that the distribution of certain taxa in the study area could be mapped. Taxonomic nomenclature in this investigation follows Gleason (7).

Twenty-six stands were studied within the morainic area (Figure 4). This number was sufficient to allow an analysis of the distribution of selected taxa. Stands were selected for inclusion in the survey on the basis of three criteria. The first of these was stand size; only stands large enough to allow placing the plots ten yards or more from all margins, thus avoiding "edge effect," were included. The smallest woodlot studied was approximately five acres in size. Second, only upland stands on generally level sites were chosen; sites favoring excessive moisture accumulation or depletion were avoided in an attempt to eliminate topography as a variable factor. Locations of stands surveyed are given in Appendix I.

The third criterion, degree of disturbance, was more difficult to assess. All wooded tracts in the study area have been disturbed by human activity to some extent. Stands being considered for inclusion in the survey were evaluated by inspection and in some cases through conversation with the owners. Stands in which old-growth trees were few, or which had clearly been subjected to excessive grazing or cutting, were not used in this study. The problem of disturbance in surveyed stands was anticipated, but it was believed that the forest contrast being examined would stand above any "noise" introduced by this factor.

From the data collected in the forest survey, absolute and relative frequencies of species in the canopy were calculated for each stand. For shrub species, presence lists

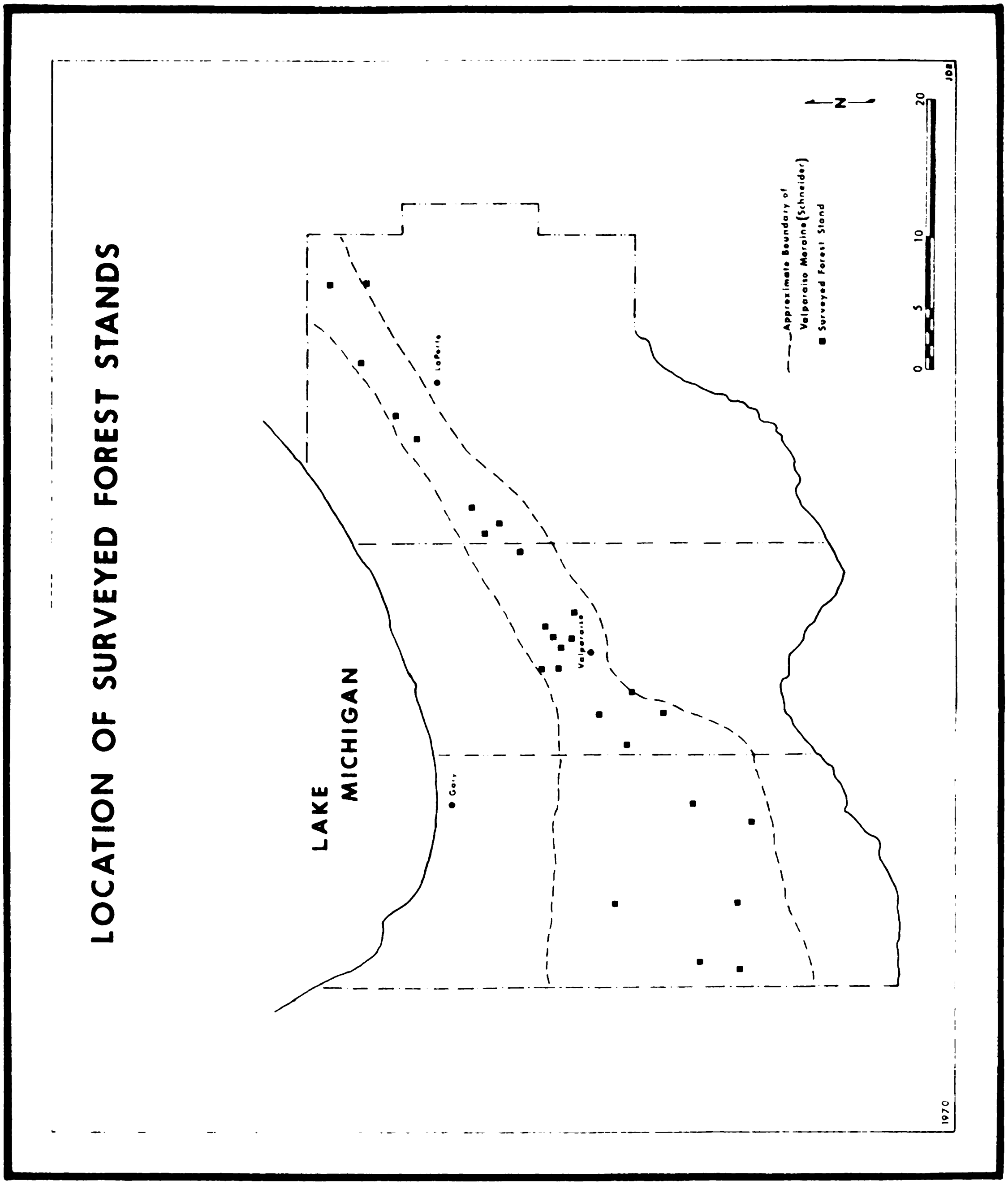
LOCATION OF SURVEYED FOREST STANDS
LAKE MICHIGAN
Gary
LaPorte
Valparaiso
Approximate Boundary of Valparaiso Moraine (Schneider)
Surveyed Forest Stand
N
0
5
10
20
JDB
1970

FIGURE 4

were compiled. In addition, coefficients of similarity as used by Morgan (8) and based on the number of tree species in common were computed for all pairs of stands.

In addition to forest composition data, soil samples were also collected at two locations in each forest stand. All collection sites were on level upland areas within the stands. At each site two samples were taken, one at the depth of apparent maximum clay accumulation in the B horizon and one immediately below a depth of four feet. Samples were gathered with a bucket-type soil auger and placed in plastic bags for return to Michigan State University. Samples taken at the four-foot depth were tested in the field with dilute hydrocholoric acid for the presence of carbonates.

At the University, all samples were analyzed to determine their particle size distributions using the Bouyoucos hydrometer method as described by Day (9), with the following modifications. First, the sand fraction was determined by weighing the material separated out by a sieve with a 74 micron mesh. Second, the silt fraction was determined by subtracting the combined percentages of sand and clay from 100 per cent. Finally, the hydometer readings normally taken at 270 minutes and 720 minutes were replaced by one reading at 480 minutes. The Bouyoucos method has been shown to be sufficiently accurate and detailed for most analyses of forest soils (10). Replication was carried out for approximately one-tenth of the samples; since corresponding results were in close agreement in these cases, no further replication was performed. Soil texture was selected for study because evidence indicates that it is an important property in controlling the available moisture within a soil, possibly the single most important such property (11,12). In addition, pH was determined for each sample using a Beckman meter.

Because the two soil samples at corresponding depths in each stand were found in most cases to be similar in their measured characteristics, they were combined to yield an average stand value for each parameter. Simple correlation coefficients were then calculated between each of these parameters and the percentages of selected species or groups of species in the stand canopy.

In order to evaluate the climatic hypothesis proposed in this study, data regarding wind direction and speed for the period June 11 through August 31, 1969, were collected by a network of six instrument stations in northwestern Indiana and northeastern Illinois (Figure 5). The arrival of a lake breeze at a station is usually marked by a shift in wind direction, a temperature decrease, and an increase in relative humidity (13). Therefore measurements of these parameters could be employed in an attempt to determine the presence or absence of a lake breeze. Previous studies (14,15), however, have indicated that intense heating at

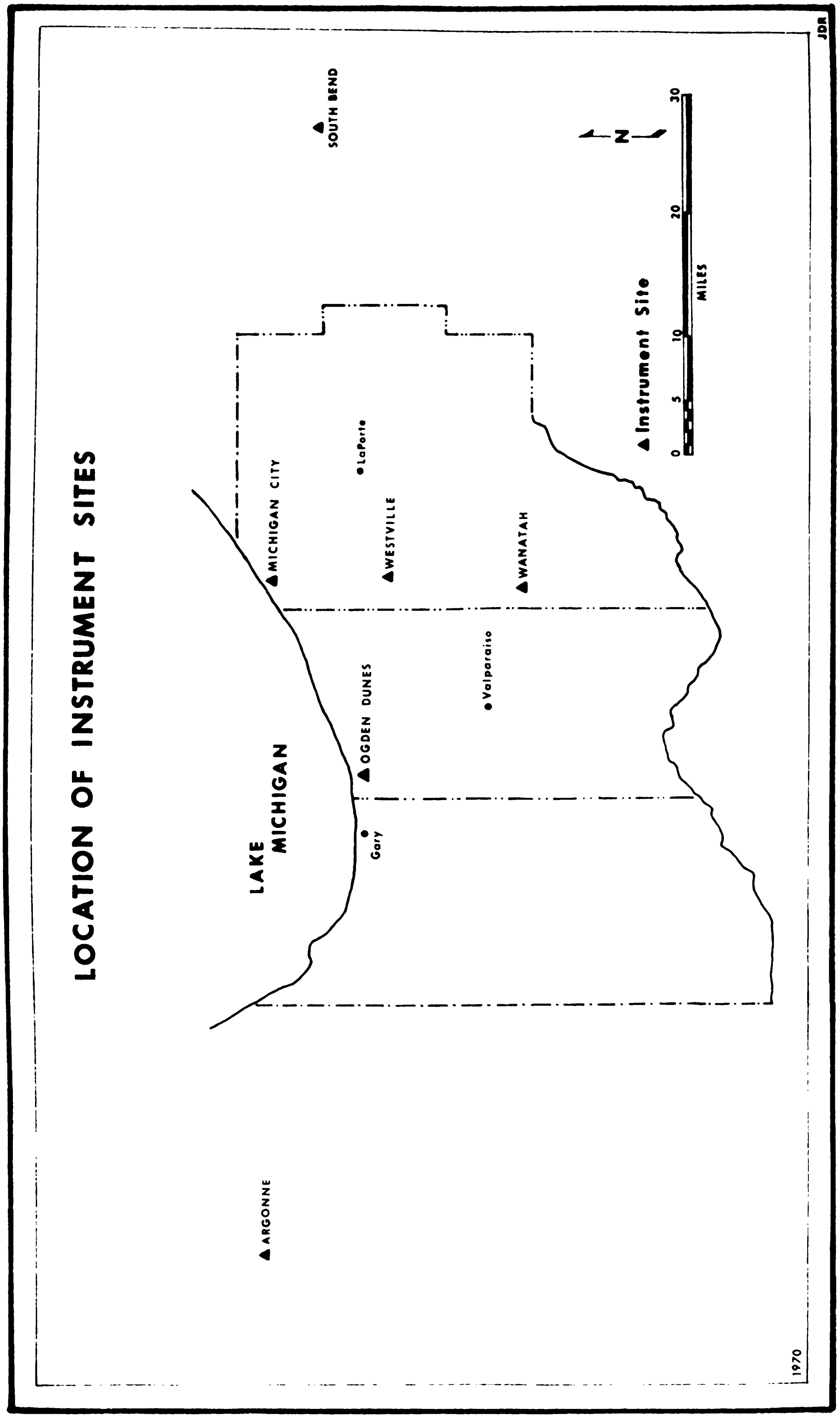
LOCATION OF INSTRUMENT SITES
LAKE MICHIGAN
ARGONNE
Gary
OGDEN DUNES
Valparaiso
MICHIGAN CITY
WESTVILLE
WANATAH
LaPorte
SOUTH BEND
N
Instrument Site
0 5 10 20 30
MILES
1970
JDR

FIGURE 5

the ground may modify the temperature and relative humidity characteristics of lake air as it moves inland, making these parameters less reliable as indicators of lake breeze flow. For these reasons, data regarding wind direction and speed were selected for analysis of lake breeze penetration in the present project.

The instrument site at Westville, Indiana (Figure 5), was established on a temporary basis by the Department of Geography, Michigan State University. A Meteorological Research, Incorporated, automatic weather station, with sensors and recorders for wind direction, wind speed, and temperature, was placed on the roof of the main building at Purdue University's North Central Campus, approximately forty feet above the ground. It was capable of operating for thirty-one days without servicing and was in operation from June 11 to September 10, 1969.

The other five instrument sites (one in Illinois, four in Indiana) are operated by various institutions or individuals as follows: Argonne, Illinois, by Argonne National Laboratory; Ogden Dunes, by Mr. Robert A. Ward, U. S. Weather Bureau cooperating observer; Michigan City, by the Northern Indiana Public Service Company; Wanatah, by the Pinney-Purdue Farm of Purdue University; and South Bend, by the U. S. Weather Bureau. Instruments at these sites are between twenty and forty feet above the ground. Records from these stations were made available to the investigator by the persons or agencies responsible for them.

In addition to differences in the heights of the instruments above the ground, there also was some variation in the type of site. At Ogden Dunes the instrument tower is located on a dune crest among trees only slightly shorter than the tower, while the instrument at Westville was subject to updrafts and eddies caused by the building on which it was situated. The other sites are in generally open areas. This lack of uniformity in instrument situation is recognized; because the study was concerned with the approximate mean position of a boundary between contrasting wind fields, however, it was believed that these differences would not be important.

In keeping with the hypothesis stated in Chapter I, wind analysis was limited to those days on which the regional (non-lake breeze) air flow possessed a westerly component. Those days were identified by examination of data from the Argonne and South Bend stations. All days during the period June 11 through August 31 on which the wind direction at 0700 Eastern Standard Time was from 180° to 360°, inclusive, were accepted initially. The U. S. Weather Bureau's Daily Weather Maps (16) for the study period were examined and days on which fronts passed through northwestern Indiana or the immediate vicinity were eliminated. This was done to avoid confusing wind shifts due to frontal conditions with those due to lake breezes.

Wind direction and speed data were then extracted from the records of all stations for the remaining days. Data were extracted for three times during each day: 1000, 1300, and 1600 EST. These times were selected on the basis of earlier studies. Field investigations on the southwestern (14) and eastern (17) shores of Lake Michigan first detected lake breeze flow between 0930 and 1030. Thus data for 1000 should represent the early stages of lake breeze development. Moroz and Hewson (17), working on the Lake's eastern shore, reported that maximum lake breeze penetration was attained sometime after 1500; Olsson (18), in the same area, found that this stage was reached about 1830. Therefore data for 1600 should describe the lake breeze near its maximum development. Data were also extracted for the intermediate time of 1300.

In the process of extracting these data, days for which there was evidence of lake breeze development at the Michigan City station were recorded. A shift of the wind during the day which resulted in an increased northerly component, followed later by a shift back to approximately the early morning direction, was accepted as evidence of lake breeze influence. These days were cross-checked against data from Argonne to ensure that the shift was not a regional event. Twenty-two such days were identified. Collectively, these lake breeze days constituted the intensive study period.

In order to graphically portray the frequency of lake breezes throughout the study area, wind roses were prepared. A wind rose indicates, for some locality, the proportion of winds blowing from each major compass direction over a specified period of time (19). Wind roses were selected over the resultant wind technique because they reveal the variability of the wind during the study period and are perhaps more easily interpreted as well. They do not incorporate the relative strengths of winds from various directions; however, variations in wind speed with direction were not expected to be marked in this study.

Tables were prepared indicating the number of days on which the wind was blowing from each of sixteen compass directions at 1000, at 1300, and at 1600 for each of the six stations. Finally, a sixteen point wind rose was drawn for each station and each hour (except for Ogden Dunes, where wind direction was recorded using only eight points). Placed on a map, the roses illustrate the spatial variation of wind direction in northwestern Indiana on the identified lake breeze days.

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CHAPTER III

THE PLANT GEOGRAPHY

Physical Setting

The study area for this project lies within the three northwestern counties of Indiana which border on Lake Michigan: Lake, Porter, and La Porte Counties (Figure 3). The region is located between 41 degrees and 42 degrees north latitude and between 86°30' and 87°30' west longitude.

The topographic features of northwestern Indiana are the product of Pleistocene glaciation and associated fluvial and lacustrine processes. The region was glaciated during the Wisconsin glacial stage and consists of three physiographic units (1). The Valparaiso Morainal Area, which is the study area for the forest survey, extends through the three counties from northeast to southwest approximately five to ten miles inland from Lake Michigan. To the north, between the moraine and the Lake, lies the Calumet Lacustrine Plain, and to the south the Kankakee Outwash and Lacustrine Plain. In La Porte County, the morainic area consists of a single belt averaging approximately eight miles in width; westward from there it widens to twelve or thirteen miles and loses its single-ridge character (2). In Lake County

and western Porter County, the northernmost portion of the Valparaiso Morainal Area may actually represent the superimposed Tinley moraine (3) which is recognized as a distinct morainic unit in Illinois (4). According to Schneider (3), however, there are no demonstrable textural or lithological differences between Tinley and Valparaiso till in Indiana. Drift thicknesses within the morainic area range from less than 150 feet to more than 250 feet (2), with perhaps 65 feet belonging to the Valparaiso moraine proper (5).

Elevations in the morainic area range from approximately 650 feet to over 950 feet above sea level (6), thus rising to a maximum of about 370 feet above the level of Lake Michigan. Maximum elevations decline from northeast to southwest. The Valparaiso moraine forms the divide between the Great Lakes and Mississippi River drainage systems.

Soils in the morainic area vary widely in texture with the most prevalent types being the medium to moderately fine textured members of the Galena and Morley catenas (7,8, 9,10). In the western one-third of the area dark-colored soils developed under grassland vegetation occur interspersed with the lighter forest soils.

Northwestern Indiana has a temperate continental climate designated Dfa according to the Koppen classification (11). Summers are warm with a mean July temperature of approximately 73°F; winters are cold, January having a mean temperature of about 25°F. The mean annual temperature is approximately 49°F. Annual precipitation in the western half of the study area averages 34 to 35 inches with about 20 inches falling during the warm season (April through September) (12), while the 1931-1960 average at La Porte was about 50 inches with 29 inches falling in the warm season (13). Snowfall ranges from less than 40 inches in Lake County to over 60 inches in northeastern La Porte County (14). The prevailing wind is from the southwest during the summer and the northwest in the winter (12).

Local climate is the result of several interacting controls. For the region which includes the study area, two of these controls deserve particular attention (15). Largely because of the barrier effect of the Rocky Mountain system, westerly air flow at middle and upper tropospheric levels over North America often assumes a wave pattern which may remain nearly stationary for long periods of time. The typical spacing of these waves results in a mean upper level trough overlying the eastern United States; this condition favors surface cyclogenesis and the advection of air masses into the region. In addition, the absence of major east-west topographic barriers in eastern North America permits air masses advected from the Gulf of Mexico and the Artic area to arrive in relatively unmodified condition, thus further augmenting cyclogenesis. These factors result in the highly variable climate of the eastern

United States. For further discussion of the climate of the region see Trewartha (15) and Visher (12).

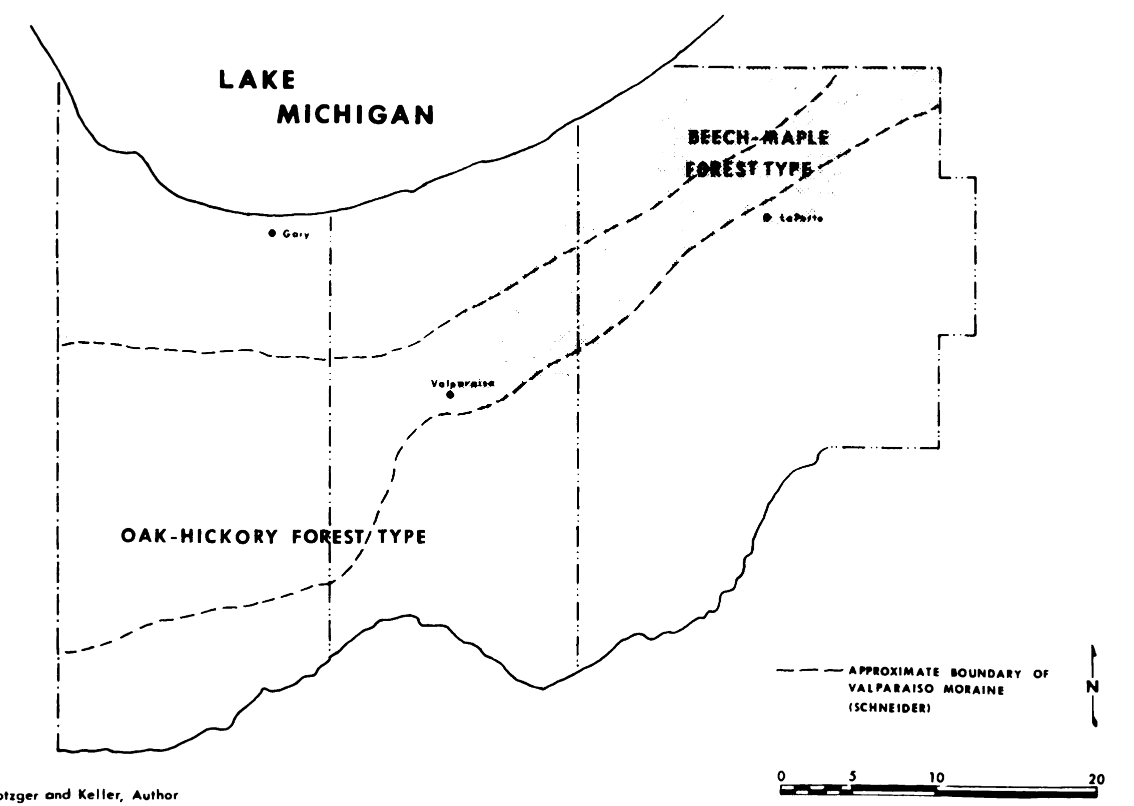
Review of the Literature

Northwestern Indiana is a region of transition between several vegetation types. Braun (16) described the area as a tension zone between the beech-maple forest region, which occupies most of central and eastern Indiana as well as southwestern Michigan, and the oak-hickory region of Illinois and western Indiana. Shelford (17) characterized the area as ecotonal between the beech-maple, maple-basswood, and oak-hickory forest types. In addition, prairie vegetation occurred in northern Indiana, notably on the sandy soils of the Kankakee Outwash and Lacustrine Plain (16,18). For a complete review of the literature concerning the vegetation of the entire state of Indiana see Petty and Jackson (19).

The most conspicuous feature of the plant geography of northwestern Indiana is a peninsula of mesophytic species, particularly *Fagus grandifolia* (beech) and *Acer saccharum* (sugar maple), which extends southwestward from Michigan along the Valparaiso moraine. This projection is surrounded on three sides by forests in which *Quercus velutina* (black oak), *Q. alba* (white oak), and *Q. macrocarpa* (bur oak) predominate (Figure 6).

No known studies which specifically discuss the forest contrast along the Valparaiso moraine have been made.

GENERAL FOREST DISTRIBUTION OF NORTHWESTERN INDIANA



Source: Potzger and Keller, Author
1970

FIGURE 6

Several investigations covering larger regions which include the morainic area have been conducted, however. Cowles (20,21) observed that morainic hills in the vicinity of Chicago supported forests of Quercus alba, Q. borealis (red oak), Q. macrocarpa, and species of Carya (hickory), while those both north and east of Chicago were occupied by beech-maple forests. He believed that the beech-maple type ultimately would develop in the Chicago area as well. Shreve (22) placed northwestern Indiana in a grassland-deciduous forest transition zone and stated that Quercus macrocarpa, Q. velutina, and Q. alba were the most common tree species. The change in forest composition on morainic uplands between Indiana and Illinois was also noted by Fuller (23); like Cowles, he considered the beech-maple forest to the east to be the true regional climax on such sites. Gordon (24), having mapped Indiana vegetation by reconnaissance survey, found a peninsula of beech-maple forest projecting from northwestern La Porte County to the Porter County boundary through an area otherwise supporting oak-hickory forest. Braun (16) mapped the boundary between the beech-maple and oak-hickory forest regions as cutting across the Valparaiso moraine near the midpoint of its Indiana segment but indicated that the transitional nature of the area made the placement of a boundary line quite arbitrary. Kuchler's map (25) of potential natural vegetation indicated a peninsula of beech-maple forest projecting into La Porte County from Michigan and giving way on the southwest to oak-hickory forest.

Studies by Potzger and others (26,27), based on analyses of original land survey records, have suggested that the peninsula of mesophytic species in northwestern Indiana existed prior to major European settlement of the region. Their investigation indicated an abrupt transition, near the present location of Valparaiso, from forests dominated by *Fagus grandifolia* and *Acer saccharum* on the east to those in which *Quercus velutina* and *Q. alba* predominate. Rohr and Potzger (28) found that the presettlement vegetation of Lake County consisted of open oak-hickory forest intermingled with areas of prairie. Lindsey and others (29,30), working with the original survey notes and county soil maps, attempted to correlate pre-settlement vegetation types with major well drained soil types. Their results also indicated a peninsula of beech-maple forest projecting southwestward from Michigan along the Valparaiso moraine; however, they concluded that this forest type extended only into northeastern La Porte County before being replaced by oak-hickory forests. Meyer (31) also used survey records to map broad categories of vegetation; the Valparaiso morainic area was classified as supporting broadleaved forest.

Potzger and others (26,32) have found that *Fagus grandifolia* is normally a sensitive indicator of mesic conditions in Indiana while *Quercus velutina* is an excellent indicator of dry site conditions. Rohr and Potzger (28) have suggested that the westward replacement of *Fagus grandifolia* and *Acer saccharum* by oaks and hickories in northwestern Indiana indicates that some climatic or edaphic factor is operating to produce drier site conditions toward the west. They also reported, as did Finley and Potzger (33), that microclimatic variations allow beech and sugar maple to exist in only isolated stands west of the main mesophytic association and suggested that this further implies a progressive habitat change from east to west.

The sequence of postglacial migration of forest species into northern Indiana is not entirely clear. There is general agreement that spruce-fir forests occupied the newly deglaciated areas early and persisted until approximately 8000 years ago (34,35,36). Working in southwestern Michigan, Zumberge and Potzger (37) concluded that a pine stage followed the spruce-fir period and lasted until 6000 years before the present. Then followed a period in which oaks increased in importance, with an oak-hemlock-broadleaved forest stage about 4000 years ago and an oak-hickory maximum (the xerothermic period) about 3500 years before the present. This general scheme is supported by the findings of Guennel (38) and Just (36). Potzger (39) reported that pollen studies indicated beech invaded northern Indiana later than it did Michigan, a difference Benninghoff (40) attributed to the blocking of migration from the south by an early postglacial prairie peninsula. He concluded that beech arrived in Michigan from the east and pointed out that this species first appeared or attained a strong position in the prairie peninsula region during the oak-hickory stage, a fact which is not consistent with the interpretation of that period as a dry xerothermic interval. Thus the beech forests of northern Indiana are in places no more than 3000 years old, according to Benninghoff. Potzger and Freisner (41), on the other hand, believed that the area occupied by beech has recently been decreasing.

Although agreement on details has not yet been attained, it is clear that climate and vegetation patterns in the north central states have undergone fluctuations since deglaciation of the area. The possibility that existing species distributions are not completely adjusted to the present climatic conditions must therefore be considered.

Forest Composition

Twenty-six forest stands were examined in the study area during August and September, 1969, to determine the local distribution of forest types in the study area. Twenty-five overstory species were identified in the surveyed stands. No attempt was made to distinguish *Acer nigrum* from *A. saccharum* because of the difficulty of classifying intermediate forms. This procedure is not without precedent in ecological studies (42) since the two species have similar site requirements (43). Also, Carya ovalis was not separated from Carya glabra. Harlow and Harrar (44) have indicated that such separation is generally not made except by taxonomists because of similar morphological and ecological characteristics. In addition to the canopy species, twenty shrub species were recorded. For three of these, individuals large enough to be included in the tree survey were encountered; therefore they were recorded as both canopy and shrub species.

Table 1 indicates the per cent contribution of all species to the canopy of each stand (values to the nearest 1%). The stands are numbered consecutively from northeast to southwest through the morainic area; therefore the table also indicates the geographic distribution of the species within that area. The first four species in the table, Fagus grandifolia, Acer saccharum, Tilia americana (basswood), and Liriodendron Tulipifera (tulip-tree), are important mesophytic species. These are followed by five species which generally occur on drier sites: Carya ovata (shagbark hickory), C. glabra (pignut hickory), Quercus alba, Q. velutina, and Q. macrocarpa. The remaining species are listed alphabetically. Table 2 indicates the occurrence of shrub species in the surveyed stands.

Examination of the first nine species presented in Table 1 reveals an abrupt change in forest composition between stands 13 and 14. East of that location (stands 1

TABLE 1.--Per Cent Contributions of All Tree Species* to Stand Canopies.

Species	Stand Number																									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Fagus grandifolia	27	45	22	18	4	7	7	53	10	23	32	42	11													
Acer saccharum	65	34	5		40	21	3	5	49	61	15	25	16			3										
Tilia americana	2	6			14	37	16	4	7	3	16	5	5												1	
Liriodendron Tulipifera			1		7		19				7	2														
Carya ovata				3	1	1		15			7		15	2	3	1	41	16		1	51	27	2	4	12	10
Carya glabra														2	4	1	16	3	13		9					
Quercus alba			18	9				1			1	6	1	58	30	31	23	50	21	54	32	11	65	64	45	25
Quercus velutina			31	7										28	33	16	8	21	52	10	1	5	6	8	18	7
Quercus macrocarpa																				7	4	22	7	1		19
Acer rubrum			4	6										2	3	4										
Asimina triloba		8							1																	
Carpinus caroliniana				1			3	1	2				1													
Carya cordiformis			1	7	1	2	1		1				19									2	1			
Celtis occidentalis																						2				
Cornus florida			5	1																						
Crataegus spp.									1					1	4				1			2			2	
Fraxinus americana	5		1	3	3	19	22	11		5	5	1	7			1		7			4			1	9	1
Juglans cinerea													3													
Juglans nigra						1																				
Ostrya virginiana		1			4	3	7	4	7	1	3	5	21													
Prunus serotina		1	3	21	2	1	10	2	1			9		2	23	4	10	2		20		30	18	12	9	28
Quercus borealis			2	10	1	3	5	5			11	1	1	5		37		3	12				2	11	2	
Sassafras albidum			8	14	1							2	1		3					1						
Ulmus americana		1		1	1	2			1	3		1					1									
Ulmus rubra	1	4		1	19	5	7	3	19	3		3	1			1										

TABLE 2.--Occurrence of Shrub Species* in Surveyed Stands.

Species	Stand Number																									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Asimina triloba	X	X			X	X		X	X	X			X													
Cornus alternifolia						X			X				X													
Cornus florida			X	X												X										
Cornus racemosa				X										X	X	X				X	X	X	X	X	X	X
Corylus americana																	X	X		X	X		X	X		X
Crataegus spp.				X			X		X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
Hammamelis virginiana	X										X															
Lindera benzoin	X	X	X		X	X	X	X	X	X	X	X	X	X												
Mitchella repens				X																						
Parthenocissus spp.			X		X	X	X	X	X	X	X			X	X		X	X		X	X	X			X	
Prunus virginiana																	X				X	X	X	X		X
Rhus glabra																				X			X			
Ribes Cynosbati				X	X																					
Rubus spp.	X						X							X	X		X	X	X	X	X	X	X	X		X
Sambucus canadensis														X												X
Smilax rotundifolia			X																							
Staphylea trifolia						X																				
Viburnum acerifolium			X	X																						
Viburnum Lentago														X	X					X					X	X
Vitis spp.																						X				

*Living woody stems less than 3 inches in diameter.

through 13), the four selected mesophytic species accounted for 45% or more of the canopy in all but three stands. To the west (stands 14 through 26) these species were infrequently encountered, with the five oaks and hickories contributing 49% or more of the canopy in each stand.

These data suggest the presence of two distinct forest types represented by stands 1 through 13 and 14 through 26, respectively. The remaining sixteen species in Table 1 offer further evidence to support this suggestion. _Asimina triloba_ (papaw), _Carpinus caroliniana_ (blue beech), _Ostrya virginiana_ (ironwood), and the two elms, _Ulmus americana_ and _U. rubra_, were essentially restricted to the mesic eastern part of the study area; the hawthorns, _Crataegus_ spp., were found primarily in the western stands dominated by oak and hickory. _Prunus serotina_ (black cherry) and _Quercus borealis_ (red oak), on the other hand, were more nearly ubiquitous.

Fagus grandifolia appears to be the best indicator species for the mesic forest type, since it occurred in all thirteen eastern stands and was restricted to them. _Quercus velutina_ is perhaps the best indicator of the more xeric oak and hickory stands; it was found in all thirteen western stands and was absent from all but two of those containing beech. These findings are in agreement with the conclusions reached by Potzger and others (26,32) regarding the best arboreal indicators of mesic and drier

site conditions in Indiana. Because *Acer saccharum* was associated with beech in all but one of the mesophytic stands, the forest cover of the eastern part of the study area is considered to be a beech-maple type. The forest type represented by the thirteen western stands is designated oak-hickory.

From Table 2 it is evident that the distributions of a number of shrub species reflect the change in canopy composition. *Asimina triloba*, *Cornus alternifolia*, *Lindera benzoin*, and other less common species were found almost exclusively in beech-maple stands, while *Cornus racemosa*, *Corylus americana*, *Prunus virginiana*, and *Vibernum Lentago* were nearly restricted to oak-hickory stands.

In order to further indicate the degree of compositional contrast between the two forest types, coefficients of similarity (45) were computed for all pairs of stands. The coefficient is based on the number of canopy species two stands have in common and ranges in value from 0 (no common species) to 100 (species composition identical). The coefficients for all pairs involving only the thirteen beech-maple stands were averaged to yield a mean coefficient for that forest type. The same procedure was followed for the oak-hickory stands. Finally, the coefficients for all pairs of stands of contrasting forest type were averaged. Table 3 presents the results. This coefficient probably underestimates compositional differences because it gives no weight to the importance of each species in terms of its relative density or its contribution to the total basal area of the stand. Nevertheless the mean coefficient of similarity between differing stand types is markedly less than the means between stands of the same type.

TABLE 3.--Mean Coefficients of Similarity Between Beech-maple, Oak-hickory, and Contrasting Stands.

Stands	Mean Coefficient
Beech-maple stands	63.0
Oak-hickory stands	63.5
Contrasting stands	29.5

In Figure 7 the contributions (in per cent) to each stand of two groups of species have been graphed against approximate stand location along a northeast-southwest transect within the Valparaiso morainic area from the Michigan state line to the Illinois border. The two groups of species are (1) the four mesophytic species presented first in Table 1 (*Fagus grandifolia*, *Acer saccharum*, *Tilia americana*, *Liriodendron Tulipifera*) and (2) the hickories and oaks which followed the above species in that table (*Carya ovata*, *C. glabra*, *Quercus alba*, *Q. velutina*, *Q. macrocarpa*). The graph illustrates the basic segregation of the two species groups and the abrupt shifting of predominance from one to the other.

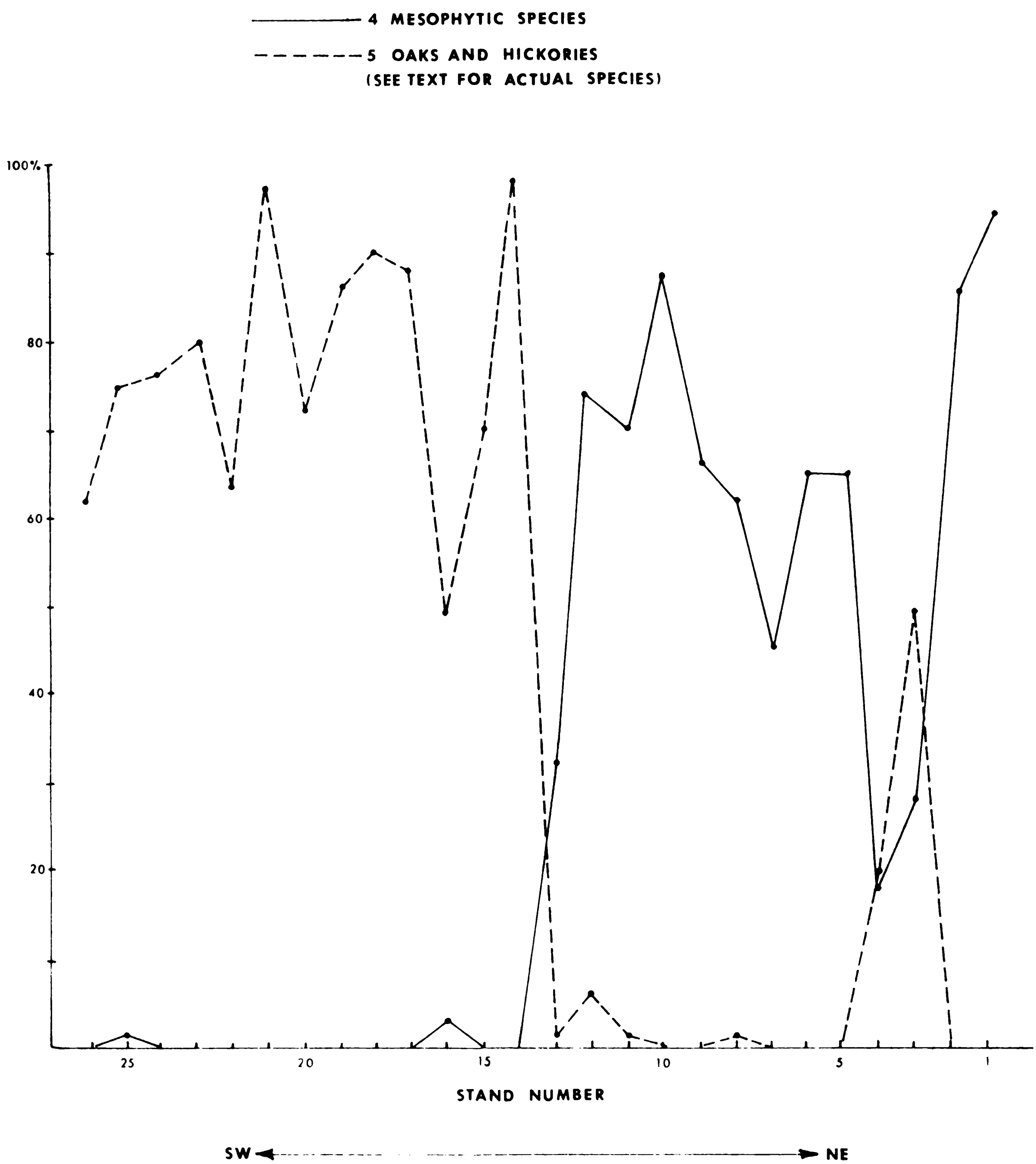


FIGURE 7
PER CENT CONTRIBUTION OF TWO SPECIES GROUPS TO STAND CANOPIES

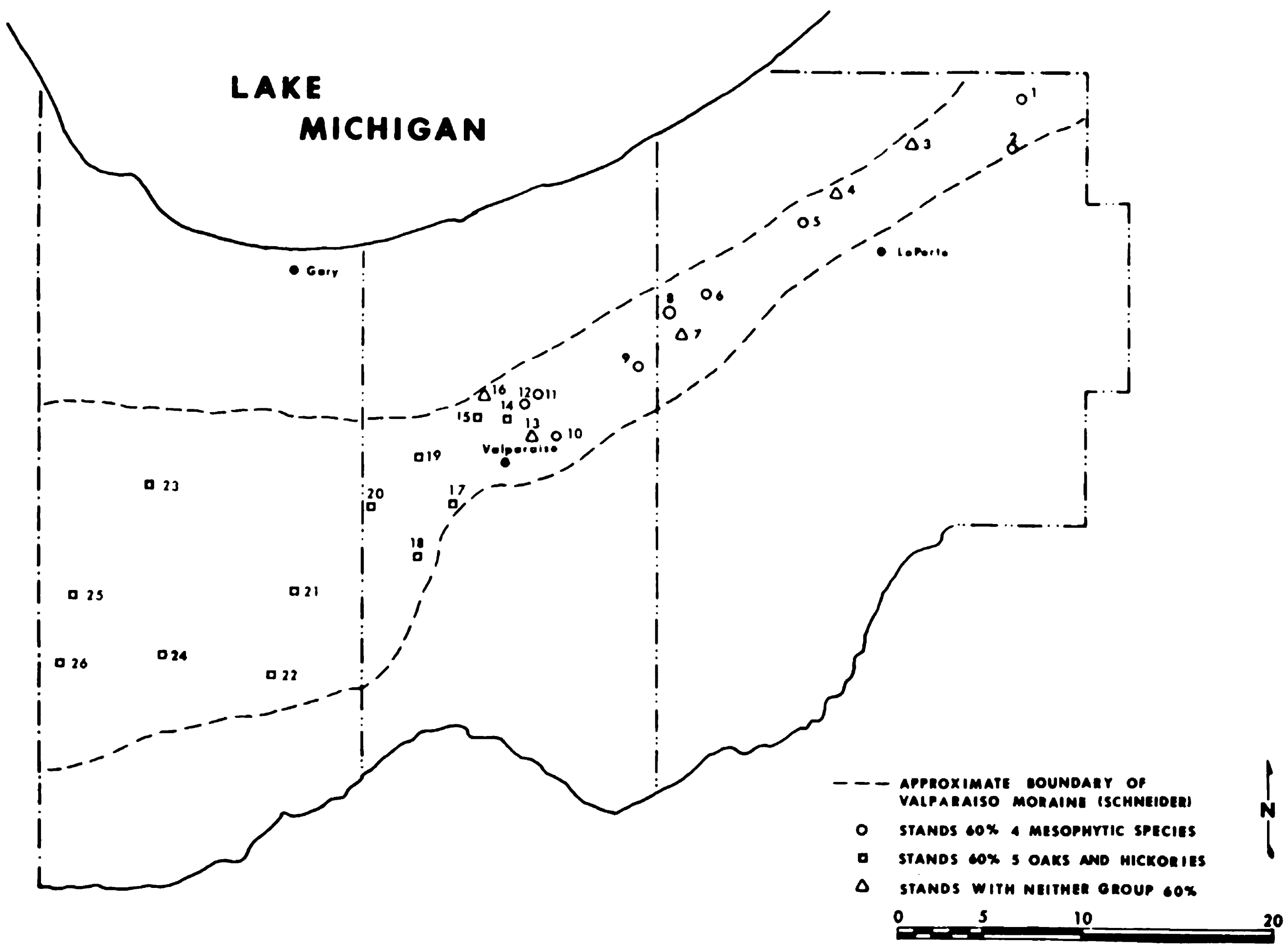
Figure 8 indicates the spatial distribution of the forest types. Stands have been classified into three groups, each represented by a different symbol: (1) those in which the four mesophytic species contributed 60% or more of the canopy stems; (2) those in which the five oak and hickory species accounted for 60% or more of the stems; and (3) those in which neither group predominated. It is apparent that the transition from one forest type to the other lay in the vicinity of the city of Valparaiso.

Table 4 presents two additional measures of comparison between the beech-maple and the oak-hickory stands. The average number of trees per acre was greater in the thirteen mesophytic stands of the eastern part of the study area. In addition, the total number of species observed (including both tree and shrub species) was greater for the beech-maple stands than for those dominated by oaks and hickories. Similar contrasts in density and compositional diversity were observed by Harman (46) between dune forests in southern Michigan and in Indiana.

TABLE 4.--Two Measures of Comparison Between Forest Types.

Forest Type	Trees/acre	Number of species
Beech-maple	144	38
Oak-hickory	96	28

CONTRIBUTION OF TWO SPECIES GROUPS TO FOREST STANDS



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Since studies by Potzger and others (26,27) have suggested that the distribution of forest types at the time of the U. S. land surveys (about 1800-1830) was similar to that described here, it appears that the forest contrast is the result of an environmental gradient and has not been produced by varying land-use practices.

The possible ecological importance of fire in the study area should also be considered. Fires apparently were frequent in the prairie areas of the central United States prior to European settlement (18). Ward (47), working in Wisconsin, concluded that fires were important in controlling the western limits of several mesophytic tree species, including *Acer saccharum*. He suggested that the abrupt rather than gradual elimination of these species to the west and their replacement by *Quercus macrocarpa* was the result of more frequent burning. Thus the possible role of fires from nearby prairie areas in influencing species distribution within the study area should not be overlooked. A critical evaluation of the probable importance of fires is beyond the scope of this project. It can be pointed out, however, that no evidence has been found suggesting invasion of one forest type by the other since the original surveys. It seems likely that regional differences in the frequency of fires have been eliminated since European settlement. No evidence of recent burning was observed in the stands surveyed. These considerations seem to suggest that fires did not play a major role in establishing the forest gradient.

Soil Patterns

The predominant forest soil of Lake County is the Morley silt loam (7,48). This soil has developed on a silty clay loam parent material and is leached to a depth of less than 40 inches. In La Porte County Galena silt loam is the most extensive upland soil (9); it is generally similar to Morley in texture but is more deeply leached. This soil is most widespread northeast of the city of La Porte; in the western part of the county, coarser soils, including the Hillsdale and Chelsea series, are interspersed with it. Soils of the moraine in Porter County appear to be primarily of the Morley and Galena series (8,10), although there is some uncertainty due to the lack of a modern soils map. According to Soils of the North Central Region of the United States (49), the portion of the moraine west of Valparaiso is characterized by relatively fine textured soils. From Valparaiso east to La Porte medium textured soils occur, while northeast of La Porte coarser soils predominate. At the northeastern end of the Indiana portion of the moraine a small area of finer textured soils similar to those in Lake County projects southward from Michigan. This general pattern is supported by the findings of Krumbein (5); he observed that the Valparaiso till is clayey west of Valparaiso and northeast of La Porte, but is considerably more sandy between.

Textural analyses were made of soil samples from each stand in order to identify any pattern of soil texture which might agree with the distribution of forest types. Two samples were taken in each stand and their analysis results averaged. Table 5 presents the average percentages of sand, silt, and clay for each stand. The values for individual samples are given in Appendix III.

In Figure 9 average percentages of sand, silt, and clay in the B horizon are graphed according to stand location, and Figure 10 is similar but represents the texture at a depth of four feet. In both diagrams, a general decrease in the sand percentage from east to west is apparent. There is also a trend toward higher clay percentages in the same direction, although this is less conspicuous at the four-foot depth than in the B horizon. The silt fraction of the B horizon displays no clear trend along the transect; there appears to be a slight tendency toward higher silt content to the west at a depth of four feet, however. Thus a gradient of soil texture within the Valparaiso morainic area is suggested.

Table 6 presents simple correlation coefficients between five species or groups of species and the percentages of sand, silt, and clay at the two depths graphed in Figures 9 and 10 (in the horizon of maximum clay enrichment and at four feet). The four mesophytic species and the oak-hickory group are the same as used in Figure 7. For

TABLE 5.--Average Percentages of Sand, Silt, and Clay in Soil Samples from Surveyed Forest Stands.

Stand No.	B Horizon			Four-Foot Depth		
	Sand	Silt	Clay	Sand	Silt	Clay
1	22.6	43.4	34.0	41.9	34.8	23.2
2	51.8	32.2	16.0	43.6	36.4	20.0
3	79.2	17.8	3.1	94.2	3.0	2.8
4	43.7	30.6	25.6	47.2	23.9	28.9
5	40.2	40.8	18.7	42.4	31.4	26.2
6	11.2	52.8	36.0	20.7	49.8	29.5
7	23.4	45.2	31.3	18.5	48.5	33.0
8	26.4	47.2	26.4	51.3	25.2	23.6
9	20.5	49.0	30.5	17.3	46.4	36.2
10	27.2	39.2	33.6	35.0	37.8	27.1
11	51.3	25.2	23.5	26.5	43.9	29.6
12	28.3	44.0	27.7	22.6	42.0	35.3
13	34.7	38.2	27.1	35.8	39.6	24.6
14	20.8	48.0	31.2	26.0	47.0	27.0
15	16.2	50.4	33.3	14.4	52.7	33.0
16	17.8	47.8	34.4	20.6	53.4	26.0
17	25.4	41.4	33.2	29.8	41.0	29.2
18	16.6	41.4	41.9	26.2	46.2	27.6
19	39.0	36.6	24.4	57.6	24.6	17.8
20	11.2	48.5	40.4	14.6	57.7	27.8
21	21.0	38.8	40.2	16.0	51.0	33.0
22	15.2	41.2	43.6	38.0	35.7	26.3
23	2.2	47.4	50.4	4.0	61.8	34.2
24	13.0	36.9	50.1	13.6	46.0	40.5
25	4.0	34.6	61.4	13.2	46.4	40.4
26	24.5	35.9	39.6	22.9	44.0	33.2

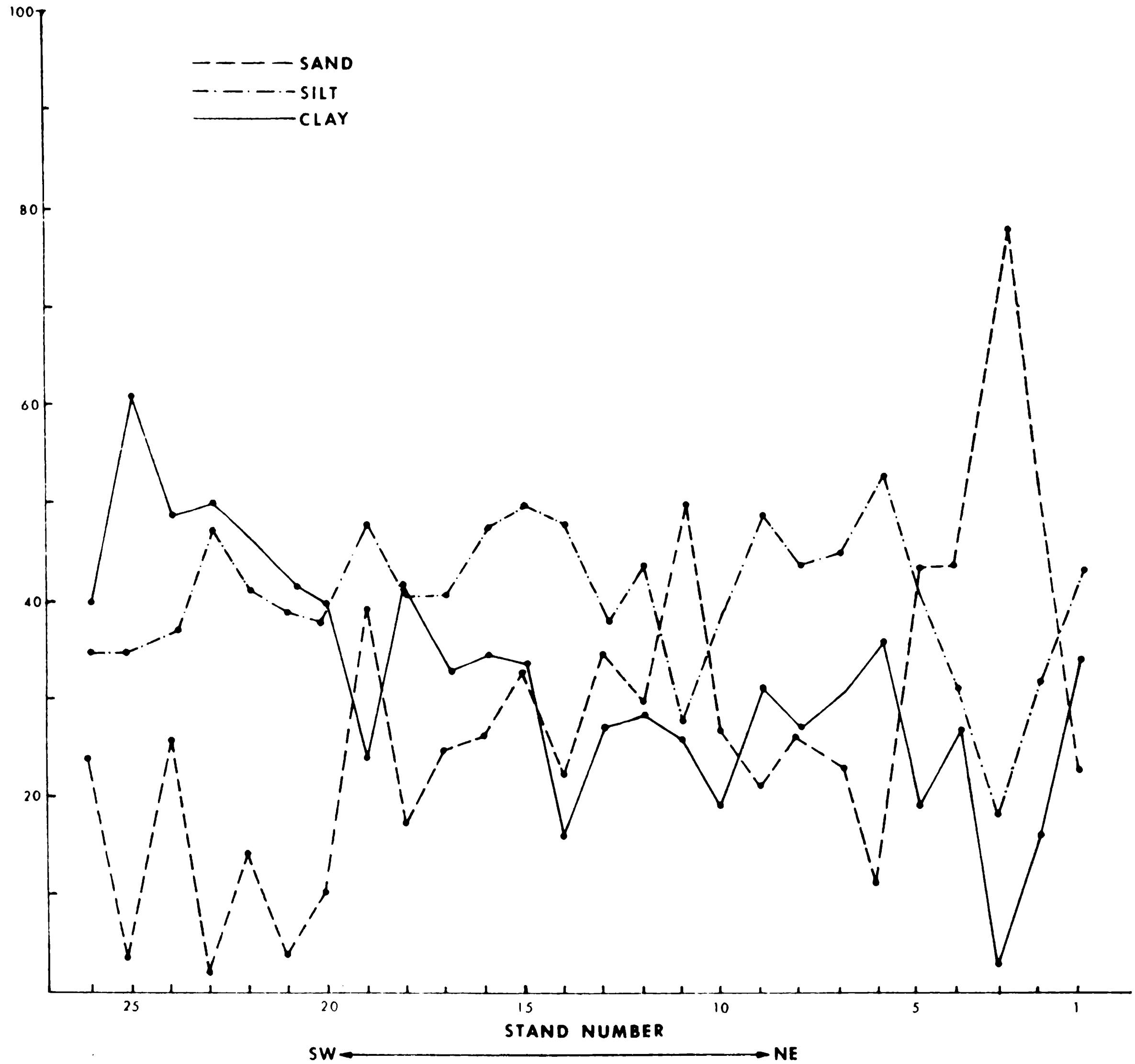

FIGURE 9

PER CENT SAND, SILT, AND CLAY IN COMPOSITE SAMPLES FROM THE B HORIZION

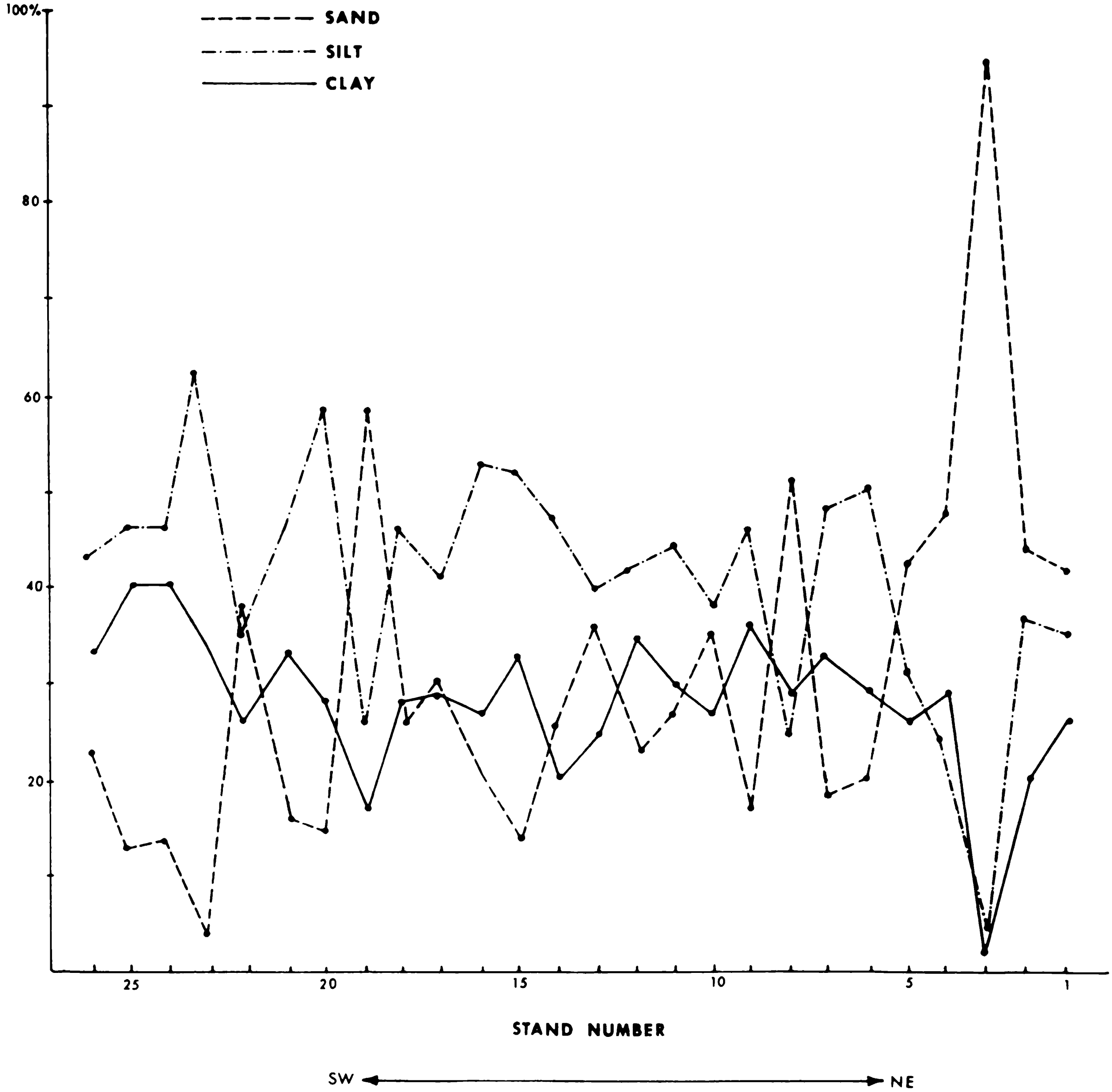

FIGURE 10

PER CENT SAND, SILT, AND CLAY IN COMPOSITE SAMPLES FROM A DEPTH OF FOUR FEET

TABLE 6.--Correlations Between Tree Species and Soil Characteristics.

Species	B Horizon				Four-Foot Depth			
	Sand	Silt	Clay	pH	Sand	Silt	Clay	pH
Fagus grandifolia	.630*	-.392	-.113	.339	.648*	-.693*	-.324	-.617*
F. grandifolia and *Acer saccharum*	.454*	-.133	-.575*	-.169	.496*	-.460*	-.376	-.384
Four mesophytic species (see text)	.575*	-.192	-.464*	.049	.554*	-.555*	-.346	-.571*
Quercus velutina	-.045	-.002	.477*	.464*	.025	-.066	.060	-.201
Five *Quercus* and *Carya* species	-.528*	.108	.480*	-.128	-.479*	.477*	.304	.527*

*Value significant at .05 level.

these correlations, two modifications were made in the original data. First, stand 3 was omitted because it was located on extremely sandy soil which occurs in a narrow belt along the northern margin of the mcraine. Second, one of the two soil samples in stand 19 was excluded because examination of the Porter County soil map suggested that it represented an isolated sandy pocket. Soil fraction values for the other sample were used instead of the two-sample average for that stand. Correlation coefficients were tested for significance using the F test described by Blalock (50).

In general, the mesophytic species and groupings had positive correlations with the percentage of sand in the soil and negative correlations with per cent silt and per cent clay. The correlations with sand at both depths, with silt at four feet, and with clay in the B horizon (except for <u>Fagus grandifolia</u> alone) were significant at the .05 level. The more xeric oak and hickory species, on the other hand, correlated negatively with sand and positively with silt and clay. <u>Quercus velutina</u> alone did not follow the trend of the larger group exactly, but did show positive correlations with per cent clay at both depths.

It appears that the soils of the western part of the Valparaiso morainic area, which support an oak-hickory forest type, tend to be higher in clay and silt content and lower in sand than those to the east on which beech-maple forest occurs. This relationship is further illustrated by Figures 11 and 12. In these figures, all individual soil samples were plotted on textural triangles using different symbols for those samples taken in beech-maple stands (stands 1-13) and those from oak-hickory stands (stands 14-26). Figure 11 displays the B horizon samples; Figure 12 represents the samples from a depth of four feet. Both diagrams indicate a tendency for higher clay content under the oak-hickory stands, particularly in the B horizon. Clay and silty clay textures were common at that depth in the western oak-hickory stands, while loams and clay loams were abundant in the beech-maple stands. The trend toward decreasing sand content westward is pronounced at both depths. Little variation in the amount of silt can be detected in the B horizon; however, larger silt percentages to the west do seem indicated at the four-foot depth.

Hydrochloric acid was used to check for the presence of carbonates at the four-foot depth. In eleven of the thirteen beech-maple stands carbonates were absent in both soil samples. Carbonates were detected in one of the two samples from each of the two remaining stands. On the other hand, carbonates were present in both samples from eight of the thirteen oak-hickory stands and were detected in one sample from each of the other five stands. Thus the depth of leaching appears to decrease from east to west along the moraine.

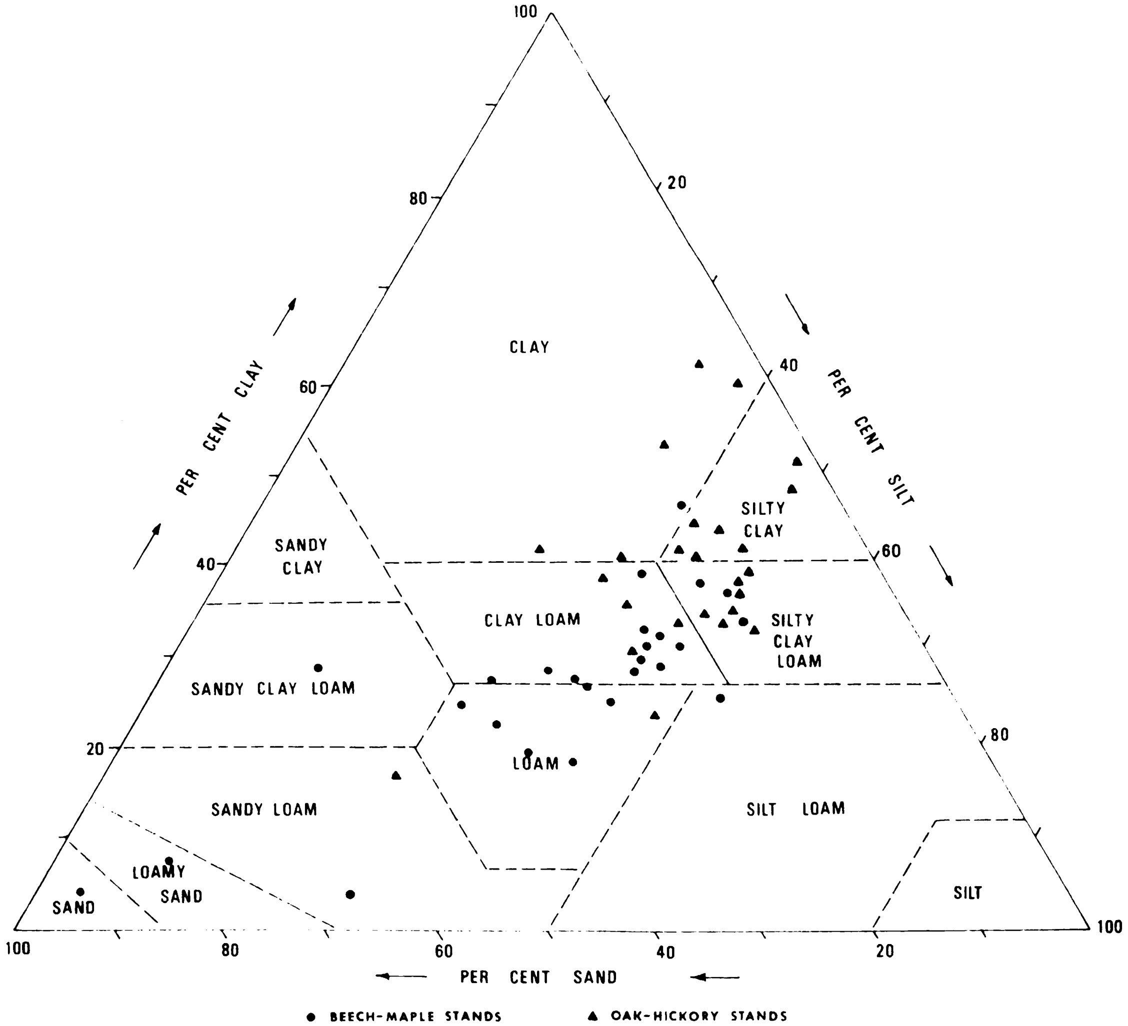

FIGURE 11

POSITION OF INDIVIDUAL SOIL SAMPLES FROM THE B HORIZION ON TEXTURAL TRIANGLE

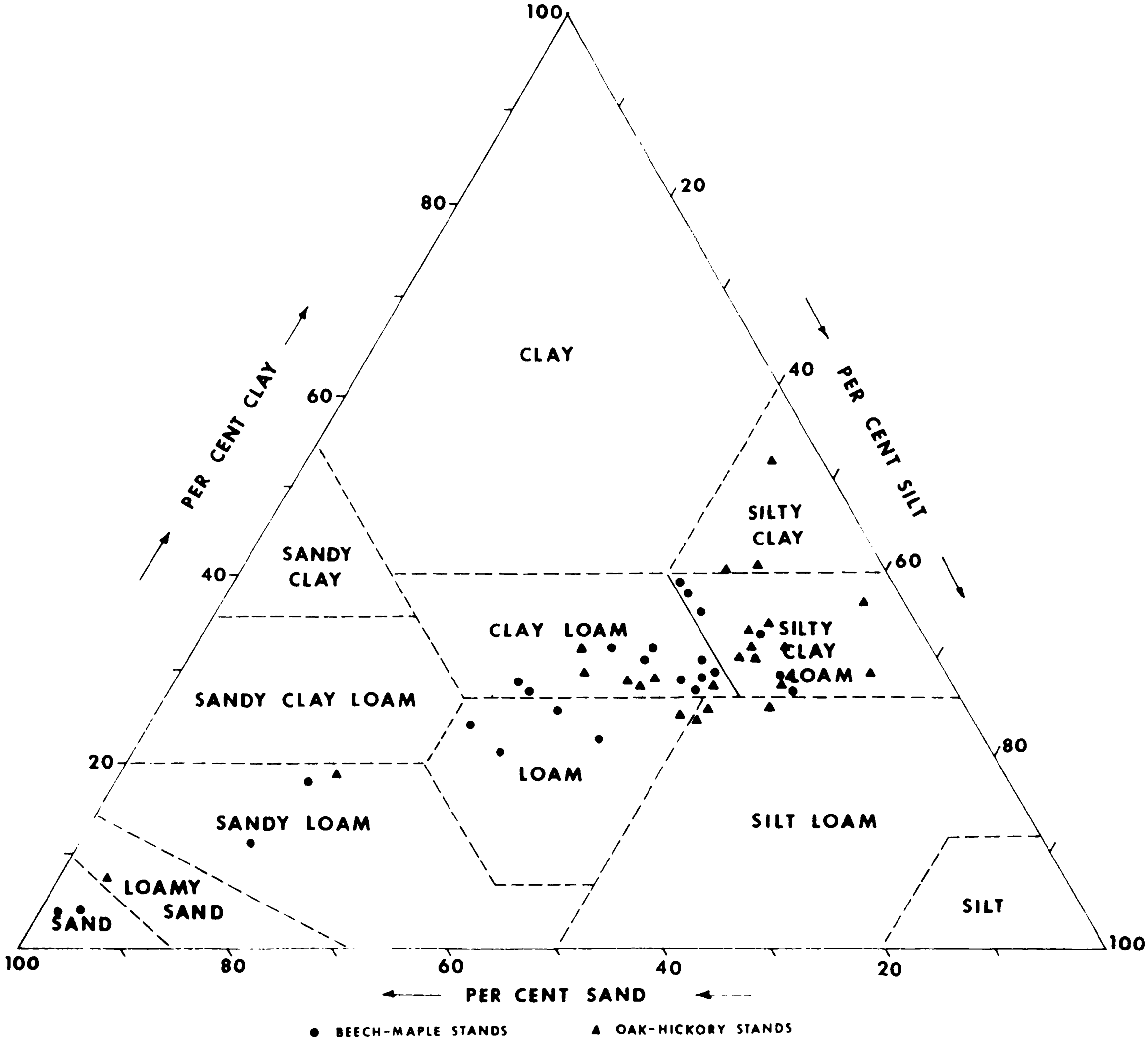

FIGURE 12

POSITION OF INDIVIDUAL SOIL SAMPLES FROM THE FOUR-FOOT DEPTH ON TEXTURAL TRIANGLE

Table 6 (p. 52) also indicates the degree of correlation between species groups and soil pH values. Several significant correlations were obtained at the four-foot depth; however, these probably reflect the variation in leaching depth between stands of the two forest types. All correlations with B horizon pH values are small and only one, that for Quercus velutina, is significant at the .05 level. Values of pH for all samples are given in Appendix IV.

Evaluating the significance of the forest type-soil texture relationship suggested in this study is difficult. The available water capacity (AWC) of a soil is most frequently defined as the amount of moisture held in the soil at tensions between .33 and 15 atmospheres. Several studies, assuming these limits, have found significant positive correlations between the silt content of a soil and its AWC (51,52,53). Based on these reports, it might be expected that the soils of the western part of the study area, being higher in silt content, would have greater AWC than those to the east. It has also often been reported that higher AWC is attained in clay loams and clays than in loams or sandy loams (54,55), a fact which would again suggest that more favorable soil moisture characteristics would be found in the western portion of the study area. Franzmeier and others (56), however, have concluded that .06 and 6.0 atmospheres more adequately delimit the range of tensions at which soil water is readily available to plants. Using

these limits, they found that loamy sands, sandy loams, and loams generally exceed clay loams and clays in readily available water capacity (RAWC). Franzmeier's study suggests that the coarser soils east of Valparaiso may have higher RAWC's than those to the west.

Northwestern Indiana is a tension zone between the beech-maple and oak-hickory forest regions (16). In such transitional areas, variations in site characteristics determine which vegetation type prevails in a given location. It seems very possible that, under these conditions, the higher clay content of the soils in the western part of the study area could reduce the readily available water capacity sufficiently to affect the vegetation type. Beech, in particular, has been found to be sensitive to reduced soil moisture conditions (57). The location of the boundary between medium textured and finer textured soils, as mapped in Soils of the North Central Region of the United States (49), corresponds closely to the transition between the two important forest types in the study area. On the basis of the results of the soil texture survey, it is tentatively concluded that the forest contrast cannot be cited as strong evidence for a long-term La Porte rainfall anomaly which might be associated with lake breeze convergence.

The forest contrast may be the result of a complex of interacting factors. Winter snowfall is considerably heavier in La Porte County than in the western part of the study area (14,58) and this could affect soil moisture conditions during the early part of the growing season. In addition, the study area lies near the margin of the "prairie peninsula" (18) within which precipitation-evaporation ratios decrease, precipitation becomes more variable from year to year, and summer drought is a frequent occurrence (59,60). It is possible that these climatic characteristics become more pronounced westward in northern Indiana. These factors, as well as soil textural differences and a long-term warm-season precipitation gradient associated with lake breeze convergence, could collectively be responsible for the forest contrast.

The differences in depth of leaching between the eastern and western parts of the morainic area could result from one or more of at least three possible causes: (1) textural variations; (2) differences in the amount of limey material originally present in the till; or (3) variations in the amount of precipitation. The soils of the western part of the study area are fine textured; subsoils occasionally fall into the clay textural class and percolation through them is often severely limited (7). These factors could have resulted in less leaching than in the coarser soils to the east. Krumbein (5) found that the average contribution of limestone to the gravel fraction of three samples taken west of Valparaiso was 10.2%, while for three

samples taken east of that city the mean was 3.3%. This suggests that the lime content of the western parent materials may have been greater than in those to the east. Finally, if the La Porte rainfall anomaly has been a long-term phenomenon, the higher precipitation could have produced greater leaching in that vicinity. Assessing the relative importance of each of these factors is beyond the scope of this study.

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CHAPTER IV

THE LAKE BREEZE

Review of the Literature

The problem of climatic modification by the Great Lakes has received considerable attention. Studies have been primarily devoted to describing the influence exerted by the lakes upon climatic elements, such as temperature and amount of snowfall, in their vicinity. A selective review of literature relating to various aspects of lake modification is presented in Chapter I. Interest in the dynamic interaction between the lakes and atmospheric processes over them and over adjacent land is more recent and has been the subject of fewer investigations. One aspect of this interaction which has been the focus of an increasing number of studies concerns the development and climatic impact of lake breezes.

Lake breezes, which are equivalent to sea breezes, illustrate on a small scale the principles involved in the conversion of radiant solar energy to kinetic energy of atmospheric motion (1). Due to several factors, of which the turbulent mixing of water may be the most important (2), water warms up much more slowly in response to incoming solar radiation than does land. On clear summer days, near the shoreline of a large water body, expansion of air over the heated land surface results in a rising of isobaric surfaces and thus produces a horizontal pressure gradient aloft with higher pressure over land. In response to this gradient, air movement aloft occurs from the land toward the water. This action increases surface pressures over the water while decreasing those over the land, thus setting up a second pressure gradient, opposite in direction to the first one, across the shoreline at the surface. Lake or sea breeze flow is a response to this pressure gradient. The offshore current aloft is referred to as the return flow, although it must actually begin before the lake breeze can be established (3).

Perhaps the earliest reference to the occurrence of lake breezes in the vicinity of the Great Lakes appeared in 1799 (4); the diurnal alternation of onshore and offshore winds near Lake Erie were discussed. Another early discussion of lake breezes, including their causes and influence on the climate of the Chicago region, was presented by Hazen (5).

The basic characteristics of lake breeze dynamics are now quite well understood. The most important factors controlling lake breeze development are the magnitude of the land-water temperature contrast and the strength and direction of the regional wind (6,7). As would be expected, lake breezes are normally most frequent during late spring and early summer when land heating is intense but lake waters are still cold (3). Excessive cloudiness can decrease heating of the land and therefore prevent lake breeze formation. Hall (8), working in the Chicago area, found that offshore winds in excess of 10 to 12 miles per hour prevented the development of a lake breeze; with onshore winds, a lake breeze circulation was able to exist at slightly higher wind speeds (15 mph). Olsson (3) reached similar conclusions in the same region. In addition, local factors such as topography and the shape of the coastline influence the characteristics of lake or sea breezes (9,10).

In the absence of superimposed regional flow, lake breezes first develop at the shoreline where the horizontal temperature gradient is strongest (11,12). With an offshore wind, however, warm land air is advected over the water and the steepest temperature gradient may occur off shore; in such cases, a lake or sea breeze would form initially over the water (1). During the day, the lake breeze advances inland and is usually deflected by the earth's rotation in a clockwise direction so as to become more nearly parallel to the shoreline (9,13).

Two distinct types of sea (lake) breezes have been recognized (2,14). The first of these is identified as the frontal type and generally occurs when the sea breeze is opposed by the gradient flow. A breeze of this type has a

well defined front, may not begin to advance inland until afternoon, and usually advances quite suddenly; passage of the front often brings a sharp temperature drop and a rise in relative humidity. A non-frontal sea breeze, on the other hand, begins early in the day and brings gradual rather than abrupt changes in temperature and relative humidity. This type occurs most frequently on days when onshore regional winds reinforce the lake breeze. Estoque (15) believed that development of frontal characteristics does not occur in such cases because initial onshore flow prevents excessive heating of the land. It seems likely that many sea and lake breezes are intermediate between these two types.

Moroz (16) investigated one lake breeze occurrence on a day of weak gradient flow on the eastern shore of southern Lake Michigan. At 0900 local time surface winds were offshore, probably representing a land breeze. The lake breeze crossed the shoreline at 1000, three hours after inland air temperature became equal to the lake surface temperature. Passage of the lake breeze front produced a temperature drop and a rise in relative humidity; these changes were marked near the shoreline but became indistinct farther inland, indicating modification of air properties by heating from below. The front apparently progressed inland in surges rather than at a steady rate; maximum inland penetration of over 10 miles was reached

about 1800 when the lake-inland air temperature difference began to decrease. Maximum depth of the lake breeze was approximately 2400 feet. The maximum onshore velocity was 15 miles per hour and occurred over the lakeshore about the time of maximum temperature contrast between water and non-lake breeze air. Studies by Munn and Richards (9), Moroz and Hewson (17), and Olsson and others (3,18) have supported these observations. Olsson (3) also reported that the lake breeze front had a slope of approximately 1:20; this can be compared with the average value for cold fronts of 1:50 to 1:150 (19). Estimates for sea breezes range from 1:20 to 1:100 (14,20).

On days with very weak gradient conditions, lake breezes may develop symmetrically around Lake Michigan (3). Because the regional prevailing wind is southwesterly, however, lake breezes on the average extend farther inland on the southeastern shore of Lake Michigan than they do on the southwestern shore (21). The frequency with which lake breezes occur in the vicinity of the Great Lakes has not been studied extensively. Biggs and Graves (6), working on the western shore of Lake Erie, observed an average of 23 lake breeze days per June-August period over three years; they eliminated all days with onshore gradient winds from their study. Hall (8) stated that lake breezes are almost daily occurrences at the shore near Chicago, but noted that over a three year period an average of only 11 breezes per

year penetrated as far as eight miles inland. Long-term figures for the eastern shore of Lake Michigan are not available.

The apparent suppression of summertime convection and precipitation by Lake Michigan and the other Great Lakes has received considerable attention. Hazen (5) noted that Chicago received less precipitation on days with onshore winds than surrounding inland stations did, and Eshleman (22) observed that stations on the Wisconsin side of Lake Michigan received more summer rainfall than those on the eastern side. More recent investigations by Changnon (23), Blust and DeCooke (24), and Stout and Wilk (25) have suggested that summer precipitation is reduced at stations along or on Lake Michigan. Weiss and Kresge (26) and Williams (27), however, did not find any significant reduction of offshore precipitation. Lansing (28) observed the apparent suppression during the summer of cumulus cloud formation over or near the lee shore of Lake Ontario. Other studies present evidence for the suppression or dissipation of cumuli (29), squall lines and air mass showers (25,30), and thunderstorms (31) by Lake Michigan. Sometimes, for reasons not yet well understood, squall lines and air mass showers pass over the Lake with little apparent modification (29,32).

On summer days a mesoscale "lake high" often develops over Lake Michigan (8,32). This dome of cool and very

stable air, resulting from a net downward flux of heat and subsidence over the Lake, is probably responsible for the suppression of cloud formation over the Lake (29,32). Olsson (3) found that the "lake high" reached a maximum intensity of 4 millibars by early evening. Satellite and aerial photography have shown that the lake-induced cloud-free zone often extends inland on the Michigan shore as much as 20 miles.

A form of climatic modification associated with lake breezes which has received less attention is related to low-level convergence near the lake breeze front. Several sea breeze studies have indicated that strong vertical air movement occurs near the front and can induce cloud formation (2,20,33). Leopold (34) reported local rainfall "islands" in Hawaii which corresponded with the mean positions of sea breeze fronts. Byers and Rodebush (35) attributed the high frequency of summer thundershowers over central Florida to convergence of two sea breezes from opposite sides of the peninsula. Estoque (12) theoretically demonstrated the existence of convergence and upward air movement at the sea breeze front.

Moroz (16) and Olsson (3) have reported strong horizontal convergence and large vertical velocities near lake breeze fronts on the eastern shore of Lake Michigan. Other studies have found that bands of cumulus clouds frequently develop along the lake breeze front around Lake Michigan

and that shower activity can occur there (32,36). Shenfield and Thompson (37) and Moroz and Hewson (17) have presented evidence suggesting that under certain conditions the presence of a lake breeze can be an important factor in triggering or intensifying localized thunderstorms.

Several investigations have indicated that lake breeze convergence may be particularly important adjacent to the southeastern shore of Lake Michigan near the area of the present investigation. Estoque (15) found from theoretical considerations that vertical motion near a sea breeze front might be especially strong when the geostrophic wind is parallel to the shore with low pressure over the water; this situation appears to be analogous to that along the southeastern shore of the Lake during southwesterly flow. Lyons (32) observed that a band of towering cumuli can develop parallel to the southwestern shore of the Lake during northwesterly flow. Similar activity might be expected along the southeastern shore during the more frequent southwesterly winds. Schaefer (38) stated that a street of cumulus clouds is commonly observed extending along the convergence zone south and southeast of Lake Michigan. A pattern of higher thunderstorm precipitation extending from northwestern Indiana into Michigan has been described by Changnon (39). Finally, Lyons and Wilson (29) have suggested that convergence and cloud formation may occur along the southeastern shore of the Lake even in the absence of a lake breeze when winds are southwesterly. This would result from veering of the wind as it passes over the low-friction lake surface, producing convergence with the unaffected flow inland.

Reviews of the literature on sea and lake breezes have been presented by Schroeder (40), Munn and Richards (9), Olsson (3), and Baralt and Brown (41).

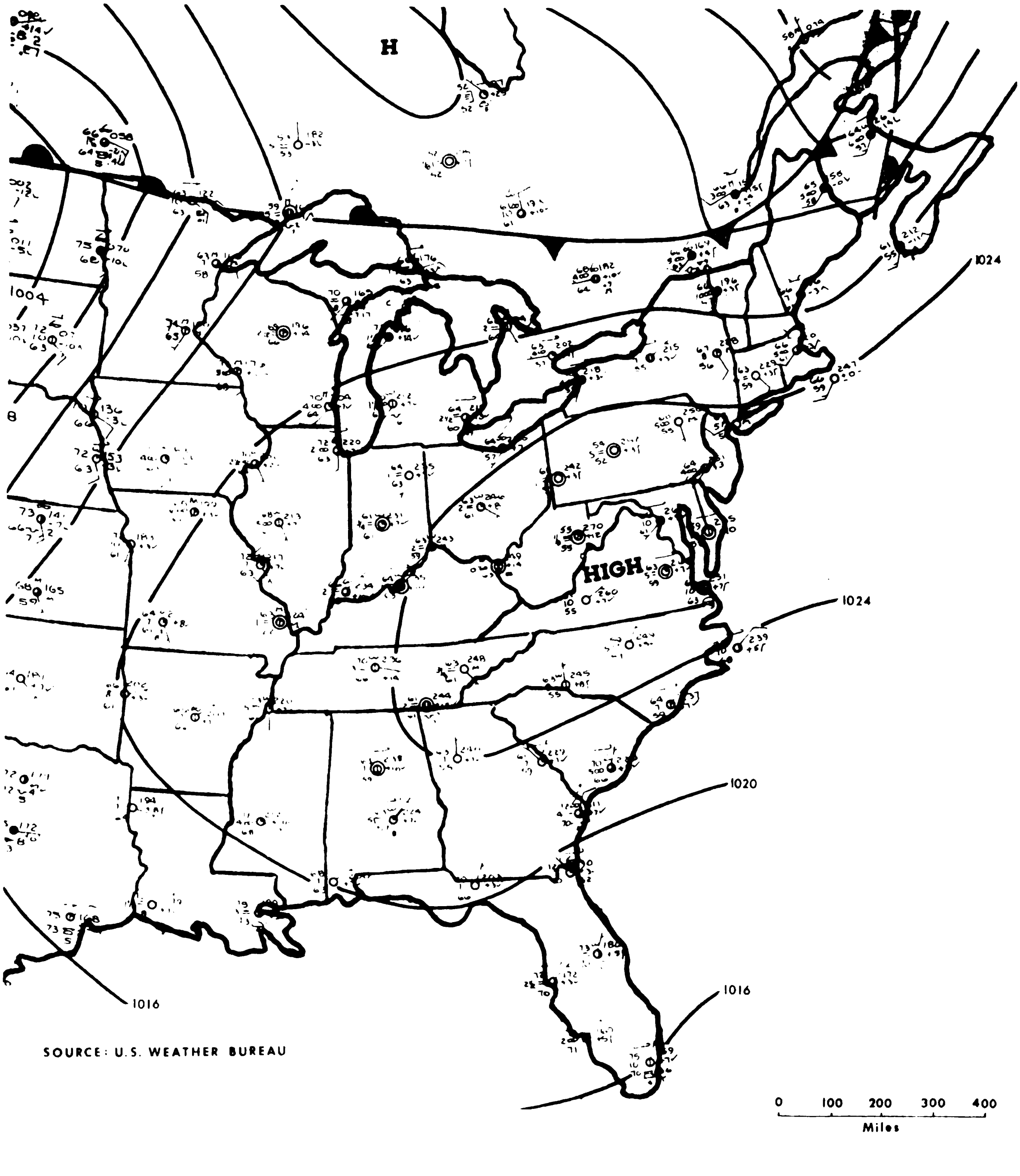
The Climatic Hypothesis

Changnon (42) has described an "island" of high warm-season precipitation centered on La Porte, Indiana, and has attributed it to the effects of atmospheric pollution from the Gary-Chicago industrial complex. Evidence of this pattern has appeared in other studies as well (21,43,44). Ogden (45), on the basis of rainfall studies near an Australian steelworks, however, has expressed doubt that the La Porte anomaly can be attributed to industrial causes. He believed that increased cloud droplet concentration as a result of nucleii addition could reduce mean droplet size and therefore reduce the likelihood of coalescence sufficient to produce rainfall. He observed variations in five-year precipitation means of individual stations similar to those which have taken place at La Porte since 1925. These variations appeared to be unrelated to changes in neighboring stations or to industrial activity.

Hodgins (46) found that for the five year period 1953-1957 the most frequent July circulation pattern over the eastern United States resembled that depicted in Figure 13. The dominant feature of this pattern is an anticyclonic system situated over the southeastern states resulting in southwesterly flow over the Midwest. Such a synoptic situation, probably associated with a mid-continent tropospheric ridge, would bring higher than normal temperatures to the Great Lakes region.

Under these conditions, with high daytime temperatures, the dome of cold air over Lake Michigan probably would be strongly developed and the front of its associated lake breeze sharply defined. Along the southwestern shore of the Lake, where the regional flow is more normal to the front, the lake breeze would be prevented from advancing inland and might even be displaced over the water (Figure 14). On the southeastern and eastern shorelines, however, the lake breeze would advance inland. Satellite photographs have indicated that this pattern does occur (32). Variations of this pattern would develop under westerly or northwesterly winds.

Since the degree of lake breeze penetration is a function of several factors, including wind direction, wind speed, and land-water temperature contrasts, there would be day-to-day fluctuations in maximum inland advance. Nevertheless, a mean frontal position could be identified. The hypothesis of this study is that on days of regional flow with a westerly component, the mean location of the



SOURCE: U.S. WEATHER BUREAU

FIGURE 13

SURFACE WEATHER MAP

August 29, 1969

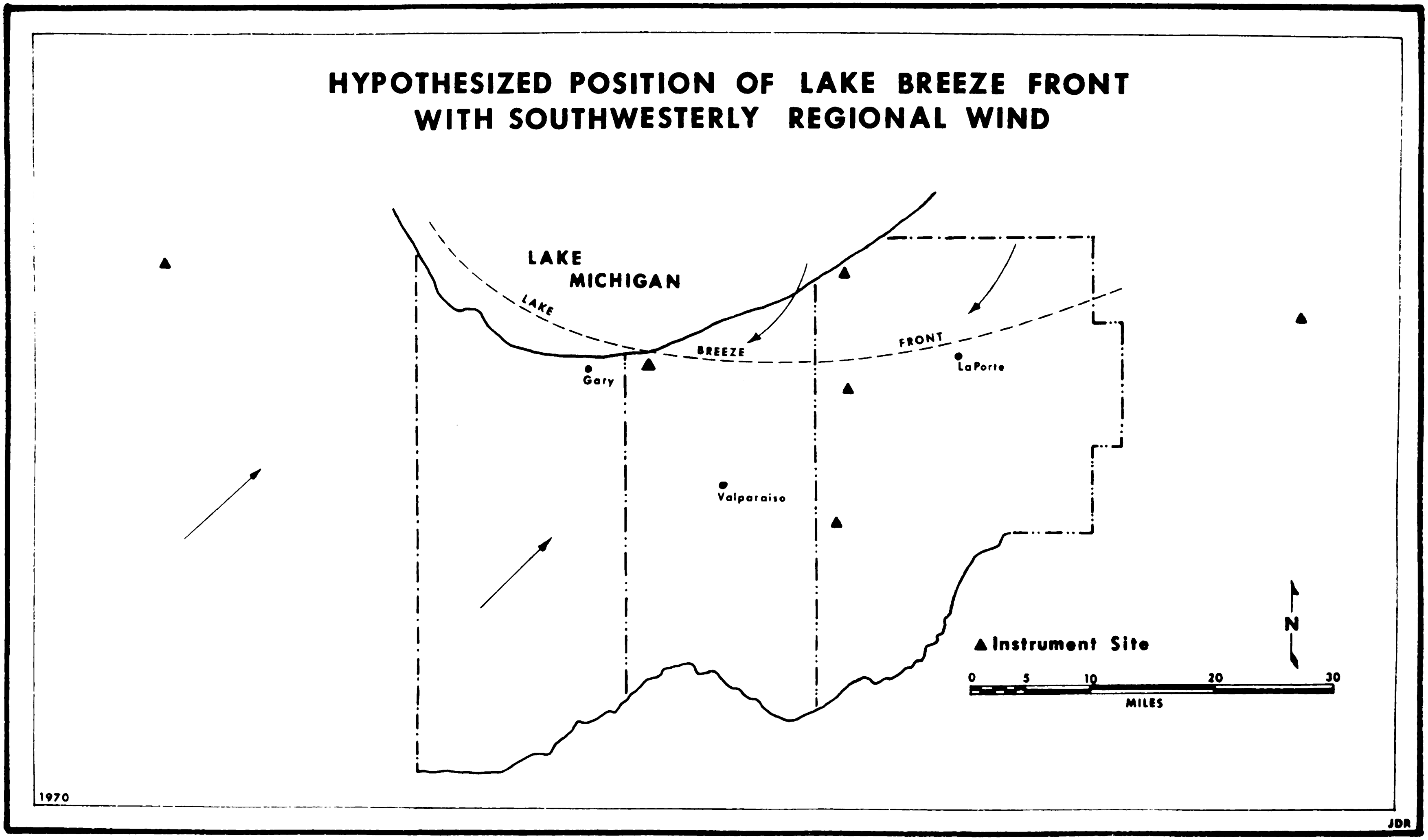

HYPOTHESIZED POSITION OF LAKE BREEZE FRONT
WITH SOUTHWESTERLY REGIONAL WIND
LAKE
MICHIGAN
LAKE
BREEZE
FRONT
Gary
LaPorte
Valparaiso
▲ Instrument Site
0
5
10
20
30
MILES
N
1970
JDR

FIGURE 14

lake breeze front, and its associated convergence zone, lies in the vicinity of La Porte and might be causally related to the La Porte rainfall anomaly (Figure 12).

It is beyond the scope of the present study to demonstrate whether increased precipitation does in fact fall in the vicinity of La Porte when the lake breeze convergence zone is situated near that city. However, some comments regarding the processes which might bring about such a precipitation pattern under those conditions are perhaps desirable. Convectional activity, as a result of convergence, presumably would occur along the length of the lake breeze front as it extends inland toward La Porte and beyond. Under suitable atmospheric conditions, this convection could initiate cloud formation which might lead to precipitation. Rainfall would naturally not begin at once, however, as time would be required for the clouds to organize and grow. During this time they would be moved down-wind along the convergence zone by the regional flow; Lyons and Wilson (29) have reported such movement by cumuli. At some point along the front, precipitation might begin; the location of this point would vary from day to day depending on the degree of lake breeze development and a complex of other factors, but presumably a mean precipitation zone would be established. If so, that region might receive measurably more rainfall than surrounding areas when lake breeze development is favored.

Results of the Survey

Twenty-two lake breeze days were identified which met the criteria outlined in Chapter II (see Appendix V). Tables 7-9 indicate, for 1000, 1300, and 1600 EST, the number of occurrences during those days of winds from 16 compass directions at the six instrument stations (at the Ogden Dunes station, only eight compass points were used in recording wind direction). Figures 15-17 present the information from Tables 7-9 in a spatial context. The six instrument sites have been abbreviated in this discussion as follows: Argonne (ARG), Ogden Dunes (OGD), Westville (WSV), Wanatah (WAH), Michigan City (MCY), and South Bend (SBD).

Several patterns can be detected in Figures 15-17. For the hour 1000 EST, there is considerable similarity between the wind roses for all stations, although that for Michigan City appears to show some lake breeze influence. By 1300 the MCY rose clearly indicates the influence of lake breezes, while it appears that Ogden Dunes, Westville, and South Bend occasionally experienced lake breeze flow. The pattern for 1600 suggests slightly increased lake breeze influence at OGD, WSV, and possibly as far inland as Wanatah, about 18 miles from the lakeshore. South Bend, on the other hand, appears to have experienced less lake breeze flow at 1600 than at 1300. At both MCY and OGD, winds off the lake shifted from northwesterly at 1300 to

TABLE 7.--Number of Occurrences of Wind from Sixteen Directions During Twenty-two Lake Breeze Days: 1000 EST.

Station	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm
Argonne	1				1			1		2	4	1	10		2		
Ogden Dunes*	1		1						12		3		4		1		
Michigan City	1	1		1					1	1	5		3	6	1	2	
Westville	1								6	3			6	2	3	1	
South Bend	2							1	1	3	3	3	3	5		1	
Wanatah	5		1				1		2	2	2	1	2	3	1	2	

*Eight directions used at Ogden Dunes.

TABLE 8.--Number of Occurrences of Wind from Sixteen Directions During Twenty-two Lake Breeze Days: 1300 EST.

Station	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm
Argonne											6	4	8	1	2	1	
Ogden Dunes*			3		1				5		3		5		3		2
Michigan City	3	2	1										1	2	8	5	
Westville									3	1	3	2	3	2	5	3	
South Bend		2							2	3	2		3	7	3		
Wanatah	1					2	1		2		5	1	4	2	3	1	

*Eight directions used at Ogden Dunes.

TABLE 9.--Number of Occurrences of Wind from Sixteen Directions during Twenty-two Lake Breeze Days: 1600 EST.

Station	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm
Argonne	1								2	3	4	3	6	2		1	
Ogden Dunes*			5		2				6		2		3		2		2
Michigan City	1	5	6	1								2	2	1		4	
Westville	3								2	5	4		2	1	3	2	
South Bend	1			1		1			3		2	4	3	4	2	1	
Wanatah	1					1			1	1	7	2	2	2	2	3	

*Eight directions used at Ogden Dunes.

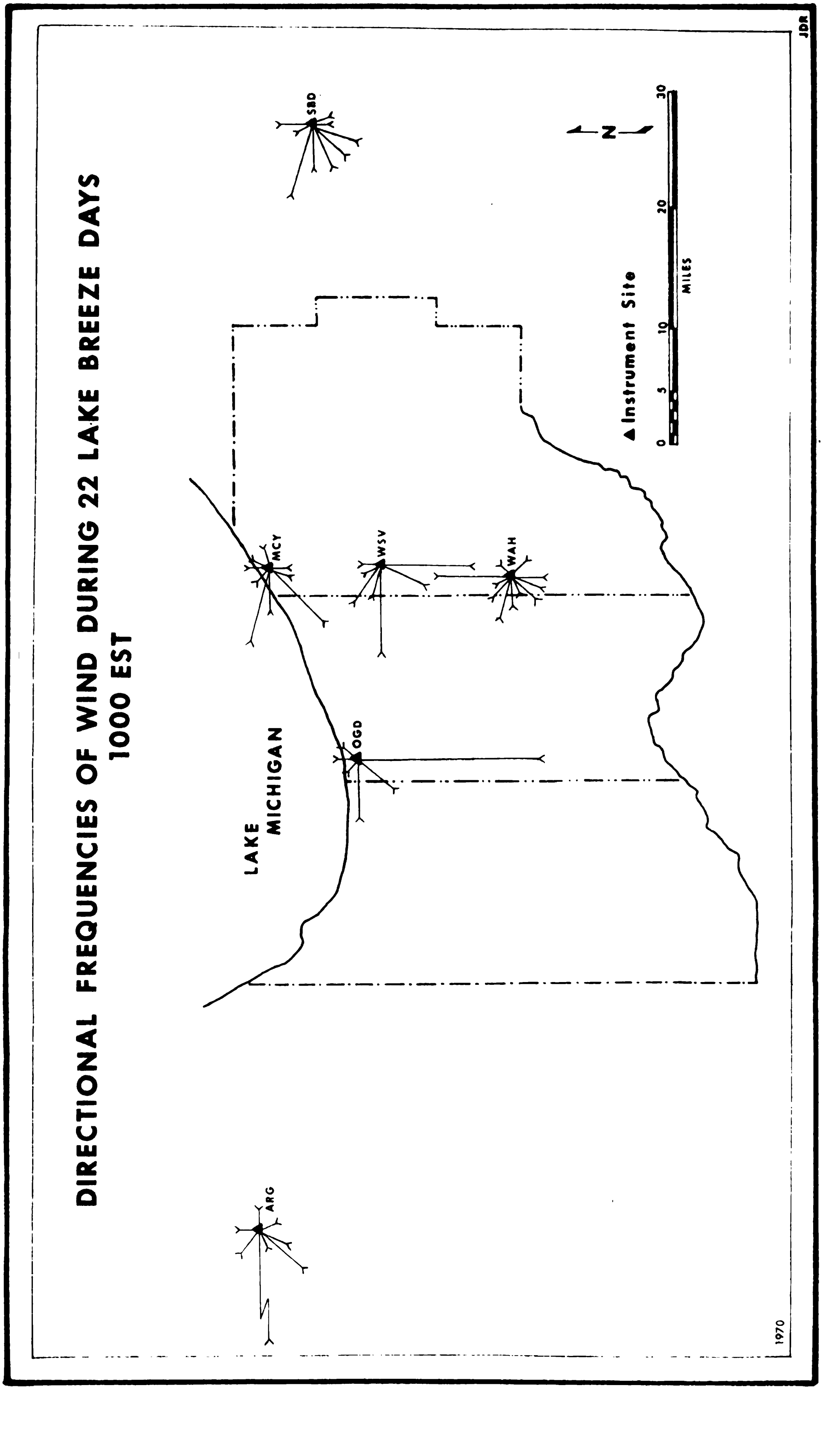

DIRECTIONAL FREQUENCIES OF WIND DURING 22 LAKE BREEZE DAYS
1000 EST
LAKE
MICHIGAN
MCY
WSV
WAH
OGD
SBD
ARG
▲ Instrument Site
0
5
10
20
30
MILES
N
1970
JDR

FIGURE 15

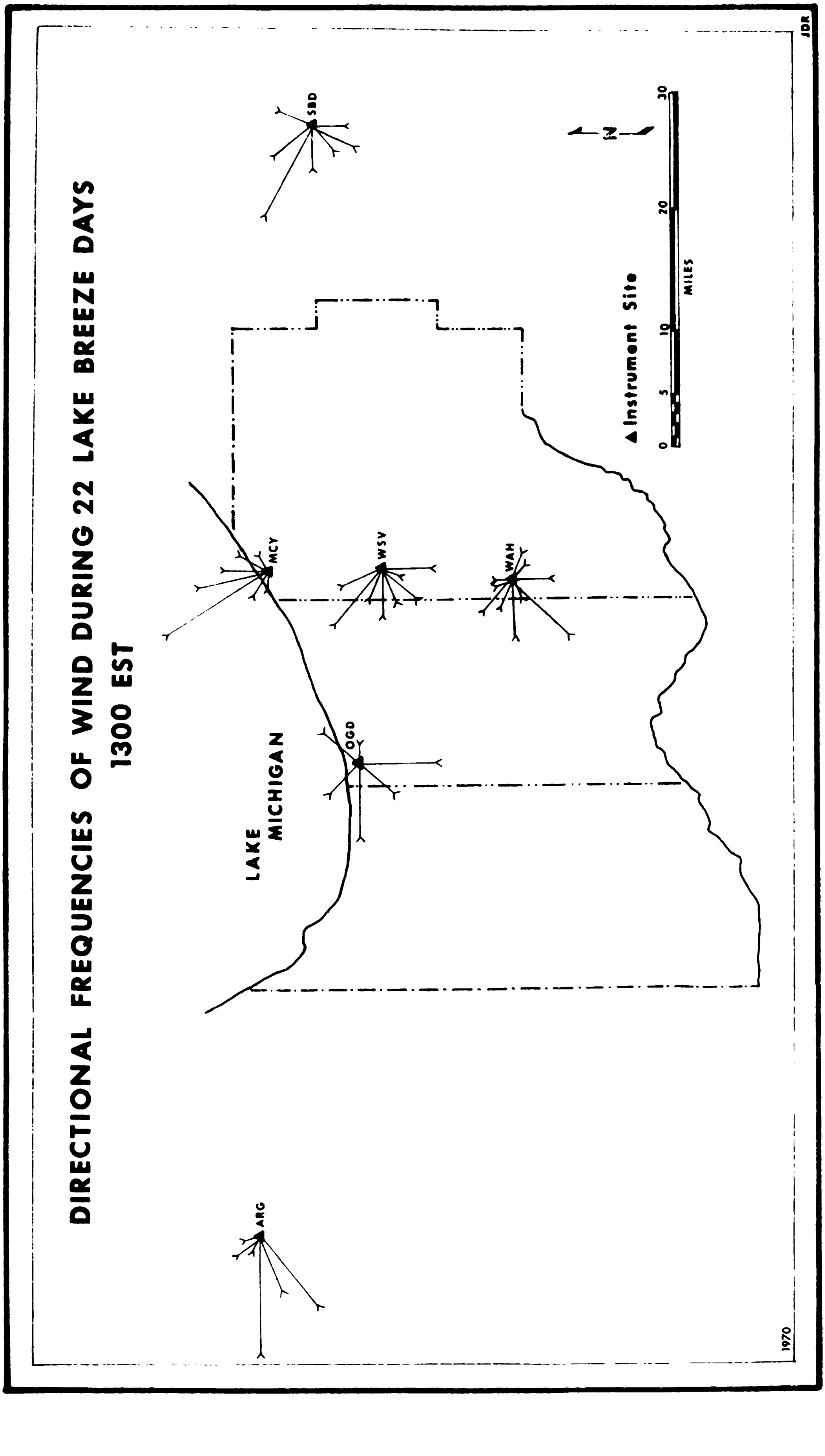

DIRECTIONAL FREQUENCIES OF WIND DURING 22 LAKE BREEZE DAYS
1300 EST
LAKE
MICHIGAN
SBD
MCY
WSV
WAH
OGD
ARG
▲ Instrument Site
N
0
5
10
20
30
MILES
1970
JDR

FIGURE 16

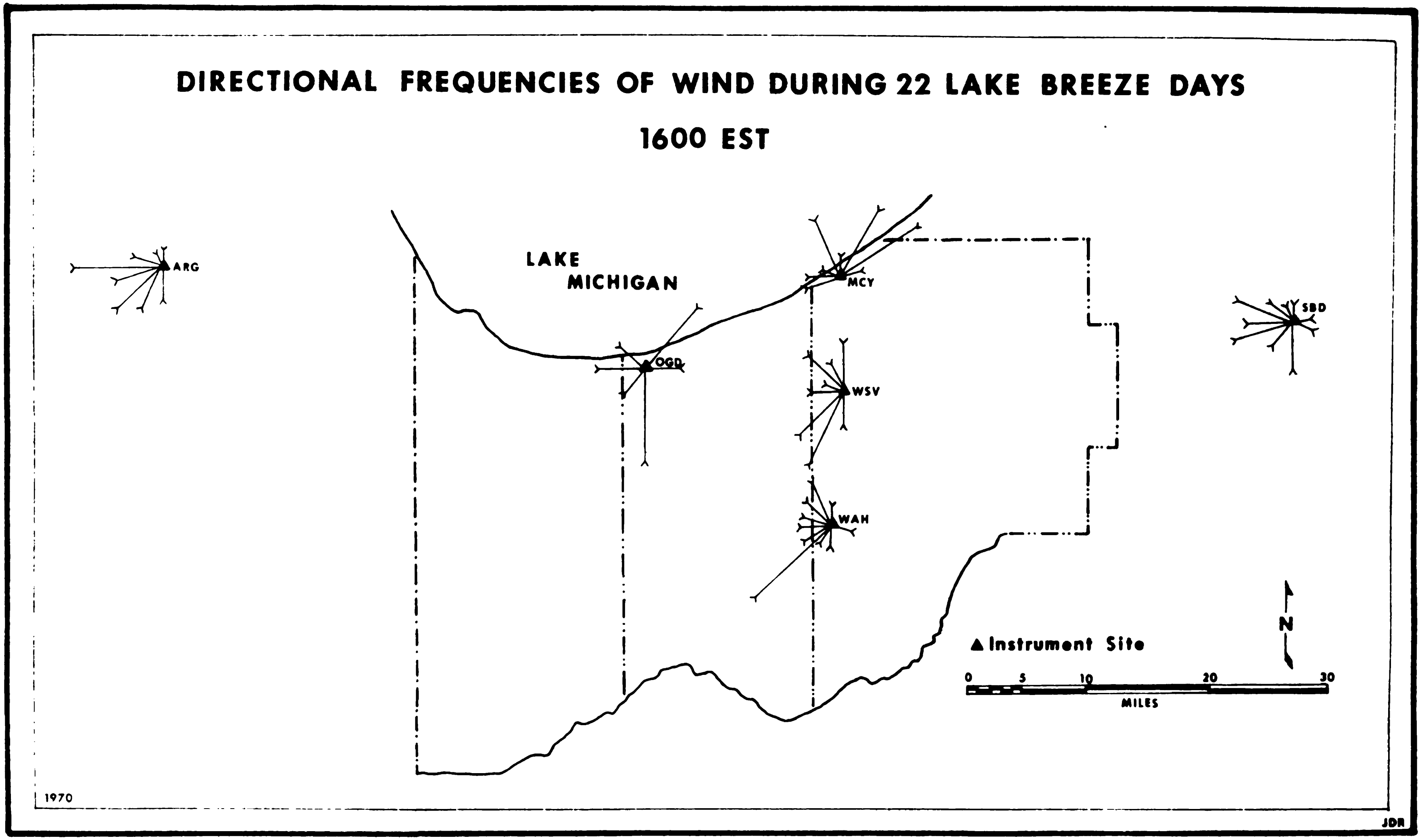

DIRECTIONAL FREQUENCIES OF WIND DURING 22 LAKE BREEZE DAYS
1600 EST
LAKE
MICHIGAN
ARG
MCY
OGD
WSV
WAH
SBD
▲ Instrument Site
0
5
10
20
30
MILES
N
1970
JDR

FIGURE 17

northeasterly at 1600, probably as a result of deflection by the earth's rotation (9).

In an effort to obtain a clearer picture of mean lake breeze penetration, the number of days on which lake breeze flow apparently reached each station was recorded. Some subjectivity was involved in determining lake breeze presence or absence. Essentially, any day during which the northerly component of the wind increased markedly at a station, and on which a similar shift at Argonne was not recorded, was counted as a lake breeze day. Figure 18 presents the results in per cent of MCY lake breeze occurrences. A line approximately delineating the extent to which lake breezes penetrate during about one half of Michigan City's lake breeze days was drawn; this line could be considered as estimate of the mean position of the lake breeze front. It appears that this zone crossed the shoreline near Ogden Dunes and may have passed near the city of La Porte. With the limited number of stations presently available in the study area, however, such conclusions are only tentative.

In order to further visualize lake breeze penetration, the Michigan City lake breeze days were divided into two groups according to the prevailing direction of the regional surface wind at the Argonne station. One group consisted of days on which the wind was from 180° to 269° (the southwest quadrant), the other of days with winds from

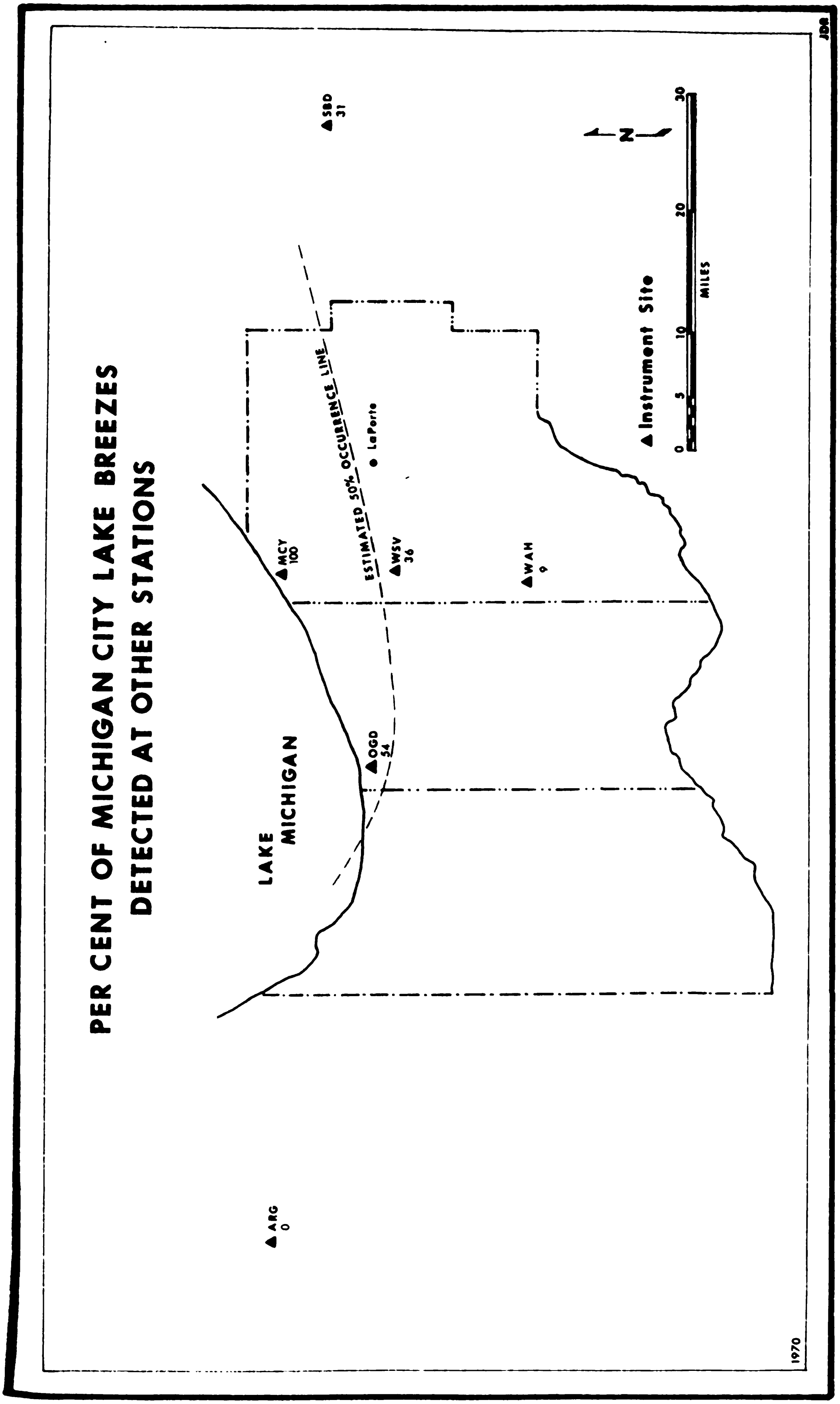

PER CENT OF MICHIGAN CITY LAKE BREEZES
DETECTED AT OTHER STATIONS
LAKE MICHIGAN
ESTIMATED 50% OCCURRENCE LINE
LaPorte
MCY 100
WSV 36
WAH 9
OGD 54
SBD 31
ARG 0
Instrument Site
0 5 10 20 30
MILES
N
1970
JDB

FIGURE 18

270° to 359° (the northwest quadrant). Each group contained eleven days. Again the number of those days on which lake breeze flow reached each station was determined. Figures 19 and 20 present the results as per cent of MCY lake breeze days.

It is evident that days with westerly to northwesterly regional air flow were more favorable for inland penetration of the lake breeze in northwestern Indiana than those with winds from the southwest quadrant. When the former situation prevailed it appears that over 60% of the lake breezes recorded at Michigan City penetrated at least as far inland as La Porte and nearly 20% reached Wanatah, about 18 miles from the Lake. Under regional flow from south of west, however, perhaps less than 40% of the lake breezes reached La Porte and none were detected at Wanatah.

Figures 18-20 also indicate a sharp decrease in lake breeze frequency westward through Indiana along the lakeshore. During the days examined in this study, lake breezes occurred approximately one-half as often at Ogden Dunes as at Michigan City, 18 miles to the northeast. Most of this reduction occurred when the regional flow was from the southwest quadrant; lake breeze frequency at Ogden Dunes was only one-fourth that at Michigan City when that situation existed.

It appears from Figures 18-20 that, for the 22 days analyzed, the lake breeze front may have had a mean position

PER CENT OF MICHIGAN CITY LAKE BREEZES DETECTED AT OTHER STATIONS ON DAYS OF SOUTHWESTERLY REGIONAL SURFACE FLOW

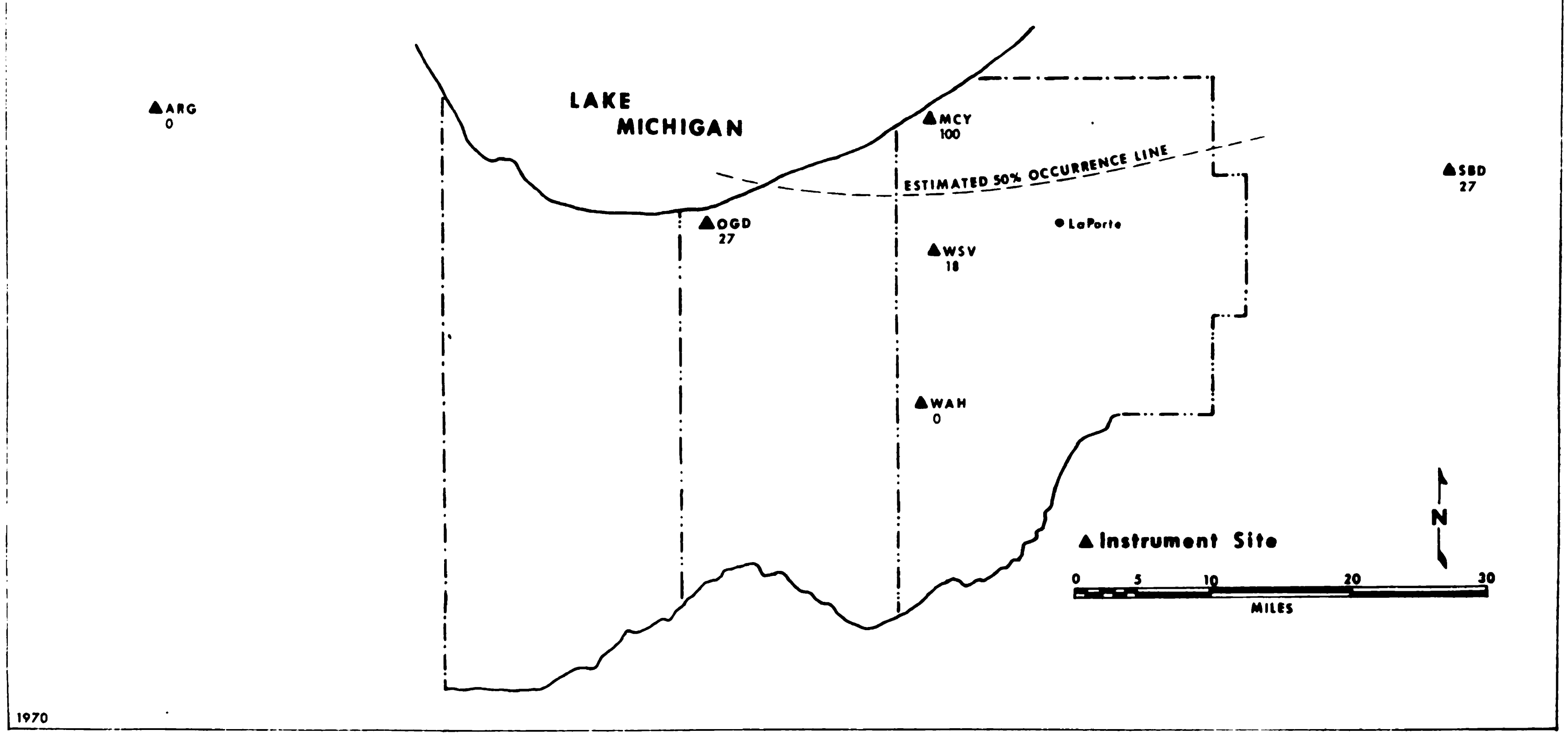


FIGURE 19

PER CENT OF MICHIGAN CITY LAKE BREEZES DETECTED AT OTHER STATIONS ON DAYS OF WESTERLY-NORTHWESTERLY REGIONAL SURFACE FLOW

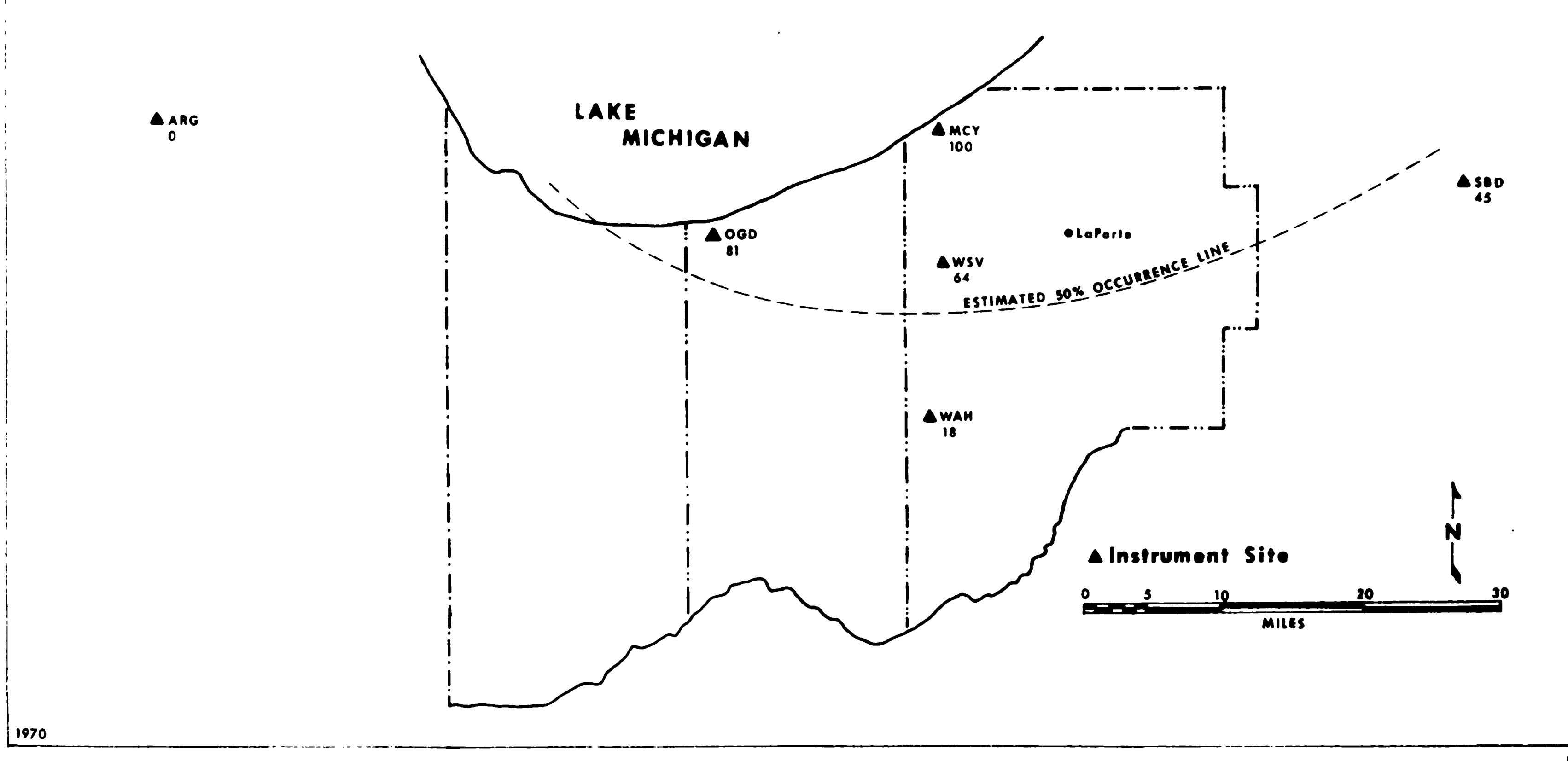


FIGURE 20

in the vicinity of La Porte, particularly during those days on which the prevailing regional wind was westerly to northwesterly. A denser network of observation stations and a longer period of observation would be required to confirm the apparent pattern of lake breeze penetration and accurately determine the mean frontal position. However, these findings tentatively suggest that the lake breeze may be a factor in the regional precipitation pattern.

Although not directly related to the hypothesis under consideration, further analysis of the data might contribute to an understanding of the conditions which govern lake breeze development in northwestern Indiana. Thirty-seven days between June 11 and August 31, 1969, during which the regional air flow possessed a westerly component and fronts did not pass through the study area, were identified. These included the 22 Michigan City lake breeze days and 15 others. For each of these days, the following values were calculated: (1) the difference between Lake Michigan water temperature at Chicago (5) and the maximum air temperature measured at the Argonne station; and (2) the mean of the hourly wind speed readings from 1000 to 1600 EST, inclusive, at Argonne. These two variables, plus wind direction, are probably the primary controls of lake breeze formation and inland penetration. Argonne was selected to represent inland conditions because it would be little affected by lake breeze flow.

The thirty-seven days were then plotted on a coordinate system in which the vertical axis represented the land-water temperature difference (ΔT) and the horizontal axis represented the mean wind velocity at Argonne (w). Two different symbols were used depending on whether or not a lake breeze occurred that day at Michigan City. Figure 21 presents the results. It was found that a line representing a ΔT:w ratio of 2.2:1 separated lake breeze and non-lake breeze days with an accuracy of 65%. If ratios between 2.0:1 and 2.4:1 are considered transitional, and one day on which the reported lake temperature seemed anomalouly high is not included, the accuracy rises to 72%.

In Figure 22, only days on which the regional wind was from south of west were plotted. Figure 23 displays those days with regional air flow from the west or north of west. For the southwesterly wind days, a ΔT:w ratio of slightly less than 2.2:1 separated lake breeze and non-lake breeze days with 77% accuracy. Days of northwesterly winds were too few to give very meaningful results; however, a line representing a ΔT:w ratio of 0.9:1 provided 79% accuracy in separating lake breeze and non-lake breeze days (again not considering one day with seemingly anomalously high recorded lake temperature).

The graphs thus indicate that greater land-water temperature contrasts and/or weaker regional winds are required for development of lake breezes at Michigan City

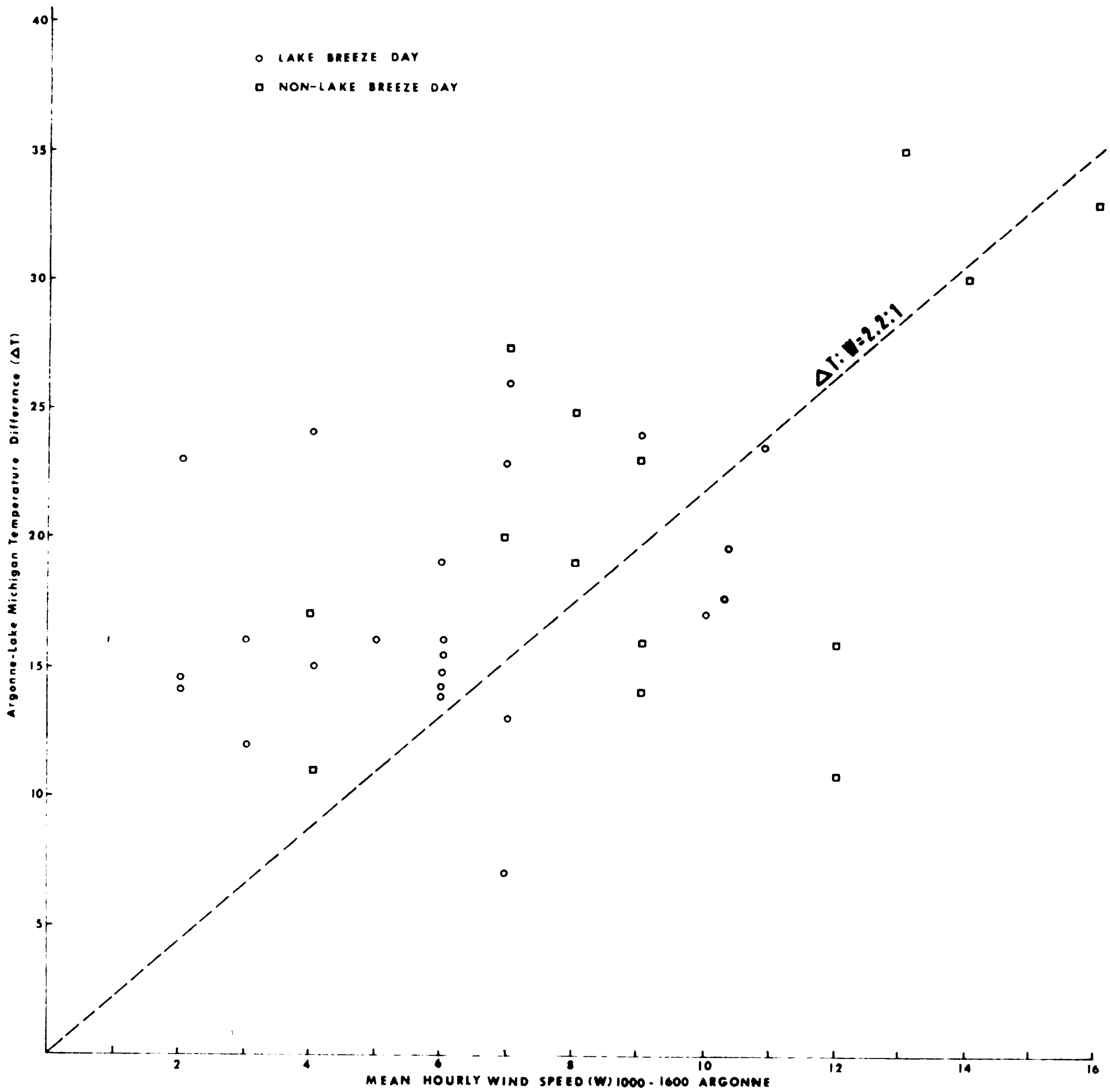


FIGURE 21

LAKE BREEZE AND NON-LAKE BREEZE DAYS AT MICHIGAN CITY PLOTTED BY LAND-WATER TEMPERATURE CONTRAST AND MEAN WIND SPEED: REGIONAL FLOW FROM 180°-360° INCLUSIVE

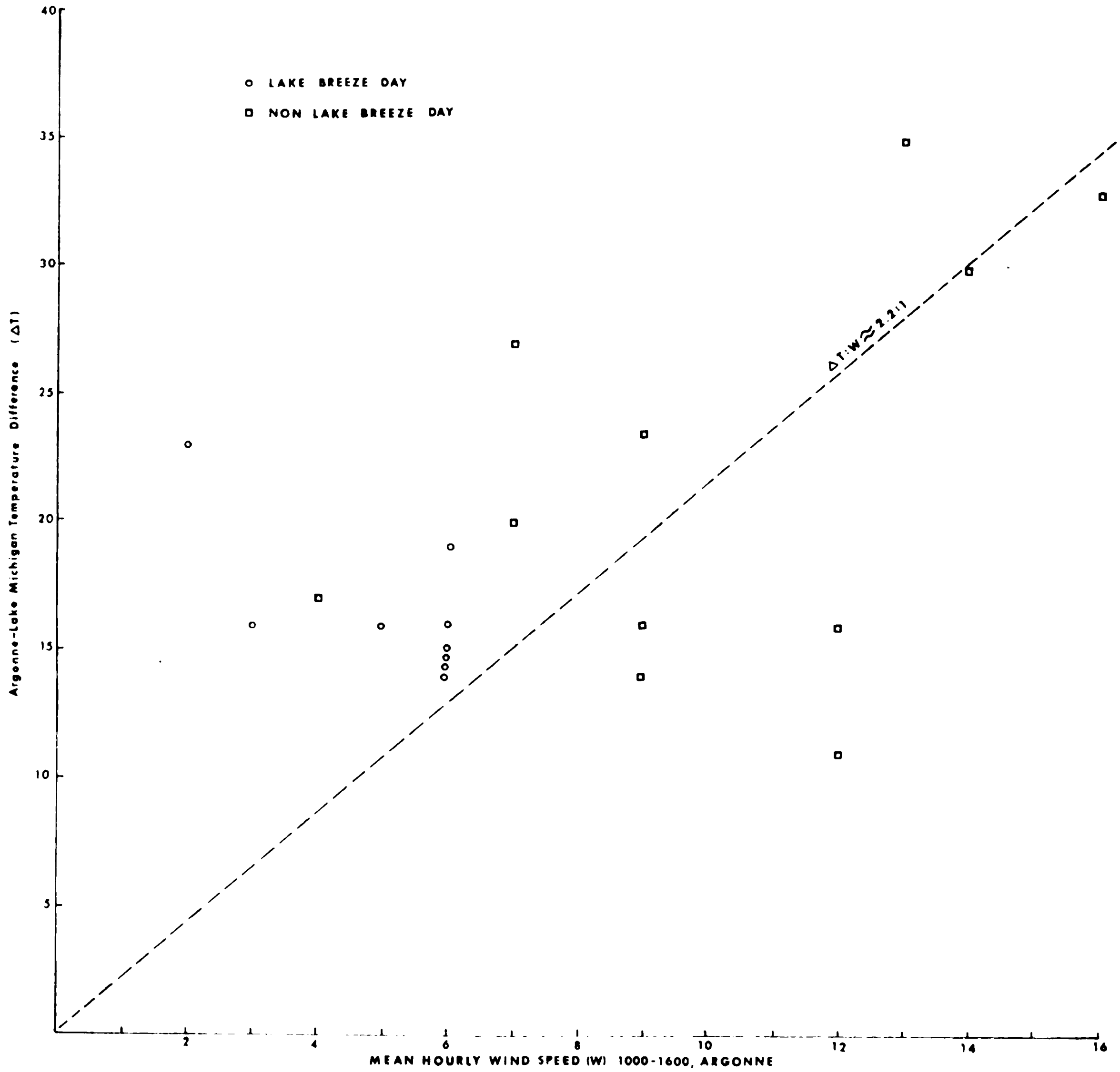


FIGURE 22

LAKE BREEZE AND NON LAKE BREEZE DAYS AT MICHIGAN CITY PLOTTED BY LAND-WATER TEMPERATURE CONTRAST AND MEAN WIND SPEED: REGIONAL FLOW FROM 180°-269° INCLUSIVE

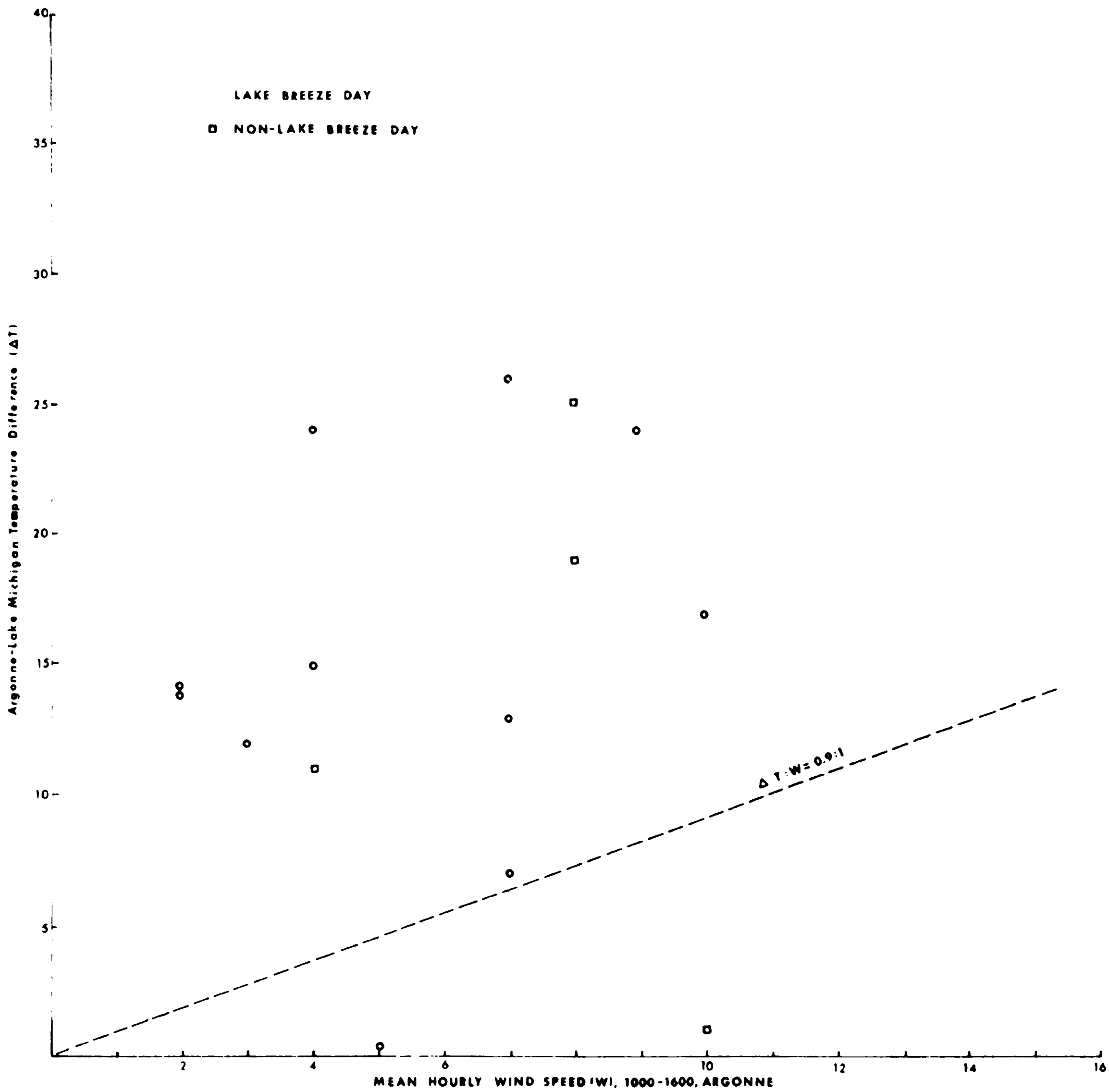


FIGURE 23

LAKE BREEZE AND NON-LAKE BREEZE DAYS AT MICHIGAN CITY PLOTTED BY LAND-WATER TEMPERATURE CONTRAST AND MEAN WIND SPEED: REGIONAL FLOW FROM 270°-360° INCLUSIVE

during a southwesterly flow than with westerly or northwesterly flow. During the study period, lake breezes did not develop under southwesterly regime when the temperature contrast was less than 14°F or when the wind speed exceeded 11 miles per hour. With westerly to northwesterly flow, lake breezes formed with a temperature contrast as low as 7°F; maximum favorable wind speed appeared to be about the same as for southwesterly flow.

The same 37 days were also divided on the basis of whether lake breeze development seemed to take place at Ogden Dunes and were plotted as above. Figure 24 presents the results. A line representing a $\Delta T:w$ ratio of 2.9:1 differentiated lake breeze and non-lake breeze days with 73% accuracy. The following summary statements can be made regarding lake breeze occurrence at Ogden Dunes during the study period: (1) lake breezes developed on markedly fewer days at Ogden Dunes than at Michigan City (13 vs. 22); (2) most of this reduction occurred during southwesterly air flow (3 lake breeze days at OGD under such flow vs. 11 at MCY); (3) lake breezes occurred under southwesterly flow at Ogden Dunes only under conditions of high land-water temperature contrast (16°F or more) and weak regional flow (6 miles per hour or less); (4) the steeper slope of the $\Delta T:w$ line, as compared with that for Michigan City, indicates that on the average greater land-water temperature differences and/or weaker regional winds are required for

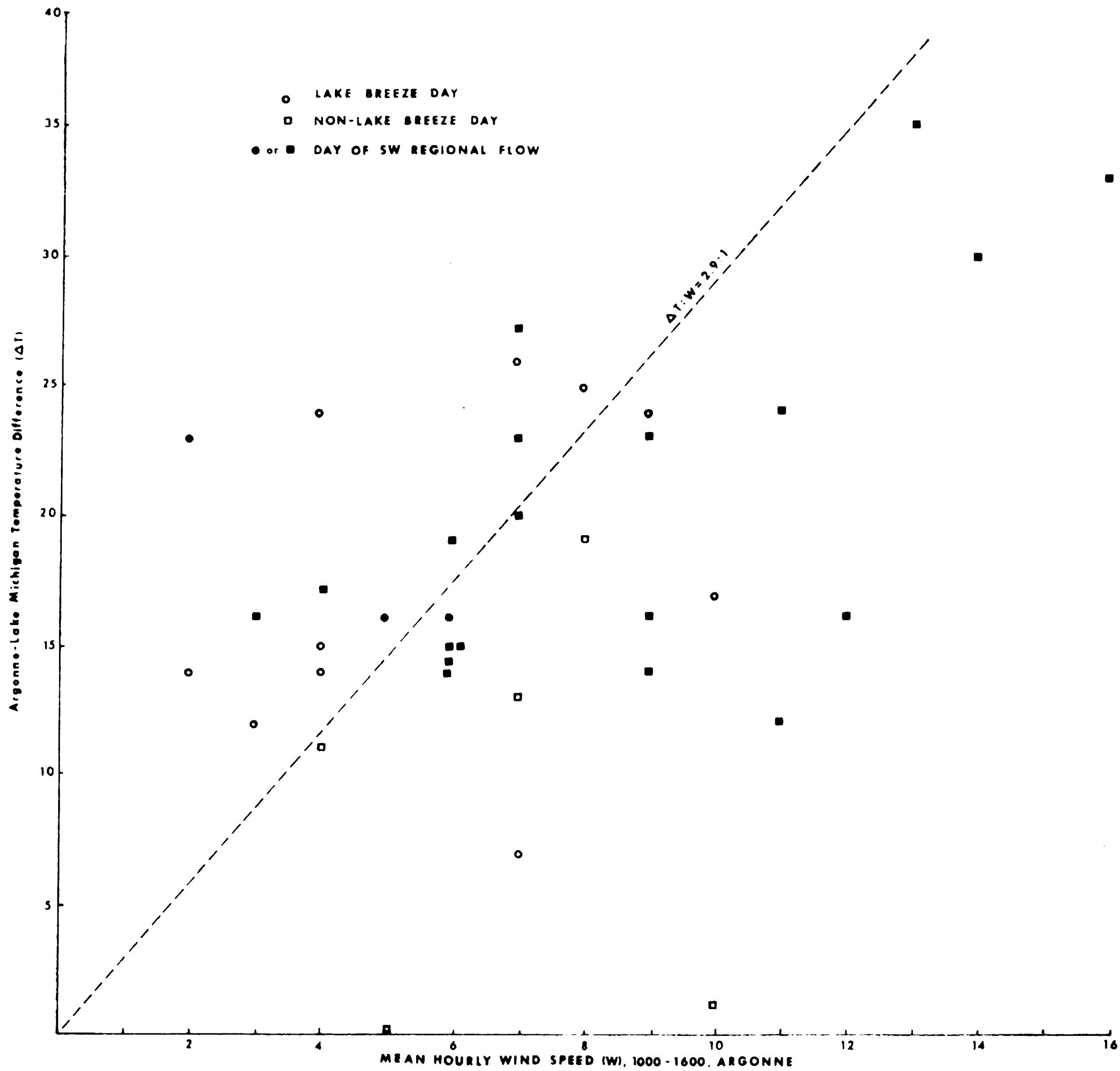


FIGURE 24

LAKE BREEZE AND NON-LAKE BREEZE DAYS AT OGDEN DUNES PLOTTED BY LAND-WATER TEMPERATURE CONTRAST AND MEAN WIND SPEED: REGIONAL FLOW FROM 180°-360° INCLUSIVE

lake breeze development at Ogden Dunes; this is understandable since OGD is situated on a more windward shoreline than is MCY.

The ratio of land-water temperature contrast to mean inland wind speed used above is similar to the "lake breeze index" derived through dimensional analysis by Biggs and Graves (6). The only major difference is that the latter index utilized the square of wind speed rather than the measured value. Biggs and Graves found that their index separated lake breeze and non-lake breeze days on the western shore of Lake Erie with 95% accuracy. Several factors might help explain the lower accuracy attained in the present study. First, the study period of one season was too short to allow accumulation of sufficient data. Second, the station used to represent inland temperature and wind conditions (Argonne) is a considerable distance west of the sites being investigated (about 60 miles from Michigan City) and may not accurately indicate the local situation in which a lake breeze would have to develop. Finally, the water temperatures used were taken at a depth of about six feet near Chicago (8). Although one study has found that lake surface temperatures are nearly uniform within ten miles of the shore between Benton Harbor and Chicago (51), there may be as much as 10°F difference between surface temperatures and those at 6 feet (8). Surface temperature readings nearer the study area would have been desirable.

During much of the summer of 1969, anomalous weather conditions prevailed over the western United States (47,48, 49). In June, a deep trough at upper tropospheric levels over the North Central States brought unusually strong northerly flow, frequent storms and persistent cloudiness to the Great Lakes region; these factors resulted in negative temperature departures which did not favor lake breeze development. During July the pattern normalized somewhat but temperatures remained slightly below normal. Only August was favorable for lake breeze development, and 15 of the 22 days analyzed occurred during that month.

These anomalous conditions reduced the amount of data available for the present investigation. A longer period of observation would greatly aid both the attempt to determine the mean position of lake breeze fronts and the effort to identify conditions of land-water temperature contrast and regional wind speed which are favorable to lake breeze development.

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CHAPTER V

DISCUSSION

The results of the climatic survey reported in Chapter IV suggest that during June through August of 1969, on days when lake breezes developed on the southeastern shore of Lake Michigan, the lake breeze front frequently penetrated to the vicinity of La Porte. Literature has been cited which indicates that convergence, vertical air motion, and cloud formation can occur along the front of a lake breeze. The role which the location of this convergence has played in the existence of the La Porte rainfall anomaly can not be assessed by this project. Some conjecture and discussion is possible, however.

Changnon (1) believed that lake breeze development in northwestern Indiana might assist in the overall process resulting in the anomaly. He concluded, however, that the addition of nuclei, heat, and moisture to the atmosphere by the industrial complex near Gary, Indiana, was the primary cause. His data showed that warm season precipitation at La Porte began increasing above that of Valparaiso and South Bend about 1925 and remained anomalously high through approximately 1960. Changnon believed that the temporal pattern of rainfall at La Porte correlated well with that of

steel production by the Gary-Chicago complex over the same period.

Ogden (2), however, believed that a 20% increase in the average reading due to a change of gage site in 1927 could account for all precipitation changes up to 1940. Changes since 1940 have been on the order of 20%, and he observed variations of this magnitude occurring frequently in Australia unrelated to changes in neighboring stations or industrial activity. Holzman and Thom (3) concluded that measurement error following a change in observer and instrument site in 1927 was responsible for the apparent anomaly.

The possibility must also be considered, however, that mean macroscale climatic patterns between 1925 and 1960 were different from those before and after that period, and that the patterns prevailing during that period somehow favored the La Porte anomaly. Namias (4,5) found that during the 1960's the mean position of a mid-tropospheric long-wave trough which normally lies over the eastern United States during the summer shifted offshore. This resulted in subsidence and stability over the northeastern part of the country; it also produced below normal temperatures as a result of an increased northerly component in upper level winds. Wahl and Lawson (6) have suggested that the cooling since 1960 represents a return to conditions which prevailed in the late 1800's. Lamb (7) also believed that post-1960 climatic conditions have been similar to those of the late 19th century and noted an increase in meridional air flow over extratropical regions. Thus there is some evidence that the climatic regime of the eastern United States may have undergone variations within the last 75 years which correspond temporally with the apparent emergence and subsequent decline of the La Porte rainfall anomaly.

In an effort to gain some further understanding of climatic conditions in northwestern Indiana before, during, and after the period when the La Porte anomaly was most pronounced, Table 10 was prepared. In this table the June-August rainfall totals for La Porte and Valparaiso are presented for each year since 1914. The difference in precipitation between the two stations is also given (positive when La Porte's rainfall exceeds that at Valparaiso). In addition, the mean daily maximum temperature for June through August at La Porte and its departure from the 1931-1962 normal mean daily maximum is presented for each year. Data for these figures were obtained from <u>Climatological Data</u> (8).

It can be seen that prior to 1930 and after 1960 mean daily maximum temperatures were predominantly below normal; the average departure was -1.5°F for the period 1913-1929 and -1.5°F for 1961-1969. During the intervening years positive departures were more frequent than negative departures, with the average being +0.2°. These findings are in agreement with those of the studies mentioned above

TABLE 10.--Summer Precipitation and Temperature Data for La Porte and Valparaiso, 1914-1969.

Year	June-August Precipitation, Inches			June-August Temperature, °F	
	La Porte	Valparaiso	Difference	Mean Maximum	Departure from normal*
1969	11.37	11.33	+ .04	82.3	-1.9
1968	11.99	15.86	- 4.87	84.3	+0.1
1967	10.53	12.61	- 2.08	81.6	-2.6
1966	13.37	9.11	+ 3.26	84.2	0.0
1965	9.21	10.58	- 1.37	81.6	-2.6
1964	11.05	8.88	+ 2.17	83.4	-0.8
1963	10.42	11.89	- 1.47	82.7	-1.5
1962	10.22	8.22	+ 2.00	82.4	-1.8
1961	13.83	13.24	+ 0.59	82.0	-2.2
1960	14.94	11.61	+ 3.33	--	--
1959	17.88	11.04	+ 6.84	86.2	+2.0
1958	27.79	16.63	+11.16	80.1	-4.1
1957	14.98	16.87	- 1.89	83.4	-0.8
1956	10.28	9.03	+ 1.25	84.6	+0.4
1955	15.47	12.58	+ 2.89	86.1	+1.9
1954	19.76	15.36	+ 4.40	83.9	-0.3
1953	10.81	9.86	+ 0.95	86.6	+2.4
1952	14.55	9.69	+ 4.86	85.5	+1.3
1951	10.38	14.36	- 3.98	79.8	-4.4
1950	21.17	14.59	+ 6.58	--	--
1949	10.62	8.64	+ 1.98	85.8	+1.6
1948	12.01	4.93	+ 7.08	82.9	-1.3
1947	13.45	8.26	+ 5.19	83.7	-0.5
1946	12.38	15.10	- 2.72	83.0	-1.2
1945	20.22	12.16	+ 8.06	80.6	-3.6
1944	9.82	6.90	+ 2.92	86.7	+2.5
1943	20.19	15.07	+ 5.12	86.0	+1.8
1942	16.12	10.11	+ 6.01	82.6	-1.6
1941	12.96	11.60	+ 1.36	84.3	+0.1
1940	13.34	10.30	+ 3.04	84.0	-0.2
1939	18.84	12.79	+ 6.05	83.5	-0.7
1938	22.72	14.94	+ 7.78	82.3	-1.9
1937	11.27	10.93	+ 0.34	82.9	-1.3
1936	8.79	7.46	+ 1.33	88.6	+4.4
1935	10.60	10.44	+ 0.16	82.8	-1.4

TABLE 10.--Continued

Year	June-August Precipitation, Inches			June-August Temperature, °F	
	La Porte	Valparaiso	Difference	Mean Maximum	Departure from normal*
1934	9.03	9.18	- 0.15	89.1	+4.9
1933	9.21	8.29	+ 0.92	87.4	+3.2
1932	13.43	16.06	- 2.63	84.6	+0.4
1931	12.11	9.71	+ 2.40	85.4	+1.2
1930	8.02	6.49	+ 1.53	84.4	+0.2
1929	14.12	10.28	+ 3.84	81.2	-3.0
1928	11.14	12.30	- 1.16	79.9	-4.3
1927	11.31	11.35	- 0.04	76.7	-7.3
1926	12.03	14.02	- 1.99	83.3	-0.9
1925	10.32	7.94	+ 2.38	86.0	+1.8
1924	12.48	15.45	- 2.97	82.0	-2.2
1923	15.65	15.94	- 0.29	83.9	-0.3
1922	5.07	4.67	+ 0.40	82.5	-1.7
1921	8.51	8.44	+ 0.07	87.1	+2.9
1920	--	9.18	--	--	--
1919	--	6.73	--	--	--
1918	6.49	7.63	- 1.14	83.3	-0.9
1917	--	7.96	--	--	--
1916	10.52	10.21	+ 0.31	84.8	+0.6
1915	11.89	14.10	- 2.21	77.1	-7.1
1914	9.37	--	--	85.9	+1.7

*Based on 1931-1962 mean daily maximum for June-August (1950 and 1960 data missing).

and suggest that more very warm days occurred between 1930 and 1960 than before or after that period. Since daily maximum temperature is one important factor in determining whether a lake breeze develops, these data might suggest that lake breezes could have been more frequent during the 1930-1960 period.

A general correspondence between the La Porte-Valparaiso precipitation difference and the mean maximum temperature departure at La Porte can be seen in Table 10. During the predominantly below normal periods 1913-1929 and 1961-1969, the June-August precipitation contrast between the two stations averaged -0.23 inches and -0.19 inches, respectively. From 1930 through 1960, when summer mean maximum temperatures were more frequently above normal, the average precipitation difference was +2.97 inches. The relationship between temperature departure and precipitation difference for individual years is not marked; in 29 of 49 years the two variables had the same sign. This fact would not be surprising, however, even assuming that lake breezes were more frequent during the period in which the La Porte anomaly was most pronounced. Maximum temperature is only one of several variables which determine whether a lake breeze will develop on a given day. Furthermore, the June-August mean maximum temperature is too coarse a measurement to yield a high degree of correlation. Even in the coolest years there presumably were days conducive to lake breeze development, and only one or two such days might be required if other conditions were favorable to produce a positive rainfall anomaly at La Porte. It would be expected, however, that over a period of years cool mean maximum temperatures would reduce the probability that such favorable days would occur, while higher temperatures would increase that probability. The climate of northwestern Indiana during the 1930-1960 period differed from that of preceding and subsequent years in general temperature regime as well as in the development of the La Porte anomaly. This fact suggests that the La Porte anomaly could have been favored in some way by other climatic characteristics which existed during those years.

In order to determine whether the La Porte anomaly appears to be associated with particular upper level circulation patterns, eight specific years were selected for consideration; a detailed examination of such an association is beyong the scope of this research, however. In five of these years, 1939, 1945, 1947, 1948, and 1958, the La Porte anomaly was strongly developed during June-August; in the remaining three years, 1961, 1966, and 1967, the anomaly was not evident. For each of the three summer months in these years La Porte and Valparaiso precipitation values were obtained from Climatological Data (8) and mean upper level circulation was determined from Monthly Weather Review (9) or Climatological Data-National Summary (10).

In eight of the 23 months examined (no upper level charts were available for July, 1939), rainfall at La Porte exceeded that at Valparaiso by two inches or more; in the other 15 months precipitation at the two stations differed by less than two inches. For seven of those eight months in which the anomaly was pronounced, charts indicated that northwestern Indiana was overlain by a mean upper-level trough or the eastern edge of a trough. In such locations divergence aloft generally favors atmospheric instability and precipitation. On the other hand, during 12 of the 15 months when the anomaly was not evident the study area was in the mean overlain by the center or eastern limb of an upper level ridge. In this situation, convergence aloft favors stable atmospheric conditions and reduced precipitation. It is interesting to note that this association on a monthly basis between upper level conditions and the La Porte anomaly is similar to the longer-term (pre-and post-1960) association of upper level patterns as described by Namias (4,5) and the strength of the anomaly. This preliminary investigation suggests that the apparent circulation changes which have occurred since 1960 and perhaps prior to 1930 may have had a strong influence on the occurrence of the La Porte anomaly.

In summary, it appears that the mean summer pattern of upper level circulation over the eastern United States during the years when the La Porte anomaly was most pronounced, approximately 1930-1960, was different from that which prevailed in the late 1800's and which has predominated since 1960. Furthermore, the post-1960 pattern is similar to that which prevailed on a monthly basis when the La Porte anomaly did not develop during the period 1930-1960. Thus it appears that upper level conditions may play a major role in controlling the La Porte anomaly.

The significance of these findings in terms of the hypothesis of this project that lake breeze convergence is related to the La Porte anomaly is uncertain. It is possible that stable atmospheric conditions, favored beneath and near the eastern margin of upper level ridges, reduce the likelihood that convergence along a lake breeze front will produce precipitation. The forced vertical air movement in the convergence zone might not be sufficient to overcome the stability and trigger the convection required to result in rainfall. If the increased prevalence in summer of mid-tropospheric ridges over the eastern United States since 1960, reported by Namias, in fact represents a return to a pattern that prevailed in the late 1800's, then it may be that the period 1930-1960, when the La Porte anomaly was prounounced, was an interval of more frequent and general atmospheric instability associated with a rearrangement of the mean long waves. Such conditions could have favored precipitation along lake breeze fronts. It is also possible, however, that the degree of atmospheric stability would affect the impact of industrial pollution on convection and precipitation in the same way. The industrial influence might be able to initiate or intensify convection and increase rainfall under naturally unstable conditions, but might have little effect when stability prevails.

Two findings reported by Changnon (1) are of particular interest here. First, during the period 1951-1964, 48% of the days when thunderstorms were reported at La Porte but not at neighboring stations occurred when very flat regional pressure gradients existed; only 15% occurred when gradients were steep. In order for a lake breeze to develop, the land-water pressure differential near the surface must overcome the effect of any regional gradient; therefore days with weak pressure gradients favor lake breeze development. Second, the number of thunderstorms reported at Ogden Dunes from 1949 to 1965, although less than at La Porte, was higher than at other surrounding stations. Changnon cited this as further evidence of the probable importance of industrial pollution west of these two sites. Figure 16, however, suggests that, with winds from westerly azimuths, a lake breeze front frequently crosses the shore near Ogden Dunes. Thus this station may also be near the mean convergence zone location.

The findings detailed in Chapter III may be relevant to a recent study of the plant geography of the sand dunes along the southeastern shore of Lake Michigan. Harman (11) described a forest gradient along the dunes from a more mesophytic association of species in southwestern Michigan to a more xerophytic one in Porter County, Indiana. He hypothesized that summer drought in the region was especially pronounced under southwesterly surface flow associated with a mid-continent upper level ridge. Further, he proposed that when such conditions prevailed, lake breeze flow would be more frequent along the Michigan shore than along the shore of Indiana. The presumably cooler, more humid lake air, Harman believed, could reduce the severity of summer drought sufficiently to enable mesophytic species to survive on the shore more frequently subjected to its influence. The present study (see Figure 17) lends support to Harman's hypothesis regarding lake breeze penetration. For those days of southwesterly regional flow the frequency of lake breeze occurrence declined rapidly southwest of Michigan City. At Ogden Dunes, lake breezes occurred only one-fourth as often as at Michigan City. Thus lake breeze flow does appear to be considerably more common in northern La Porte County and southwestern Michigan than in Porter County.

The research method of employing wind data collected at several stations to analyze lake breeze flow patterns was found to be very useful. Except for the station farthest from Lake Michigan, Wanatah, it was generally not difficult to determine whether a station experienced lake breeze flow at a given time.

The number of stations used in this study was not sufficient to allow accurate determination of the position of the lake breeze front at a particular time or in the mean. Unless a researcher is able to provide his own instrumentation, however, a station network of greater density will not be available in northwestern Indiana in the near future. Greater uniformity of instrument sites would be desirable also. The instrument at Westville experienced considerable oscillation due to deflection of air currents by the building on which it was situated. Wind velocities at Ogden Dunes, where the instrument tower projects only slightly above surrounding trees, were consistently lower than those at other stations; wind direction did not seem to be greatly affected.

An investigation similar to that described here, extended over several lake breeze seasons and encompassing southwestern Michigan as well as northwestern Indiana, should greatly improve our understanding of lake breeze flow patterns and their possible relationship with biogeographical patterns such as that described by Harman (11). Most previous published studies of lake breeze characteristics have been confined to examination of one or a few days. A longer study period would allow investigation of flow under more narrowly defined synoptic situations and would more clearly establish mean frontal positions.

Finally, determination of the degree of relationship between the La Porte anomaly and lake breeze convergence will require comparison of daily wind and precipitation patterns in the study area over a long period of time. It seems doubtful that such investigation could be conducted on the basis of past records, since lengthy wind records are available for only three of the six stations utilized in the present study.

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CHAPTER VI

SUMMARY AND CONCLUSIONS

I

The present study was undertaken to evaluate possible phytogeographic evidence of the La Porte rainfall anomaly (1), and to make a preliminary test of the hypothesis that the anomaly is in part the result of convergence along lake breeze fronts associated with Lake Michigan.

II

A forest composition survey was conducted within the Valparaiso morainic area in La Porte, Porter, and Lake Counties, Indiana during August and September, 1969. The per cent contribution of all tree species to the canopy of twenty-six forest stands was estimated by examination of two one-half acre plots in each stand. Shrub species observed in each stand were also recorded.

The survey indicated that an abrupt change in forest type occurs from northeast to southwest along the Valparaiso moraine. Stands in La Porte County and eastern Porter County were found to be dominated by mesophytic species, particularly *Fagus grandifolia* (beech) and *Acer saccharum* (sugar maple); stands in western Porter and Lake Counties

were dominated by more xeric species, primarily *Quercus velutina* (black oak), *Quercus alba* (white oak), *Carya ovata* (shagbark hickory), and *Carya glabra* (pignut hickory). The distribution of several shrub species paralleled the change in canopy composition.

Since studies have suggested that a similar distribution of forest types existed prior to major European settlement of the area (2,3), it is concluded that the forest contrast is probably the result of an environmental gradient and has not been produced by cultural factors.

III

A pilot survey of soil texture, and pH was also conducted within the Valparaiso morainic area. Soil samples were collected for analysis from the B horizon and from a depth of four feet within each surveyed forest stand. Clay loams and silty clay loams were found to predominate at the lower depth. Although there was considerable variation between stands, soils of the western half of the study area were found to have a higher percentage of clay and a lower percentage of sand than those of the eastern half. In general, positive correlations were found between the per cent of selected mesophytic species in the canopy and the percentage of sand in the soil, and negative correlations between these species and the per cent of clay. No important relationship between forest distribution and soil pH was detected.

Because northwestern Indiana is a tension zone between major vegetation types, it seems possible that the greater clay content in the western part of the study area could, even in the absence of a long-term La Porte anomaly, reduce readily available water capacity sufficiently to result in the absence of the mesophytic species. Therefore it is concluded that the forest contrast cannot be cited as strong evidence for a long-term climatic gradient through the area.

The forest contrast along the moraine may be the result of a complex of interacting factors. Winter snowfall is heavy in La Porte County and decreases westward through the study area (4); this could affect soil moisture conditions during the early part of the growing season. In addition, the study area lies near the margin of the "prairie peninsula" (5) within which precipitation-evaporation ratios decrease, precipitation becomes more variable from year to year, and summer drought becomes more frequent; these climatic tendencies may become more pronounced westward in northern Indiana. These factors, as well as soil textural differences and any long-term warm-season rainfall gradient associated with lake breeze convergence, could be collectively responsible for the forest contrast.

A detailed consideration of the possible ecological importance of fires from adjacent prairie areas on forest distribution in the study area is beyond the scope of the present study. Since there apparently has been little change in the position of the forest transition since the early 1800's, however, fires are not thought to have been a major control.

IV

Wind data were collected at six stations in northwestern Indiana and northeastern Illinois from June 11 through August 31, 1969. Twenty-two days on which lake breezes occurred along the southeastern shore of Lake Michigan were identified and their wind patterns intensively studied. Analysis of data for these days indicated that the lake breezes frequently penetrated to the vicinity of La Porte and that inland penetration was greater during days of northwesterly surface flow than southwesterly flow. Under a northwesterly flow regime, lake breezes apparently reached La Porte on over 60% of the lake breeze days and were detected at Wanatah, approximately 18 miles from the lakeshore, on 18% of the days. With flow from southwesterly azimuths, penetration to La Porte occurred on less than 40% of the days and no lake breezes were detected at Wanatah.

Lake breeze frequency under all winds with a westerly component was found to decrease markedly westward from Michigan City along the southern shore of Lake Michigan. During the study period lake breezes were about half as frequent at Ogden Dunes as at Michigan City. When the regional wind was from south of west, lake breezes developed only one-fourth as often at Ogden Dunes as at the latter station.

The technique of using wind direction data to study lake breeze penetration was found to be very effective. However, an accurate determination of the mean position of the lake breeze front in northern Indiana under various synoptic patterns will require the establishment of additional recording stations in the area as well as the extension of observation over several lake breeze seasons.

V

For thirty-seven lake breeze and non-lake breeze days at Michigan City the mean hourly wind speed (1000-1600 EST) at Argonne and the difference between Argonne maximum temperature and Lake Michigan water temperature were determined. The days were then graphed according to the values of these two variables. It was found that a ratio between mean regional wind speed and land-water temperature contrast of 2.2:1 separated lake breeze and non-lake breeze days with 65% accuracy. The graphs also demonstrated that stronger land water-temperature contrasts and/or weaker regional winds were required for development of lake breezes when the regional wind was from the southwest quadrant than when westerly or northwesterly winds prevailed.

Lake breeze occurrence at Ogden Dunes was examined in the same manner. A line representing a ratio between mean regional wind speed and land-water temperature contrast of 2.9:1 separated lake breeze days from the non-lake breeze days with 73% accuracy. Thus greater temperature contrasts and/or weaker regional winds were required for lake breeze formation at Ogden Dunes than at Michigan City. Lake breezes were found to occur at the former station under regional flow from south of west only when the land-water temperature difference was very high and the regional wind was weak.

It is believed that the accuracy of differentiation between lake breeze and non-lake breeze days would increase if a longer study period were employed, if wind direction categories were more narrowly defined, if a station nearer the locations being considered were used to represent inland temperature and wind conditions, and if surface lake temperatures nearer the study area could be obtained.

VI

The La Porte anomaly was most pronounced from 1930 through 1960. Studies have suggested that the period of greatest anomaly development may have corresponded to an interlude in which the climate of the eastern United States differed from that which prevailed in the 1800's and which has prevailed since 1960 (6,7). Namias (8) found that during the 1960's an upper-level long-wave trough frequently lay off the eastern coast of the U. S. during the summer, thus placing the Great Lakes Region east of a mid-continent ridge. During the 1930-1960 period, the mean

summer long-wave trough position was over the eastern United States.

Examination was made of upper-level circulation patterns for eight summer months in which La Porte rainfall exceeded that at Valparaiso by two inches or more and for 15 months in which precipitation at the two stations differed by less than two inches. During 7 of the 8 months in which the La Porte anomaly operated, the study area lay under or just to the east of a mean upper-level trough; during 12 of the 15 months when the anomaly was not developed, the study area lay under an upper-level ridge. Thus the upper air patterns which prevailed seasonally during the 1960's when the La Porte anomaly was less operative apparently also prevailed during the period 1930-1960 in those months when the anomaly did not develop.

This apparent temporal association on both a long-term and a monthly basis between the appearance and disappearance of the La Porte anomaly and the prevalence of certain upper air patterns suggests that the anomaly may not be the result of atmospheric pollution alone.

Determination of whether the La Porte anomaly is related causally to lake breeze convergence would require examination on a daily basis of wind flow and precipitation patterns in the study area over a period of several years. It is doubtful that this can be done for past years because of the scarcity of stations for which wind records exist.

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APPENDICES

APPENDIX I

LOCATIONS OF SURVEYED FOREST STANDS

Stand No.	County	Congressional Land Description		Road
1	La Porte	Sec. 20	T38N,R1W	NE side Emergy W of 750E
2	La Porte	Sec. 16	T37N,R1W	NE corner 350N-850E
3	La Porte	Sec. 15	T37N,R2W	SW corner 600N-150E
4	La Porte	Sec. 20	T37N,R3W	S side 300N near 400W
5	La Porte	Sec. 19	T37N,R3W	W side 500W S of Johnson
6	La Porte	Sec. 16	T36W,R4W	N side 250S
7	La Porte	Sec. 20	T36N,R4W	E side 1100W
8	La Porte	Sec. 18	T36N,R4W	N side 300S
9	Porter	Sec. 36	T36N,R6W	S side 700N E of 625E
10	Porter	Sec. 16	T35N,R5W	W side of 325E ¼ mi. N of 300N
11	Porter	Sec. 4	T35N,R5W	E side of 300E
12	Porter	Sec. 5	T35N,R5W	N side of 500N
13	Porter	Sec. 18	T35N,R5W	S side of 400N ¼ mi. W of 200E
14	Porter	Sec. 7	T35N,R5W	E side Rt. 49 S of 450N
15	Porter	Sec. 2	T35N,R6W	NE corner 550N - 50W
16	Porter	Sec. 26	T36N,R6W	SW corner Meridian Rd.-U.S.6
17	Porter	Sec. 4	T34N,R6W	W side Rt. 2
18	Porter	Sec. 7	T34N,R6W	E side 500W N of C&O tracks
19	Porter	Sec. 19	T35N,R6W	S side U.S.30
20	Porter	Sec. 34	T35N,R7W	N side Division Rd.
21	Lake	Sec. 19	T34N,R7W	E side Gibson N of 129th
22	Lake	Sec. 11	T33N,R8W	W side Colorado near 157th
23	Lake	Sec. 30	T35N,R8W	N side 91st E of Whitcomb
24	Lake	Sec. 36	T34N,R9W	W side Clark
25	Lake	Sec. 29	T34N,R9W	S side Brunswick
26	Lake	Sec. 5	T33N,R9W	S side 151st W of Magoun

APPENDIX II

TOTAL NUMBER OF ARBOREAL STEMS

SURVEYED IN EACH STAND*

Stand Number	Number of Stems
1	118
2	83
3	202
4	148
5	139
6	204
7	155
8	111
9	152
10	92
11	184
12	130
13	150
14	98
15	80
16	71
17	99
18	106
19	82
20	89
21	82
22	64
23	108
24	101
25	163
26	100

*Data in this Appendix can be used in conjunction with Table 1 to determine absolute densities (per acre) of individual species.

APPENDIX III

PER CENT SAND, SILT, AND CLAY FOR INDIVIDUAL SOIL SAMPLES

Stand No.	B Horizon			Four-Foot Depth		
	Sand	Silt	Clay	Sand	Silt	Clay
1	27.8	42.5	29.7	62.5	22.0	15.5
	17.4	44.4	38.2	21.3	47.7	31.0
2	21.4	52.7	25.9	15.1	56.0	28.9
	82.3	11.7	6.0	72.1	16.9	11.0
3	91.0	5.9	3.1	95.8	0.9	3.3
	67.3	29.6	3.1	92.5	5.2	2.3
4*	46.0	29.8	24.2	47.2	23.9	28.9
	41.4	31.5	27.1	--	--	--
5	38.7	43.2	18.1	38.5	33.1	28.4
	42.2	38.2	19.3	46.2	29.7	24.1
6	6.8	57.1	36.1	20.3	49.7	30.0
	15.5	48.6	35.9	21.1	49.8	29.1
7	25.3	43.2	31.3	19.3	41.7	39.0
	21.5	47.2	31.3	17.7	55.3	27.0
8	24.3	42.8	26.9	38.9	32.5	28.6
	28.4	45.7	25.9	63.7	17.8	18.5
9	25.8	46.6	27.6	19.6	40.7	39.7
	15.2	51.4	33.4	15.0	52.2	32.8
10	32.9	39.4	27.7	45.0	34.2	20.8
	21.6	39.0	39.4	25.1	41.5	33.4
11	58.5	15.9	25.6	29.4	38.7	31.9
	44.1	34.5	21.4	23.6	49.1	27.3
12	24.2	44.4	31.4	26.6	41.6	31.8
	32.2	43.6	24.0	18.7	42.5	38.8
13	36.3	36.1	27.6	34.7	42.0	23.3
	33.1	40.3	26.6	36.8	37.3	25.9

Appendix III--Continued

Stand No.	B Horizon			Four-Foot Depth		
	Sand	Silt	Clay	Sand	Silt	Clay
14	28.0	47.5	24.5	23.2	50.6	26.2
	13.7	48.5	37.8	28.8	43.3	27.9
15	14.7	51.7	33.6	14.7	51.4	33.9
	17.8	49.2	33.0	14.0	54.0	32.0
16	17.4	48.8	33.8	18.2	55.8	26.0
	18.1	46.8	35.1	23.0	51.0	26.0
17	27.1	43.1	29.8	30.5	37.4	32.1
	23.8	39.7	36.5	29.0	44.6	26.4
18	15.9	41.9	42.2	25.0	48.8	26.2
	17.4	41.0	41.6	27.5	43.5	29.0
19	20.7	45.1	34.2	27.1	44.7	28.2
	57.4	28.0	14.6	88.0	4.6	7.4
20	10.6	47.1	42.3	14.2	57.3	28.5
	11.9	49.7	38.4	14.9	58.1	27.0
21	30.0	28.7	41.3	16.9	51.5	31.6
	12.1	48.9	39.0	15.2	50.4	34.4
22	14.3	43.0	42.7	15.8	51.1	33.1
	16.1	39.5	44.4	60.2	20.3	19.5
23	3.4	47.9	48.7	5.9	63.8	30.3
	1.1	46.9	52.0	2.1	59.9	38.0
24	11.9	34.3	53.8	12.2	46.9	40.9
	14.1	39.5	46.4	14.9	45.0	40.1
25	2.6	37.4	60.0	21.3	49.8	28.9
	5.4	31.9	62.7	5.2	43.0	51.8
26	26.4	34.5	39.1	13.9	50.9	35.2
	22.6	37.3	40.1	31.9	37.0	31.1

*Only one sample taken from four feet due to nearly impenetrable gravel at a depth of about two feet.

APPENDIX IV

VALUES OF pH FOR INDIVIDUAL SOIL SAMPLES

Stand No.	B Horizon	Four-Foot Depth
1	4.65	4.68
	4.64	7.79
2	4.20	5.88
	5.11	5.30
3	5.39	6.06
	4.90	5.42
4	4.90	4.25
	4.53	--
5	4.69	4.43
	4.78	4.72
6	4.20	7.72
	4.46	7.99
7	5.46	5.11
	4.40	5.09
8	4.50	4.88
	4.25	5.98
9	4.45	6.24
	4.41	7.23
10	4.29	4.96
	4.60	7.49
11	4.10	4.48
	4.17	7.62
12	4.46	5.41
	4.51	7.59
13	4.62	7.62
	5.05	7.20

Appendix IV--Continued

Stand No.	B Horizon	Four-Foot Depth
14	4.76 4.30	7.84 7.70
15	4.14 4.41	7.54 7.58
16	6.41 5.41	7.64 7.78
17	4.59 4.38	5.14 7.70
18	4.10 4.39	7.84 7.12
19	4.40 5.30	5.21 4.72
20	4.08 4.77	7.63 7.69
21	4.42 4.15	7.91 7.68
22	4.49 4.13	7.61 6.83
23	5.15 5.49	7.92 7.81
24	4.29 4.22	7.81 7.84
25	4.20 4.38	7.71 7.80
26	4.21 4.24	6.59 7.70

APPENDIX V

LAKE BREEZE AND NON-LAKE BREEZE DAYS AT MICHIGAN CITY AND OGDEN DUNES, INDIANA, EXAMINED IN CHAPTER IV

Michigan City:

Twenty-two lake breeze days:	June 28 July 10, 12, 14, 23, 25, 30 August 1, 2, 4, 5, 8, 11, 12, 17, 18, 24, 25, 27-30
Fifteen non-lake breeze days:	June 16, 26 July 2, 4, 9, 11, 15, 16, 28, 31 August 6, 7, 10, 13, 31

Ogden Dunes:

Thirteen lake breeze days:	June 28 July 10, 12, 14 August 1, 2, 4, 8, 11, 12, 24, 25, 27
Twenty-four non-lake breeze days:	All other days listed for Michigan City