72-8688

HEHR, John George, 1941-
LAKE BREEZES AND PRECIPITATION PATTERNS
IN EASTERN UPPER MICHIGAN.

Michigan State University, Ph.D., 1971
Geography

LAKE BREEZES AND PRECIPITATION PATTERNS
IN EASTERN UPPER MICHIGAN

By

John G. Hehr

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Geography

1971

ABSTRACT

LAKE BREEZES AND PRECIPITATION PATTERNS
IN EASTERN UPPER MICHIGAN

By

John G. Hehr

An examination of summer rainfall data for a 12-year period revealed a greater frequency of precipitation in the interior of the eastern portion of the Upper Peninsula of Michigan than along the north or south shorelines. The present study was undertaken to evaluate the hypothesis that lake breezes develop on both the north and south coasts of eastern Upper Michigan and penetrate inland, where their convergence leads to augmented convection and subsequent precipitation which otherwise might not occur. It was also suggested that the presence of favorable upper-level air flow may increase the possibility of convective precipitation attending these lake breezes.

A survey of selected surface conditions was conducted during June, July, and August, 1970, which considered patterns of precipitation, cloud cover, temperature, relative humidity, insolation, water temperature, and wind flow across the eastern Upper Peninsula in order to provide

evidence of lake breeze convergence and subsequent precipitation. During the three month sample, ten days were identified as days of interior rain associated with lake breeze convergence after all days of cyclonic or frontal precipitation were eliminated. According to verification in the field two other sample groups were also identified: (1) days of lake breeze convergence with no rain; and (2) days of no apparent lake breeze convergence.

Precipitation data revealed that each interior rain swath occurred farther north as the summer progressed; variations of wind direction at the 300 mb. level accounted for much of this shift. A pattern of mean onshore surface wind flow during the afternoon hours verified the presence of a convergence zone somewhere over the eastern portion of the peninsula during interior precipitation days. These lake breezes often reached the interior, as indicated by abrupt shifts of wind direction during the afternoon in the central portion of the peninsula.

The insolation record indicated that interior cloud development occurred on both groups of days of interior convergence, while the coastal areas were generally cloud-free during the afternoon hours. The hygrothermograph record revealed that a decrease of temperature and increase of relative humidity normally occurred with lake breeze passage. Finally, cloud photography recorded lake-breeze-associated cloud development, cloud streets suggesting lake breeze convergence, and interior precipitation occurring from the narrow convergence zone.

A survey of selected upper-tropospheric conditions was also conducted during the three month study period in order to evaluate the assumption that certain types of upper-level air flow were associated with lake breeze convergence which resulted in precipitation. Troughs prevailed west of Michigan during the days with interior convergence and precipitation, suggesting the presence of general divergence patterns in the mid or upper troposphere. Days of interior convergence but no rain were associated with mean northwesterly flow, indicating a prevalence of ridges west of the study area and general atmospheric stability. Thus, whether convergence of lake breezes ultimately led to rainfall seemed to depend in part upon the pre-existing tropospheric environment.

Rawinsonde data including temperature, dew point, wind direction, wind speed, and pressure height were collected for the 850 mb., 500 mb., and 300 mb. levels. Days of interior convergence and rainfall were warmer, more humid, and characterized by lower wind speeds than were days of convergence without rain. A greater southerly component of the mean wind was also evident on those days of interior precipitation.

John G. Hehr

The data gathered and analyzed during the study period support the original hypothesis. The findings also suggest that certain mid or upper-level tropospheric conditions may enhance convection along the lake breeze convergence zone which then leads to precipitation.

ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to the many individuals who assisted in the completion of this study. Special appreciation is expressed to Dr. J. Harman, whose guidance and advice made this dissertation possible. Professors D. Brunnschweiler and H. Winters of the Department of Geography and H. Foth of the Department of Crop and Soil Science provided additional suggestions.

Among the individuals who aided in various phases of this study are: Mr. F. Day of the Sault Ste. Marie Weather Bureau, whose assistance in data collection was invaluable for the completion of this project; Mr. N. Strommen, State Climatologist for Michigan; Mr. M. Vanderstar, Mr. J. Hesselink, Mr. C. Erfourth, and Mr. C. Harrison, whose properties were used for instrumentation; and Mr. S. Hollander, who completed the final draft of the maps and diagrams.

Financial support during the completion of this study was provided by a graduate assistantship through the Department of Geography at Michigan State University.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

LIST OF APPENDICES

CHAPTER I

INTRODUCTION

The sea breeze and its effects upon a coastal area have been the subject of a considerable amount of research. Many authors have reported that the inland penetration of the sea breeze is attended by an abrupt decrease in temperature, increase in relative humidity, and convection along the mesoscale sea breeze front (1, 2, 3, 4). This convection can give rise to cumulus and cumulonimbus clouds that may produce showers and thundershowers along the narrow front (5, 6). Recently a considerable portion of the summer precipitation in Florida has been attributed to convection associated with sea breeze frontal zones (7).

The convergence of sea breezes (lake breezes if they occur near a large inland lake) over a peninsula has had little general documentation. An exception as noted above, the Florida peninsula has been the subject of several studies concerning the inland penetration of sea breezes from both the east and west coasts and their subsequent convergence, leading to precipitation (7, 8, 9). An early lake breeze study was also conducted over the Door Peninsula of Wisconsin and concluded that interior precipitation appeared to be related to lake breeze development (10).

Field reconnaissance in Upper Michigan indicated that interior warm season precipitation patterns may be similarly affected by lake breeze interaction where the peninsula is relatively narrow. To initially evaluate this possibility, the author analyzed 12 years of rainfall data for two groups of climatological stations across the eastern and central portion of the peninsula before the present study was undertaken (11). The results from the easternmost group indicated that the number of days during which precipitation was observed only at interior stations exceeded the number of coastal-only precipitation days. The pattern of more frequent interior precipitation seemed especially evident during the summer months, when lake breeze development should be at a maximum, and suggested that some mesoscale mechanism may operate to increase the incidence of precipitation in the interior.

The meteorological conditions that prevail over Florida during the summer period differ greatly from those found over the northern portion of the Great Lakes. Summertime air masses over Florida are usually horizontally homogeneous and stable, with little vertical wind shear, and the north-south orientation of peninsula Florida is normal to the easterly or southeasterly lower-atmospheric flow which prevails during the summer months when sea breeze development would be most favored (12, 13). Over the northern Great Lakes, on the other hand, migrating tropospheric waves are characteristic of the summertime flow. Thus, there is little temporal consistency to the air masses passing over the area, and highly variable stability and vertical wind shear conditions result. Furthermore, the east-west orientation of Michigan's Upper Peninsula is generally parallel to the mean tropospheric flow pattern, which is westerly (14). Thus, meteorological conditions associated with sea breeze development in Florida differ substantially from those prevalent in northern Michigan, and detailed application of climatological concepts developed in Florida is unjustified.

Theoretical models of sea breeze situations constructed by Estoque (15) indicate that sea breeze development and vertical air movement at the associated mesoscale front are especially strong when the geostrophic flow is parallel to the coast with general low pressure located offshore. With prevailing westerly winds during the summer over the Upper Peninsula, the development of strong lake breezes from Lake Superior would be particularly favored. A weaker lake breeze would be expected along the Lake Michigan and Lake Huron shore, and inland penetration and vertical movement might be less than in the case of the Lake Superior systems because the onshore flow of low-level air reduces the effect of diurnal land heating. A weaker gradient and circulation thus develop (15).

The flow of air through long wave systems, usually above 10000 feet, favors the development of upper-level convergence and divergence that often are compensated at the surface by opposite patterns of air flow (16). In areas east of a trough axis upper-level divergence occurs which favors low-level convergence and surface instability (17). During the summer months trough-associated low-level convergence combined with high relative humidity favors the development of convective motions and precipitation (18), and these convective motions might be strengthened and organized further by convergence of lake breezes (19). Therefore, with the approach of an upper-tropospheric trough, the interior of the Upper Peninsula would be in an area in which convective precipitation would be especially likely.

The present study concerns itself with the possible convergence of lake breezes from Lakes Superior, Michigan, and Huron over the eastern portion of the Upper Peninsula of Michigan and increased interior precipitation that may result from augmented convection along the lake breeze convergence zone (Figure I). This report, based upon a three month field survey conducted in eastern Upper Michigan, has two principal aims. First, the results of a survey of selected surface data concerning the occurrence or non-occurrence of lake breezes and interior precipitation will be presented. Second, the results of

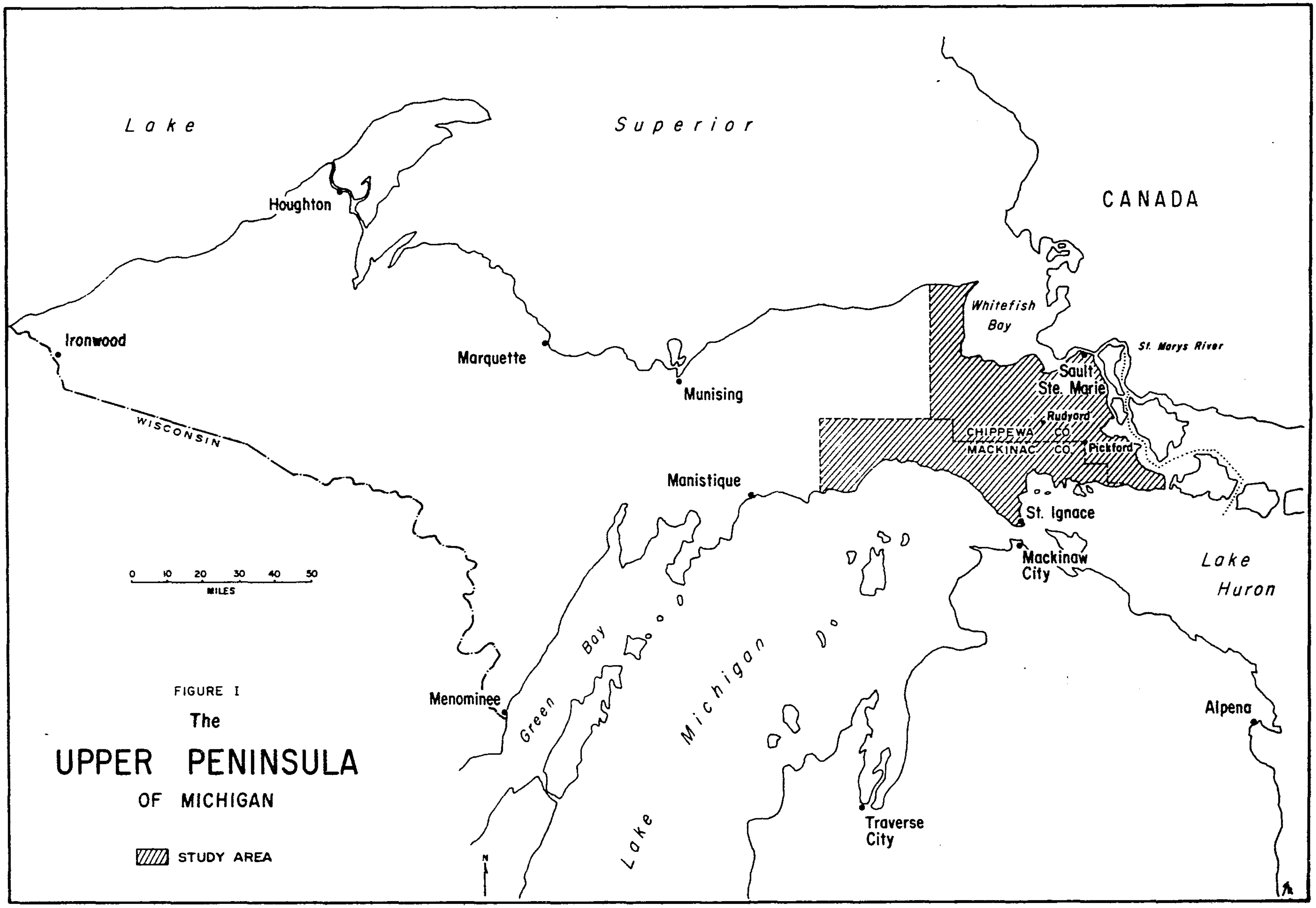


FIGURE I

The

UPPER PENINSULA

OF MICHIGAN

a survey of selected upper-level conditions which were found to be associated with interior, possibly lake breeze related, precipitation will be described. In brief, the hypothesis of this research is that lake breezes form on both the north and south coasts of Michigan's Upper Peninsula on warm summer days which possibly result in augmented convection and precipitation in the interior. It is also suggested that the presence of favorable upper-level flow may further encourage convective precipitation attending lake breezes at certain times.

CHAPTER I--REFERENCES

1. Frizzola, J. A., and Fisher, E. L. 1963. A series of sea breeze observations in the New York City area. J. Appl. Meteor. 24: 722-739.

2. Moroz, W. J. 1967. A lake breeze on the eastern shore of Lake Michigan: observations and model. J. Atmos. Sci. 24: 337-355.

3. Leopold, L. B. 1949. The interaction of trade wind and sea breeze, Hawaii. J. Meteor. 6: 312-330.

4. Defant, F. 1951. Local winds. In Compendium of Meteorology. Boston: Amer. Meteor. Soc. 655-672.

5. Eddy, G. A. 1966. The Texas coast sea breeze: a pilot study. Weather. 21: 162-170.

6. Wexler, R. 1946. Theory and observations of land and sea breezes. Bull. Amer. Meteor. Soc. 27: 272-287.

7. Byers, H. R., and Rodebush, H. 1948. Causes of thunderstorms of the Florida peninsula. J. Meteor. 5: 275-280.

8. Moore, P. L. 1963. A radar study of shower activity associated with the sea breeze. Proc. 10th Weather Radar Conf. Boston: Amer. Meteor. Soc. 8-12.

9. Gentry, R. C., and Moore, P. L. 1954. Relation of local and general wind interaction near the sea coast to time and location of air-mass showers. J. Meteor. 11: 507-511.

10. Miller, E. R. 1939. The land and sea breeze of Door Peninsula, Wisconsin. Bull. Amer. Meteor. Soc. 20: 209-211.

11. U. S. Weather Bureau. 1958-1969. Climatological Data, vols. 64-75.

12. Golden, J. H. 1971. Waterspouts and tornadoes over south Florida. Mon. Wea. Rev. 99: 146-154.

13. Butson, K. 1959. Climates of the States: Florida. Washington, D. C.: U. S. Govt. Printing Office.

14. Eichmeier, A. H. 1964. Climate of Michigan. In Readings in the Geography of Michigan. C. M. Davis (ed.). Ann Arbor: Ann Arbor Publishers. 41-49.

15. Estoque, M. A. 1962. The sea breeze as a function of the prevailing synoptic situation. J. Atmos. Sci. 19: 244-250.

16. Jenrette, J. P. 1960. An objective application of vorticity principles to precipitation forecasting. Bull. Amer. Meteor. Soc. 41: 317-323.

17. Palmén, E., and Newton, C. W. 1969. Atmospheric Circulation Systems. New York: Academic Press.

18. Curtis, R. C., and Panofsky, H. A. 1958. The relation between large-scale vertical motion and weather in summer. Bull. Amer. Meteor. Soc. 39: 521-531.

19. Reiter, E. R. 1963. Jet-Stream Meteorology. Chicago: Univ. of Chicago Press.

CHAPTER II

REVIEW OF THE LITERATURE

The modification of shoreline climates by sea breeze circulations has been recognized for many years. As early as 1799, Ellicott (1) described lake breezes over the shoreline of Lake Erie near Erie, Pennsylvania, noting that these phenomena were especially well developed from spring until the end of fall. Tannerhill (2), in a study along the Texas coast near Corpus Christi, found that fresh Gulf air flowed inland almost daily during the summertime, often resulting in convective showers. Subsequent investigations of the sea breeze has led to an understanding of the dynamics of this circulation system.

Perhaps the most important preconditions for the initiation of a sea breeze circulation are the temperature contrast between the water and adjacent landmass and the prevailing synoptic situation (3, 4). The sea breeze develops from a pressure gradient formed by differential heating of water and land (5, 6, 7). For several reasons, including the turbulent mixing of water, land heats up more rapidly than does water in response to solar heating (8). As a result, near the shoreline of a large water body expansion of air over rapidly heating land leads to increasing heights of isobaric surfaces and a horizontal pressure gradient develops aloft between the land and water (3, 9). In response to this gradient aloft air begins to flow down the isobaric slope toward the water which increases the pressure over the water at the surface, and a second pressure gradient develops initiating a flow of air from the water to the land at the surface (10). A complete circulation system is thus developed with the initial flow of air occurring aloft. The formation of lake breezes in the middle latitudes is favored in the spring and early summer when the temperature contrast between the rapidly warming land and the cool lake waters is at a maximum (11).

Sea breeze circulation is closely related to the prevailing synoptic situation (4). For example, the initiation of sea breeze circulation is in part controlled by the amount of cloud cover present. In order for a large temperature differential to develop between land and water, cloud cover must be at a minimum, especially during the early morning hours when the sea breeze first forms (3). Sea breeze development is also dependent upon the strength and direction of the prevailing geostrophic flow (12). Frizzola and Fisher (13) indicated that the maximum speed of the gradient flow that permits sea breeze development ranges from 9 to 18 mph, while Wexler (8) and Kimble (9) found that a 17 to 22 mph offshore wind would allow sea breeze circulation to pass inland in only the most favorable of circumstances. Hall (14), studying lake breezes in Chicago, indicated that wind speeds at the 2000 foot level of 10 to 15 mph, depending upon direction, were the maximum that would allow lake breeze development.

The direction of the geostrophic flow has a considerable influence upon the magnitude of the temperature differential between land and water (8). With an offshore gradient flow warm air is advected over the coastline, the initial temperature gradient is thus situated offshore, and a strong circulation will result (4). In this situation the sea breeze is first developed over water and subsequent penetration inland usually brings a dramatic drop in temperature, rise in humidity, and a sudden change in wind direction (15, 16, 17, 18). This type of sea breeze circulation resembles a cold front and is called a frontal sea breeze (3, 8). A micro-climatological study on the Texas coast by Hsu (19) revealed that the temperature drop within one-half hour after a frontal type sea breeze passed inland averaged 6°F. An onshore gradient flow, on the other hand, advects cool air over the land and thus reduces the effects of diurnal land heating (20), resulting in a weak circulation system (4). Such a weakened system has been called the non-frontal type (3, 8). As both types of sea breezes penetrate inland during the day, the surface flow is usually deflected by coriolis force so that it may become nearly parallel to the coast by late afternoon (21, 22, 23).

As the sea breeze front penetrates inland, changes in temperature, humidity, and wind direction decrease in intensity because of modification of the sea air as it passes over land (24). Moroz (25) and Wallington (26) found that as the sea breeze front penetrated inland it did so in a pulsating manner. Munn and Richards (17) noted that the lake breeze is often modified so strongly that it disappears completely, permitting a new lake breeze front to form, a condition that may account for the pulsating manner in which the sea breeze moves inland. Byers (27) found that the average value for the slope of most macroscale cold fronts ranges from 1:50 to 1:150, a value that compares favorably with lake and sea breeze fronts which range from 1:20 to 1:100 (11, 13, 28).

A number of studies have been concerned with the apparent suppression of convection over Lake Michigan and the other Great Lakes during the summer. Eshleman (29) and O'Dell (30) found that the incidence of daily precipitation along the Lake Michigan shore was reduced during the summer, and that more rain was received along the western shore than the eastern shore where subsident flows would be more frequent. Recent studies by Stout and Wilk (31), Lansing (32), Changnon (33, 34) and Blust and

DeCooke (35) concerning the suppression of convection and precipitation along the Lake Michigan and other shorelines also indicated that summer precipitation is reduced over the Great Lakes and along the immediate shoreline. Lyons and Wilson (36) and Bellaire (37) in studies over Lake Michigan found evidence for suppression of cumuli, while others (31, 38, 39) have noted that thunderstorms, squall lines, and airmass showers are also suppressed by the lakes. Investigations by Williams (40) and Weiss and Kresge (41), on the other hand, have suggested that in fact there is little difference between the amount of precipitation offshore and that over land.

The suppression of convection and precipitation over the Great Lakes has been attributed in several studies to a mesoscale "high" that often develops over the lakes during the summer (11, 14, 24). Because of a downward flux of heat and subsidence over the lakes a cool stable airmass forms that may suppress convection and precipitation (36). Fujita, Mendez, and Gargard (42) noted that a mesoscale high exists over Lake Michigan and acts as a continual source for a lake breeze; they maintain that Tiros satellite photographs often show a 15-20 mile wide cloud-free zone along the eastern shore of the lake associated with lake breeze circulation. Richards and Loewen (43) found from preliminary pyrheliometric data that summertime insolation receipts are as much as 1.56 times greater over the Great Lakes than over adjacent land stations.

Lyons (24), studying a lake breeze on the southeast shore of Lake Michigan, found that lake breeze circulation crossed the shoreline at 0800 local time*, while Moroz and Hewson (44), investigating the eastern shore of Lake Michigan, noted that initial onshore flow usually occurred between 0900 and 1030. This agrees with other studies of the land and sea breeze conducted in the middle latitudes by Craig, Katz, and Harvey (45) and Watts (16). Sea breeze studies by Frizzola and Fisher (13) near Block Island indicated that maximum inland penetration of the sea breeze was 25 to 30 miles with a reinforcing gradient flow; however, a superposed flow opposite to the sea breeze resulted in reduced inland penetration (14, 46). Investigations along the eastern shore of Lake Michigan by Moroz (47), Moroz and Hewson (44), and Olsson, Cole, and Hewson (48) revealed that the inland penetration of the lake breeze under light onshore gradient conditions was only 10 to 12 miles. Maximum inland penetration of the wind system was found to occur near 1500 by Moroz and Hewson (44) and Hsu (49), while Fisher's (12) investigations along the New England coast revealed that maximum penetration occurred between 1500-1530.

---

*All times used in this study are local times.

Moroz (47) and Lyons (24) both concluded that lake breeze onshore air flow approaches 10 mph within 800 feet of the surface just inland from the coast, while Olsson, Cole, and Hewson (48) found onshore velocity in the lowest 1000 feet to be 15 mph. In all cases maximum onshore velocity was found near the shoreline when the largest temperature contrast between lake breeze and non-lake breeze air occurred. A depth of 5000 feet has been reported for some sea breezes in the tropics (3), whereas those in the middle latitude areas are less than 3000 feet deep (13, 50). Moroz (47) found that lake breezes on the eastern shore of Lake Michigan have a depth of just over 2000 feet.

The number of lake breeze occurrences during the spring and summer has not been extensively documented in the Great Lakes region. Hall (14), in a study of lake breezes along the Chicago shoreline, indicated that a lake breeze developed nearly every day, but those that penetrated inland eight or more miles occurred normally only 11 times per year. Biggs and Graves (7), investigating lake breezes on the western shore of Lake Erie, found that during a three year period an average of 23 lake breezes occurred during the summer months; however, they eliminated onshore gradient wind days from their study.

The role of friction in the development of the sea breeze has had limited documentation. McAuliffe (51), in

1922, speculated that the treeless plain that rises gradually inland from Corpus Christi, Texas, allowed for better development of the sea breeze because of increased local heating and decreased friction. Pearce (52), Fisher (53), and Haurwitz (54), on the other hand, found that the rate of sea breeze penetration was not affected by surface friction, but was primarily a function of surface heating. Other studies (8, 17, 20, 55) are in agreement with this conclusion and also suggest that the amount and type of vegetation just inland from a coast would affect the amount of surface heating, and thus influence the land-water temperature difference.

McAuliffe, in a study along the Texas coast (51), found that the shape of the coastline appeared to have an effect upon the intensity of the sea breeze. He maintained that the coastline in the vicinity of Corpus Christi was normal to the onshore flow of sea breeze circulation and therefore led to a stronger flow of sea air than at other locations along the coast. McPherson (56, 57), in a quantitative study of a large bay along the Texas coast, found that the most intense convergence and vertical motion developed northwest and northeast of the corners of the bay, and that these areas would be preferred locations for convective showers. Neumann (58), investigating land breezes in the eastern Mediterranean, noted that the coast, which was concave toward the sea, promoted the development of convergent wind fields which led to an increase in nocturnal thunderstorms.

Several studies have shown that low-level convergence along the sea breeze front and subsequent convection can cause cumuli to develop which may produce isolated lines of showers and thundershowers (3, 8, 28, 59). Leopold (60), studying sea breezes in Hawaii, noted that convergence zones with attending vertical motions were common in certain locations, and that the local climatology was often altered by precipitation occurring along these convergent sea breeze fronts. Investigations of the sea breeze front by Wallington (26, 61) and Edinger and Helvey (62) revealed that vertical motions within the frontal zone, which averages 500 feet in width, vary considerably, with maximum velocities approaching 30 feet per second.

In the Great Lakes region, Moroz (47) and Lyons (24) have reported strong low-level convergence with resulting vertical motion along the lake breeze front. Lyons (24) and Fujita, Mendez, and Gargard (42) have noted that precipitation is common along the convergence zone, and Moroz and Hewson (44) and Shenfield and Thompson (63) have suggested that lake breezes can be important in thunderstorm intensification and development.

Theoretical models of sea breeze situations constructed by Estoque (4) indicate that sea breeze development and vertical air movement at the associated mesoscale front are especially strong when the geostrophic flow is parallel to the coast with general low pressure located offshore. The prevailing winds over the east-west oriented Upper Peninsula of Michigan are westerly (64), and thus the development of strong lake breezes that would flow south and east from Lake Superior are favored. Lyons and Wilson (36), Harman (65), and Elton (66), working on the southeast shore of Lake Michigan, found that strong lake breezes and attending cumuli developed under a southwest gradient flow which parallels the shore, a finding which follows Estoque's model. Results of sea breeze studies near Bombay, India, by Dixit and Nicholson (67) have also been in general agreement with Estoque's model.

During the summer months the Florida peninsula experiences the largest number of thunderstorms in the United States (68). Investigations of these phenomena have suggested that large-scale low-level convergence of sea breezes from both sides of the peninsula may be responsible for a high percentage of these thunderstorms in that the onshore movement and frontal convection associated with sea breezes may be the triggering mechanism (68, 69, 70, 71, 72).

Under a weak surface flow the sea breeze fronts from both sides of the peninsula penetrate inland and possibly merge in the interior, resulting in a large zone of precipitation (73, 74), and daily recurrence of this circulation produces higher mean precipitation in the interior than along the coasts (75). With prevailing easterly and southeasterly winds in the summer months (76), the south and east coasts would be favored for maximum sea breeze penetration, while only a weak front would develop on the leeward coast (74). Golden (77), studying the southeast coast of Florida, noted that during the spring and early summer sea-breeze-associated showers and thundershowers often produced record rainfalls that constitute a climatological singularity.

Aerial photographs taken over Florida by Oliver and Oliver (78) show conspicuous rows of cumuli just inland from the coast while no clouds are present over the ocean, suggesting strong sea breeze development. Moore (73), utilizing radar to investigate sea-breeze-associated showers, found that maximum shower activity occurred where Estoque's (4) models indicated positive vertical motions would be at a maximum and also that there was a tendency for suppression of activity where downward motions were favored.

Miller (79, 80), in early lake-breeze-studies in Wisconsin, found that rainfall was suppressed near the shore and increased in the interior during the summer period, and that inland penetration of lake breezes over the Door Peninsula was restricted to within one mile of the shore. Baralt and Brown (81), Munn and Richards (17), Olsson, Cole, and Hewson (48), and Schroeder et al. (20) have recently conducted reviews of lake and sea breeze literature.

Low-level convergence and attending precipitation can also be initiated by flow conditions at higher atmospheric levels. Within the westerlies wave motion is the preferred mode of air flow (82). These upper-tropospheric waves are normally characterized by warm ridges and cool troughs of varying amplitudes which normally migrate slowly downstream (83).

The flow of air through long wave systems, usually above 10000 feet, favors the development of areas of upper-level convergence and divergence that often are compensated at the surface by opposite patterns of air flow (84, 85, 86). Sutcliffe (87), Riehl (88), and Starrett (89) in early studies of jet stream location and precipitation occurrence found that rainfall is especially likely in areas of positive relative vorticity advection east of a trough axis where upper-level divergence favors low-level convergence and surface instability. More recent studies by Riehl and Teweles (90), Johnson and Daniels (91), Ramaswany (92), and Reiter (70) have substantiated these early ideas. On the western side of a trough axis in areas of negative vorticity advection upper-level convergence occurs which favors low-level divergence and surface stability (93, 94).

Important upper-level divergence may be present at several levels of the atmosphere. Riehl, Norquest, and Sugg (95) related positive vorticity advection at the 300 mb. level to low-level convergence and precipitation, while Jenrette (84) made use of the 500 mb. level when applying vorticity projections to precipitation forecasting. Thus, the use of facsimile charts to correlate upper-level divergence with low-level convergence and convective precipitation is an important forecasting tool.

Recently, studies by Riehl (96) and Sourbeer and Gentry (97) have attributed heavy localized showers and thundershowers in Florida to areas of divergence aloft associated with high-level jet streams, and these convective motions might be strengthened further by convergence associated with sea (lake) breeze fronts (70). Curtis and Panofsky (98) have noted that convective precipitation requires other conditions than only large-scale vertical motion and suggested that the most dominant influence on this type of rainfall is the relative humidity. Thus, in areas of upper-level divergence coupled with high relative humidity convective showers and thundershowers might be especially likely.

CHAPTER II--REFERENCES

1. Ellicott, A. 1799. Miscellaneous observations relative to the western parts of Pennsylvania, particularly those in the neighborhood of Lake Erie. Amer. Philos. Soc. Trans. 4: 224-229.

2. Tannehill, I. R. 1921. Wind velocity and rainfall frequency on the south Texas coast. Mon. Wea. Rev. 49: 498-499.

3. Defant, F. 1951. Local winds. In Compendium of Meteorology. Boston: Amer. Meteor. Soc. 655-672.

4. Estoque, M. A. 1962. The sea breeze as a function of the prevailing synoptic situation. J. Meteor. 19: 244-250.

5. Frenzel, C. W. 1962. Diurnal wind variations in central California. J. Appl. Meteor. 1: 405-412.

6. Pearce, R. P. 1955. The calculation of a sea breeze circulation in terms of the differential heating across the coastline. Quart. J. Roy. Meteor. Soc. 81: 351-381.

7. Biggs, W. G., and Graves, M. E. 1962. A lake breeze index. J. Appl. Meteor. 1: 474-480.

8. Wexler, R. 1946. Theory and observations of land and sea breezes. Bull. Amer. Meteor. Soc. 27: 272-287.

9. Kimble, G. H. L. 1946. Tropical land and sea breeze (with special reference to the East Indies). Bull. Amer. Meteor. Soc. 27: 99-113.

10. Estoque, M. A. 1961. A theoretical investigation of the sea breeze. Quart. J. Roy. Meteor. Soc. 87: 136-146.

11. Olsson, L. E. 1969. Lake Effects On Air Pollution Dispersion. Univ. of Michigan, Dept. of Meteor. and Oceanography, Tech. Rept. Ann Arbor.

12. Fisher, E. L. 1960. An observational study of the sea breeze. J. Meteor. 17: 645-660.

13. Frizzola, J. A., and Fisher, E. L. 1963. A series of sea breeze observations in the New York City area. J. Appl. Meteor. 2: 722-739.

14. Hall, C. D. 1954. Forecasting the lake breeze and its effects on visibility at Chicago Midway Airport. Bull. Amer. Meteor. Soc. 35: 105-111.

15. Hass, W. A. and others. 1967. Tetroon flights over New York City. Quart. J. Roy. Meteor. Soc. 93: 483-493.

16. Watts, A. J. 1955. Sea breeze at Thorney Island. The Meteorological Magazine. 84: 42-48.

17. Munn, R. E., and Richards, T. L. 1964. The lake breeze: a survey of the literature and some applications to the Great Lakes. Great Lakes Res. Div. Pub. 11: 253-266.

18. Schmidt, F. H. 1947. An elementary theory of the land and sea breeze circulation. J. Meteor. 4: 9-15.

19. Hsu, S. A. 1969. Land and sea breeze fronts near 50 cm. on the Gulf Coast. Bull. Amer. Meteor. Soc. 50: 880-882.

20. Schroeder, M. J. and others. 1967. Marine air invasion of the Pacific coast: a problem analysis. Bull. Amer. Meteor. Soc. 48: 802-808.

21. Eddy, G. A. 1966. The Texas coast sea breeze: a pilot study. Weather. 21: 162-170.

22. Staley, D. O. 1957. The low level sea breeze of northwest Washington. J. Meteor. 14: 458-470.

23. Angell, J. K., and Pack, D. H. 1965. A study of the sea breeze at Atlantic City, N.J., using tetroons as lagrangian tracers. Mon. Wea. Rev. 93: 475-493.

24. Lyons, W. A. 1966. Some effects of Lake Michigan upon squall lines and summertime convection. Great Lakes Res. Div. Pub. 15: 259-273.

25. Moroz, W. J. 1965. The lake breeze circulation along the shoreline of a large lake. Ph.D. Dissertation, Univ. of Michigan, Ann Arbor.

26. Wallington, C. E. 1959. The structure of the sea breeze front as revealed by gliding flights. Weather. 14: 263-270.

27. Byers, H. R. 1959. General Meteorology. New York: McGraw-Hill.

28. Malkus, J. S., Bunker, A. F., and McCasland, K. 1951. A formation of pileus-like veil clouds over Cape Cod, Massachusetts. Bull. Amer. Meteor. Soc. 32: 61-66.

29. Eshleman, C. H. 1922. Do the Great Lakes diminish rainfall in the crop growing season? Mon. Wea. Rev. 49: 500-502.

30. O'Dell, C. B. 1931. Influence of Lake Michigan on east and west shore climates. Mon. Wea. Rev. 59: 405-410.

31. Stout, G. E., and Wilk, K. E. 1962. Influence of Lake Michigan on squall line rainfall. Great Lakes Res. Div. Pub. 9: 111-115.

32. Lansing, L. 1965. Airmass modification by Lake Ontario during April-November period. Great Lakes Res. Div. Pub. 13: 257-261.

33. Changnon, S. A., Jr. 1961. Precipitation contrasts between Chicago urban area and an offshore station in southern Lake Michigan. Bull. Amer. Meteor. Soc. 42: 1-10.

34. _______. 1968. Precipitation from thunderstorms and snowfall around southern Lake Michigan. Proc. 11th Conf. Great Lakes Res.: 285-297.

35. Blust, F., and DeCooke, B. G. 1960. Comparison of precipitation on islands of Lake Michigan with precipitation on the perimeter of the lake. J. Geophysical Res. 65: 1565-1572.

36. Lyons, W. A., and Wilson, J. W. 1968. The Control of Summertime Cumuli and Thunderstorms by Lake Michigan During Non-Lake Breeze Conditions. Satellite and Mesometeorology Research Project. Res. Pap. 74. Chicago: Univ. of Chicago Press.

37. Bellaire, F. R. 1965. The modification of warm air moving over cold water. Great Lakes Res. Div. Pub. 13: 249-256.

38. Pearson, J. E. 1958. Influence of lakes and urban areas on radar observed precipitation echoes. Bull. Amer. Meteor. Soc. 39: 79-82.

39. Changnon, S. A., Jr. 1966. Effect of Lake Michigan on severe weather. Great Lakes Res. Div. Pub. 15: 220-234.

40. Williams, G. C. 1964. Comparative rainfall study, 68th street crib and Chicago area, summer and fall 1963. Great Lakes Res. Div. Pub. 11: 311-320.

41. Weiss, L. W., and Kresge, R. F. 1962. Indications of shore and offshore precipitation for southern Lake Michigan. J. Appl. Meteor. 1: 271-274.

42. Fujita, T., Mendez, R., and Gargard, S. J. M. 1963. Cloud distribution over the Great Lakes region as observed by TIROS meteorological satellite (Abst.). Bull. Amer. Meteor. Soc. 44: 704.

43. Richards, T. L., and Loewen, P. 1965. A preliminary investigation of solar radiation over the Great Lakes as compared to adjacent land areas. Great Lakes Res. Div. Pub. 13: 278-282.

44. Moroz, W. J., and Hewson, E. W. 1966. The mesoscale interaction of a lake breeze and low level outflow from a thunderstorm. J. Appl. Meteor. 5: 148-155.

45. Craig, R. A., Katz, I., and Harvey, P. J. 1945. Sea breeze cross sections from psychometric measurements. Bull. Amer. Meteor. Soc. 26: 405-410.

46. Strong, A. E. 1967. The overwater development of a lake breeze in an offshore gradient flow. Proc. 10th Conf. Great Lakes Res.: 240-250.

47. Moroz, W. J. 1967. A lake breeze on the eastern shore of Lake Michigan: observations and model. J. Atmos. Sci. 24: 337-355.

48. Olsson, L. E., Cole, A. L., and Hewson, E. W. 1968. An observational study of the lake breeze on the eastern shore of Lake Michigan, 25 June 1965. Proc. 11th Conf. Great Lakes Res.: 313-325.

49. Hsu, S. A. 1969. Mesoscale Structure of the Texas Coast Sea Breeze. Atmospheric Science Group. Rept. No. 16. Austin: Univ. of Texas.

50. Sutcliffe, R. C. 1937. The sea breeze at Felixtowe. A statistical investigation of pilot balloon ascents up to 5500 feet. Quart. J. Roy. Meteor. Soc. 63: 137-148.

51. McAuilffe, J. P. 1922. Cause of the accelerated sea breeze over Corpus Christi, Texas. Mon. Wea. Rev. 50: 581-582.

52. Pearce, R. P. 1962. A simplified theory of the generation of sea breezes. Quart. J. Roy. Meteor. Soc. 88: 20-29.

53. Fisher, E. L. 1961. A theoretical study of the sea breeze. J. Meteor. 18: 216-233.

54. Haurwitz, B. 1947. Comments on the sea breeze circulation. J. Meteor. 4: 1-8.

55. Hsu, S. A. 1967. Mesoscale Surface Temperature Characteristics of the Texas Coast Sea Breeze. Atmospheric Science Group. Rept. No. 6. Austin: Univ. of Texas.

56. McPherson, R. D. 1968. A Three-Dimension Numerical Study of the Texas Coast Sea Breeze. Atmospheric Science Group. Rept. No. 15. Austin: Univ. of Texas.

57. _______. 1970. A numerical study of the effect of a coastal irregularity on the sea breeze. J. Appl. Meteor. 9: 767-777.

58. Neumann, J. 1951. Land breezes and nocturnal thunderstorms. J. Meteor. 8: 60-67.

59. Atlas, D. 1960. Radar detection of the sea breeze. J. Meteor. 17: 244-258.

60. Leopold, L. B. 1949. The interaction of trade wind and sea breeze, Hawaii. J. Meteor. 6: 312-320.

61. Wallington, C. E. 1965. Gliding through a sea breeze front. Weather. 20: 140-144.

62. Edinger, J. G., and Helvey, R. A. 1961. San Fernando convergence zone. Bull. Amer. Meteor. Soc. 42: 626-635.

63. Shenfield, L., and Thompson, F. D. 1962. The thunderstorm of August 9th, 1961, at Hamilton, Ontario. Tech. Rept. 417, Meteor. Branch, Dept. of Transp., Canada.

64. Eichmeier, A. H. 1964. Climate of Michigan. In Readings in the Geography of Michigan. C. M. Davis (ed.). Ann Arbor: Ann Arbor Publishers. 41-49.

65. Harman, J. R. 1970. Forest types and climatic modification along the southeast shoreline of Lake Michigan. Annals Assoc. Amer. Geog. 60: 456-465.

66. Elton, W. M. 1970. Forest and lake breeze patterns and the La Porte, Indiana, Rainfall Anomaly. Ph.D. Dissertation, Michigan State Univ., East Lansing.

67. Dixit, C. M., and Nicholson, J. R. 1964. The sea breeze at and near Bombay. Indian J. Meteor. and Geophy. 15: 603-608.

68. Byers, H. R., and Rodebush, H. 1948. Causes of thunderstorms of the Florida peninsula. J. Meteor. 5: 275-280.

69. Boyd, J. G. 1965. Observations of two intersecting radar fine lines. Mon. Wea. Rev. 93: 188.

70. Reiter, E. R. 1963. Jet-Stream Meteorology. Chicago: Univ. of Chicago Press.

71. Byers, H. R., and Braham, R. R. 1949. The Thunderstorm. Washington, D. C.: U. S. Govt. Printing Office.

72. Gentry, R. C. 1950. Forecasting local showers in Florida during the summer. Mon. Wea. Rev. 78: 41-49.

73. Moore, P. L. 1963. A radar study of shower activity associated with the sea breeze. Proc. 10th Weather Radar Conf. Boston: Amer. Meteor. Soc. 8-12.

74. Frank, N. L., Moore, P. L., and Fisher, G. E. 1967. Summer shower distribution over the Florida peninsula as deduced from digitized radar data. J. Appl. Meteor. 6: 309-316.

75. Gentry, R. C., and Moore, P. L. 1954. Relation of local and general wind interaction near the sea coast to time and location of air-mass showers. J. Meteor. 11: 507-511.

76. Butson, K. 1959. Climates of the States: Florida. Washington, D. C.: U. S. Govt. Printing Office.

77. Golden, J. H. 1971. Waterspouts and tornadoes over south Florida. Mon. Wea. Rev. 99: 146-154.

78. Oliver, V. J., and Oliver, M. B. 1963. Cloud patterns, part I, some aspects of the organization of cloud patterns. Mon. Wea. Rev. 91: 621-632.

79. Miller, E. R. 1917. The meteorological influences of lakes. Proc. 2nd Pan American Science Congress. Washington, D. C.: U. S. Govt. Printing Office. 189-198.

80. ______. 1939. The land and sea breeze of Door Peninsula, Wisconsin. Bull. Amer. Meteor. Soc. 20: 209-211.

81. Baralt, G. L., and Brown, R. A. 1965. The Land and Sea Breeze: An Annotated Bibliography. Satellite and Mesometeorology Research Project. Chicago: Univ. of Chicago Press.

82. Riehl, H. 1965. Introduction to the Atmosphere. New York: McGraw-Hill.

83. Palmén, E., and Newton, C. W. 1969. Atmospheric Circulation Systems. International Geophysics Series, Vol. 13. New York: Academic Press.

84. Jenrette, J. P. 1960. An objective application of vorticity principles to precipitation forecasting. Bull. Amer. Meteor. Soc. 41: 317-323.

85. Bungaard, R. C. 1956. Estimating vorticity advection. Bull. Amer. Meteor. Soc. 37: 465-472.

86. Riehl, H. 1962. Jet Streams of the Atmosphere. Dept. of Atmospheric Science. Tech. Rept. No. 32. Fort Collins, Colorado: Colorado State Univ.

87. Sutcliffe, R. C. 1939. Cyclonic and anticyclonic development. Quart. J. Roy. Meteor. Soc. 65: 518-524.

88. Riehl, H. 1948. Jet streams in upper troposphere and cyclone formation. Trans. Amer. Geophys. Union. 29: 175-186.

89. Starrett, L. G. 1949. The relation of precipitation patterns in North America to certain types of jet streams at the 300 mb. level. J. Meteor. 6: 347-352.

90. Riehl, H., and Teweles, S., Jr. 1953. A further study on the relation between the jet stream and cyclone formation. Tellus. 5: 66-79.

91. Johnson, D. H., and Daniels, S. M. 1956. Rainfall in relation to the jet stream. Quart. J. Roy. Meteor. Soc. 80: 212-217.

92. Ramaswamy, C. 1956. On the sub-tropical jet stream and its role in the development of large-scale convection. Tellus. 8: 26-60.

93. Palmén, E. 1951. The aerology of extratropical disturbances. In Compendium of Meteorology. Boston: Amer. Meteor. Soc. 599-620.

94. Palmén, E., and Nagler, K. M. 1949. The formation and structure of a large-scale disturbance in the westerlies. J. Meteor. 6: 227-242.

95. Riehl, H., Norquest, K. S., and Sugg, A. L. 1952. A quantitative method for the prediction of rainfall patterns. J. Meteor. 9: 291-298.

96. Riehl, H. 1949. Florida thunderstorms and rainfall. J. Meteor. 6: 289-290.

97. Sourbeer, R. H., and Gentry, R. C. 1961. Rainstorm in southern Florida, 21 January, 1957. Mon. Wea. Rev. 89: 9-16.

98. Curtis, R. C., and Panofsky, H. A. 1958. The relation between large-scale vertical motion and weather in summer. Bull. Amer. Meteor. Soc. 39: 521-531.

CHAPTER III

METHODOLOGY

Location of the Study Area

The study area is located in the eastern portion of the Upper Peninsula of Michigan and includes parts of Chippewa and Mackinac Counties. The narrow eastern portion of the Upper Peninsula was chosen for the study area after precipitation data for 12 summer seasons had been gathered and analyzed. Two groups of climatological stations, one in the east and one in the central portion of the peninsula (Figure II), were used in the initial sample, and part of the results from the eastern most group are summarized in Table I. Data for the summer of 1966 have been specifically detailed because the pattern typical of the eastern portion of the Upper Peninsula seems to have been especially well developed during this time.

During the 12-year period the number of days during which precipitation was observed at interior stations (interior rain days) exceeded that along either coast. In the summer of 1966, the number of interior rainfall days greatly exceeded coastal occurrences, and precipitation totals, as well, were generally higher in the interior,

FIGURE II

Sources of Data for the Initial 12-Year Sample

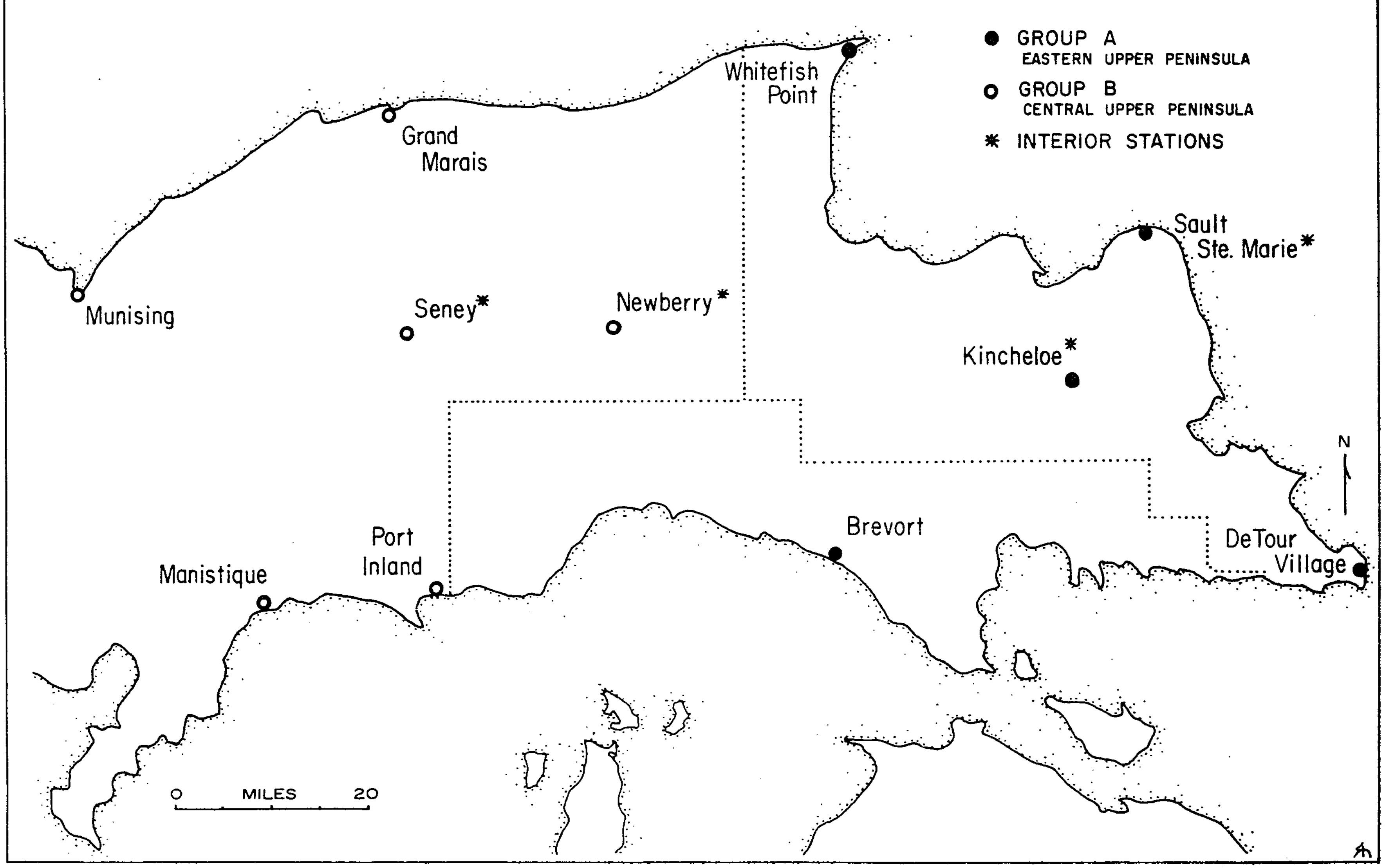


TABLE I

Interior vs Coastal Rain Days for June, July, and August, 1958-1969, Eastern Upper Peninsula

Total Rain Days*	Int. Rain Days	Coastal Rain Days
1855	386	59

Summer 1966, Precipitation Totals, in inches

	June	July	August
Brevort	2.02	.20	2.67
DeTour Village	.90	1.42	1.80
Kincheloe**	1.48	1.74	4.97
Sault Ste. Marie**	2.04	1.24	3.45
Whitefish Point	--	2.00	3.51

Total Rain Days	Int. Rain Days	Coastal Rain Days
153	22	2

*Total rain days include all days of precipitation at all the stations being considered, while interior and coastal days are totals of precipitation days in the interior or on the coast only.

**Interior stations

particularly during August. Sault Ste. Marie has been classified as an interior station because patterns of precipitation during the 12-year analysis generally resembled those of interior stations, as can be seen on Table I. Conversations with individuals familiar with the problem indicate that precipitation occurrences and totals apparently are even higher south of the city.

A similar group of stations across the central portion of the Upper Peninsula revealed a much different pattern which was particularly well developed during the summer of 1962 (Table II). During the sample period coastal rainfall occurrences were more frequent than interior occurrences. Analysis of data from interior stations for both groups for the 1958-1969 period indicated that occurrences of interior precipitation days increased substantially toward the eastern portion of the Upper Peninsula. Seney and Newberry experienced 26 and 36 interior rainfall days, respectively, while Kincheloe and Sault Ste. Marie experienced 176 and 210 interior rainfall days, respectively, in June, July, and August, during the 12-year period. It appeared that some mechanism may operate more frequently in the interior of the eastern portion of the Upper Peninsula than in the central portion. Therefore, the eastern portion of the Upper Peninsula was regarded as a favorable location to test the hypothesis

TABLE II

Interior vs Coastal Rain Days for June, July, and August, 1958-1959, Central Upper Peninsula

Total Rain Days	Int. Rain Days	Coastal Rain Days
2673	62	237

Summer 1962, Precipitation Totals, in inches

	June	July	August
Munising	1.72	.95	3.64
Grand Marais	.87	1.35	4.03
Seney*	1.57	.55	3.14
Newberry*	.86	1.76	4.55
Manistique	2.20	1.41	4.44
Port Inland	2.38	.78	4.37

Total Rain Days	Int. Rain Days	Coastal Rain Days
205	7	31

*Interior stations

that convergence of lake breezes from Lakes Superior, Michigan, and Huron was related to interior rainfall occurrences.

The Physical Setting

The eastern portion of Michigan's Upper Peninsula lies in the East Lake Section of the Central Lowlands Province (1) and the lowland-plains division of the Upper Peninsula (2). The area is bounded on the south by Lakes Michigan and Huron and on the north and east by Lake Superior and the St. Marys River, respectively (see Figure I). The entire peninsula extends approximately 325 miles east-west and has a maximum width of 40-50 miles in the study area.

The two county area was glaciated during the latest Wisconsinan glacial stage and the present surface relief is a result of deposition of glacial drift over pre-existing topography. The area is underlain by southward dipping Paleozoic sediments with higher altitudes resulting from north-facing scarps of more resistant rock (2). Total relief in the study area is approximately 300 feet, but local relief in smaller areas may range from 20 feet to 150 feet (Figure III).

The climate in the study area is a humid continental cool summer type (3) with July temperatures

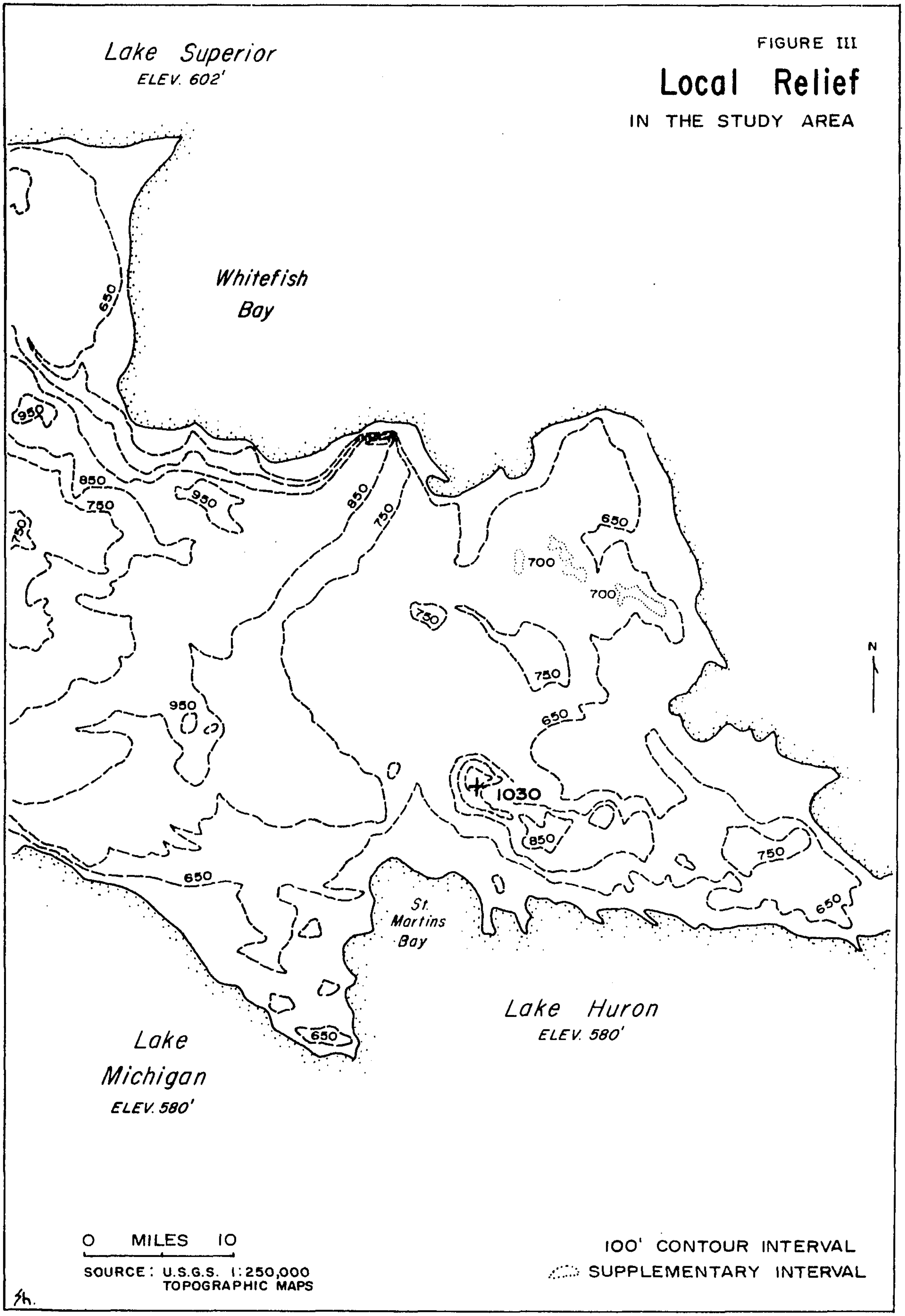


FIGURE III
Local Relief
IN THE STUDY AREA
Lake Superior
ELEV. 602'
Whitefish
Bay
650
950
850
750
750
950
850
750
650
700
700
750
750
950
650
1030
850
750
650
650
St.
Martins
Bay
650
Lake Huron
ELEV. 580'
Lake
Michigan
ELEV. 580'
N
0 MILES 10
SOURCE: U.S.G.S. 1:250,000
TOPOGRAPHIC MAPS
100' CONTOUR INTERVAL
SUPPLEMENTARY INTERVAL

averaging about 64°F* and January averaging approximately 16°F. The mean average annual temperature is approximately 41°F. Mean annual temperatures vary by several degrees depending upon distance from surrounding water bodies. Annual precipitation averages 30 inches and prevailing wind flow is from the west (4).

Methods

In order to test the hypothesis, the author planned a research design to establish the possible existence of two lake breeze systems. Lake breezes develop from a pressure gradient formed by a temperature differential between land and water (5). The extent of lake breeze development is dependent upon the regional wind flow and the strength of the pressure gradient. Maximum inland penetration of the lake breeze is favored at the time of highest diurnal temperature, which usually occurs in the early afternoon (6). During days of surface macroscale frontal passage general convection and precipitation attending the front may inhibit lake breeze development or obscure any precipitation associated only with lake breeze systems. Thus, only summer days were considered in this study during which a surface macroscale front did not pass

---

*All temperatures used in this study are in degrees Fahrenheit.

through the study area, as determined by examination of both field notes and National Meteorological Center facsimile charts. All frontal days were therefore excluded.

In this research, data concerning precipitation, clouds, temperature, relative humidity, insolation, surface wind, water temperature, and upper-level air flow were used. Surface data were collected along a north-south traverse for the period of June, July, and August of 1970. It was hoped that the limited duration of the study period and lack of complete instrumentation could in part be overcome by careful location of available instruments. Furthermore, continuous daily records were not a research aim of this project, as each day was treated as a separate, discrete set of events. After all frontal days were excluded, the remaining sample days from the three month study period were divided into three groups based upon data collected during the survey: (1) apparent lake breeze convergence days in which interior precipitation occurred, (2) apparent lake breeze convergence days in which no precipitation occurred, and (3) days in which there was no apparent lake breeze convergence. All occurrences of lake breeze convergence or interior precipitation were verified either by automobile traverse or rainfall records in the study network. Days that did not appear to fall within any of the above three groups because changing weather events during the day reversed lake breeze development were also excluded from the study.

Precipitation data. In order to collect detailed precipitation information, the author established a north-south traverse across the eastern portion of the Upper Peninsula. Twenty-two fence post raingages with a six inch capacity were spaced at approximately one mile intervals (7) along the traverse at a uniform height of 42 inches to insure an accurate record. The raingages were numbered 1-22 beginning at Brimley State Park on the north coast and ending near St. Martins Bay on the south coast (Figure IV). All the raingages were placed in open areas at least 200 feet from buildings and large trees and 100 feet from smaller vegetation so that interference was avoided. All gages were inspected daily in the late afternoon, following probable periods of lake breeze formation and precipitation. On days of general rainfall associated with frontal passage data were collected in order to compile a complete precipitation record. From this network an analysis of precipitation occurrences and totals was compiled, including width of each rainfall swath and location of each rainfall swath along the traverse for Group I days. All rain data in this study are expressed in inches. On some Group I days precipitation was detected by automobile reconnaissance either east or west of the raingage network which did not affect any of the gages. In these cases, the gages that would have been affected were extrapolated. The location of the maximum rainfall occurrence by gage

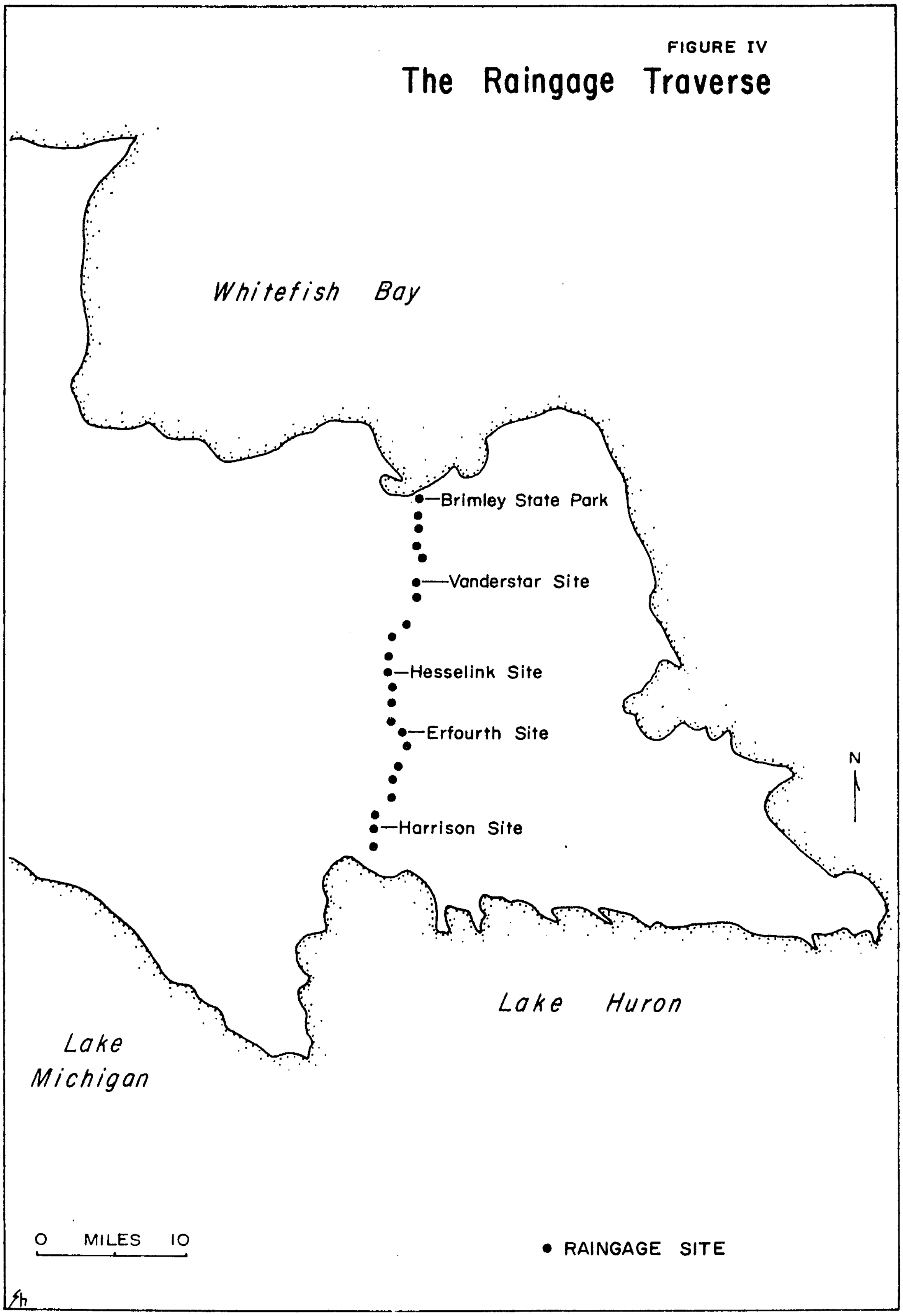


FIGURE IV
The Raingage Traverse

along the traverse was correlated with wind direction at the 300 mb., 500 mb., and 850 mb. levels in order to assess the extent to which location of each occurrence was explained by variations of wind direction. These and most subsequent calculations were made on a CDC 3600 digital computer utilizing several routines provided by the Social Science Computer Institute at Michigan State University.

Cloud photography. A Bolex H16 movie camera in time-lapse mode and a Canon 35 mm. camera were used on certain days of apparent lake breeze development and convergence to record interior cloud development and apparent precipitation. Satellite photographs depicting cloud development were also collected.

Temperature and relative humidity data. A series of three Weather Measure, Model H311, hygrothermographs and one Meteorological Research, Incorporated, automatic weather station with sensors and recorders for temperature, wind direction, and wind speed were uniformly spaced in a north-south traverse from the central area of the eastern portion of the Upper Peninsula to the Lake Superior shoreline. A traverse in this area was desirable because it was hypothesized that the development of lake breezes would be stronger along the Lake Superior shore than along the shoreline of Lakes Michigan and Huron.

Lyons (8) indicated from studies near Chicago that as the lake breeze penetrated inland from Lake Michigan intense heating at the surface gradually destroyed the inversion, and thus temperature and relative humidity may not, in that case, be a reliable indicator of lake breeze penetration. In this study, however, it was thought that the relatively lower temperatures of Lake Superior would provide a stronger temperature inversion that might be more detectable through variations of temperature and relative humidity.

The northernmost hygrothermograph was positioned in Brimley State Park approximately 1000 feet from the Lake Superior shoreline, while the first inland station was situated on the property of M. Vanderstar approximately six miles south of Brimley State Park. The automatic weather station was positioned five miles south of the Vanderstar site on the property of J. Hesselink. This location was chosen for instrument security and was approximately 1.5 miles north of the center of the peninsula. The final hygrothermograph site was situated five miles south of the Hesselink site on the property of C. Erfourth and was approximately nine miles from Lake Huron (Figure V). All instruments in this portion of the study utilized 31-day recording charts, and the temperature sensors in the hygrothermographs were calibrated frequently in the field.

The instrument shelters that housed the hygrothermographs were standard Weather Bureau shelters and

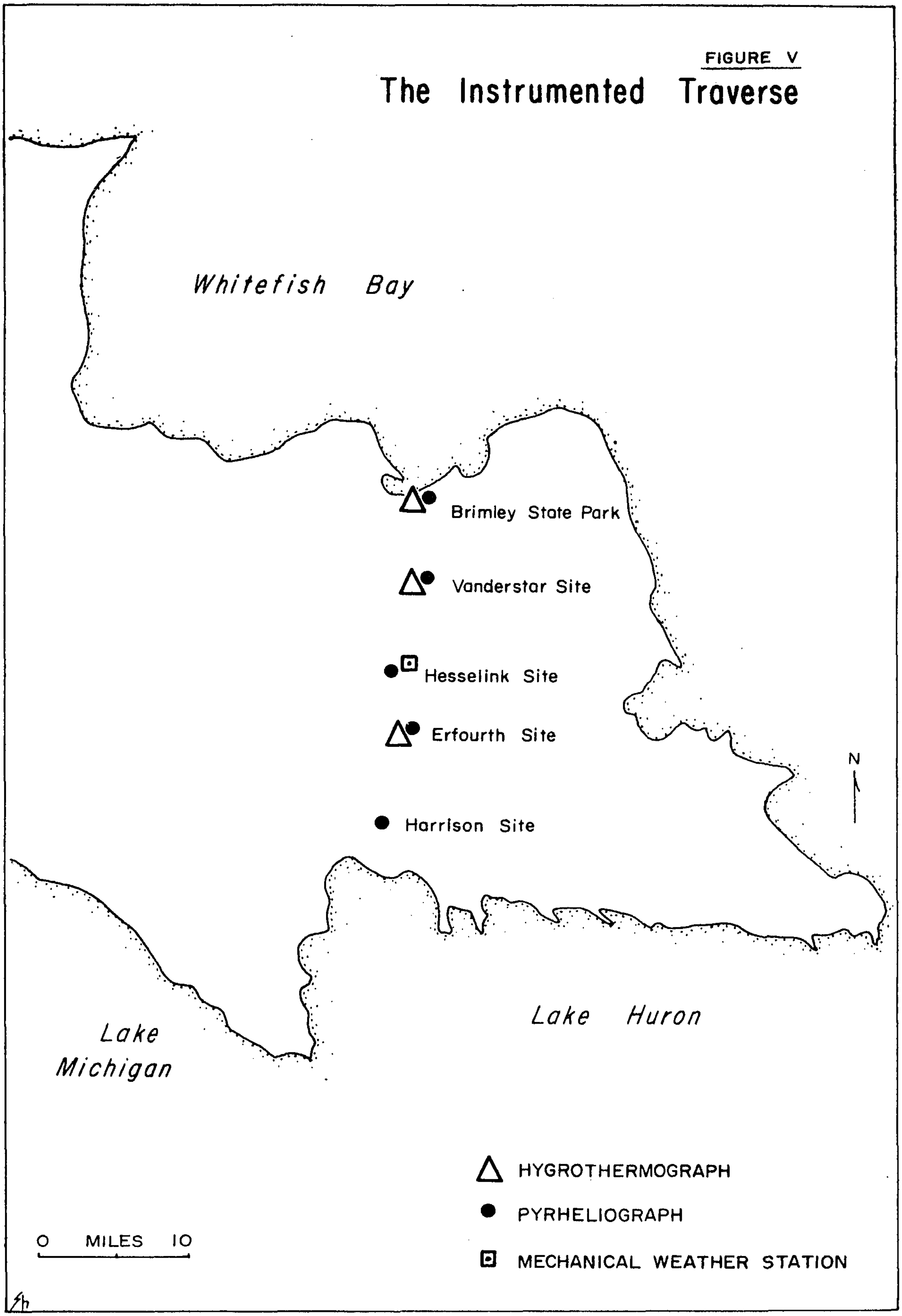


FIGURE V
The Instrumented Traverse
Whitefish Bay
Brimley State Park
Vanderstar Site
Hesselink Site
Erfourth Site
Harrison Site
N
Lake Michigan
Lake Huron
HYGROTHERMOGRAPH
PYRHELIOGRAPH
MECHANICAL WEATHER STATION
0 MILES 10

were placed 48 inches off the ground so that proper ventilation and exposure were maintained. The automatic weather station was positioned six feet above the ground so that temperature data obtained from it were generally comparable to those from the hygrothermographs. Data analyzed from the hygrothermograph record and the temperature sensor in the automatic weather station included mean drop in temperature, rise in humidity, and maximum humidity within one-half hour after lake breeze passage for the days comprising Groups I and II, and maximum temperature and relative humidity between 8 a.m. and 4 p.m. for all three groups. Surface temperatures and dew points for 0615 were also obtained from the Sault Ste. Marie Weather Bureau on all sample days.

Insolation data. A north-south traverse of five Weather Measure solar radiation recorders, Model R401, utilizing seven day recording charts, was as uniformly spaced as possible across the eastern portion of the peninsula to record the amount of solar radiation reaching the surface. The solar radiation recorders were affixed when possible to the tops of the weather shelters in a horizontal position; otherwise they were located in areas of continuous exposure to solar radiation on horizontal platforms 55 inches off the ground. Four of the solar radiation recorders were positioned at previously mentioned sites (Brimley State Park, the Vanderstar site, the

Hesselink site, and the Erfourth site). The fifth recorder was situated approximately two miles north of Lake Huron on the property of C. Harrison (see Figure V).

From these recorders the energy receipts for morning, afternoon, and the entire day were compiled for each instrument on each sample day in order to provide evidence of cloud patterns for Groups I and II. Data concerning the percentage of insolation reaching the surface were obtained by utilizing a dot overlay to determine the relative area under each curve. The three month study period was divided in half and the day of greatest solar receipt in each period was used as the curve of maximum energy receipt. This procedure was followed to accommodate the decrease of mean daily insolation during July and August. The area under the daily curves was used to find the percent deviation of each curve from the maximum receipt. These values for each site were also plotted against 300 mb., 500 mb., and 850 mb. wind direction at 40° intervals between 180° and 360° for Groups I and II in order to determine whether the zone of maximum cloud cover shifted location in the interior with change in wind direction.

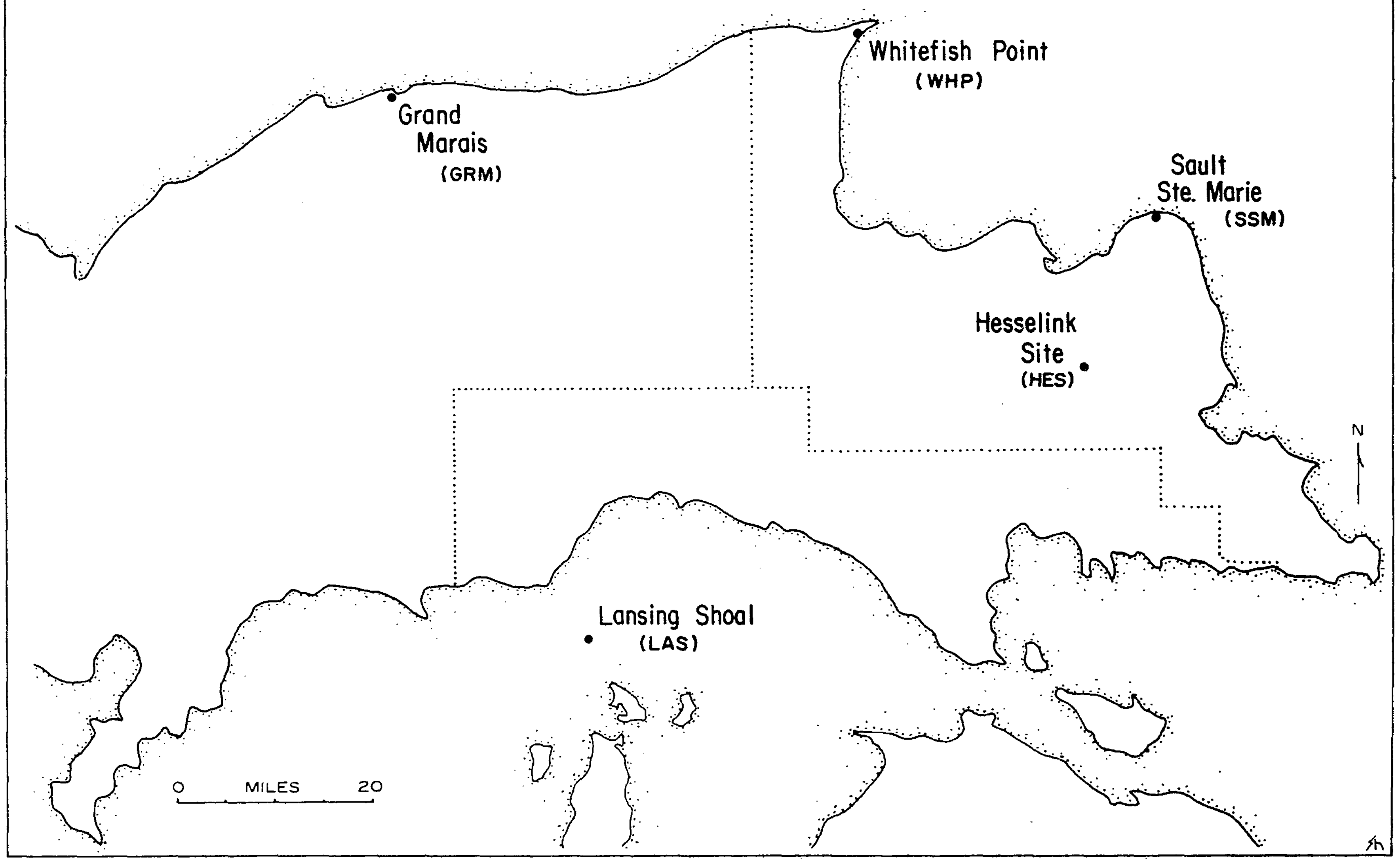
Surface wind data. Wind data below 4000 feet did not constitute the core of this study because of the lack of adequate instrumentation. Limited surface wind data were available from the automatic weather station and several Weather Bureau and Coast Guard Stations including Sault Ste. Marie, Whitefish Point, Grand Marais, and Lansing Shoal (Figure VI). The continuous recording anemometer which is part of the automatic weather station was used with the traverse of temperature and relative humidity sensors near Lake Superior where the passage of a lake breeze would probably be associated with a change of wind speed and direction. Wind data from Sault Ste. Marie were available at three hour intervals (9), while wind direction and velocity from Whitefish Point, Grand Marais, and Lansing Shoal were recorded at six hour intervals. Data from 0630, 1230, and 1830 were used in this study.

Lyons (8) and Moroz (10) indicated that lake breeze circulation began about 0900 and terminated sometime after 1500. Thus, winds at 0630 and 1830 may reflect the gradient flow, while winds at 1230 on lake breeze days were thought to reflect the mesoscale circulation and were used to infer lake breeze patterns over the peninsula.

As a lake breeze front passes a given point, a change in wind direction and velocity usually occurs (11). Data were extracted from the automatic weather station for all days in Groups I and II. In addition, both the time of apparent lake breeze passage, as inferred from an abrupt shift to an onshore flow, and temperature and wind data one-half hour afterward were recorded.

FIGURE VI

Sources of the Surface Wind Data



Water temperature. Lake breeze circulation is largely a function of the land-water temperature difference (12). Daily maximum temperatures were taken from the automatic weather station in the interior portion of the peninsula. Daily water temperatures were available from the Sault Ste. Marie power station situated on the St. Marys River and fed by a canal which brings water directly from Lake Superior. The temperature sensors are located beneath the water surface near the power plant intake; however, conversations with individuals knowledgeable of the situation (13) indicated that water temperatures recorded in the canal do not reflect surface water temperatures offshore in Whitefish Bay. It was concluded that water temperature values recorded in the canal should be decreased by 8°F. The resulting values compared favorably with water temperatures found in a study by Millar (14), who utilized values obtained from water intake systems on Great Lakes freighters.

Upper-level data. Low-level convergence favors the development of convective motions and precipitation, and when coupled with vertical motions associated with lake breezes, it may enhance interior precipitation in the study area (15). Analysis of upper-level air flow for evidence of possible divergence was carried out with the aid of facsimile charts of the 850 mb., 500 mb., and 300 mb. levels.

Trough distance and amplitude at all three levels west of Michigan were expressed as a ratio of the distance to trough axis over the difference in pressure height surfaces. Thus, the nearer a trough axis was to the study area, the smaller would be the resulting ratio. An advantage of such a ratio was that either decreasing distance to trough axis or increasing height differences, factors most likely associated with increasing vertical motion, result in a smaller number. This analysis was also done with ridges situated west of Michigan except that the ratio was expressed as the difference in pressure height surfaces over the distance to ridge axis, which resulted in a ratio where larger numbers were associated with increased subsidence. Pressure height levels at the 850 mb., 500 mb., and 300 mb. surfaces over the study area were also examined for the sample groups. Both methods were employed to identify any association that might exist between interior precipitation days and certain aspects of the atmospheric circulation.

Daily rawinsonde data were available from the Sault Ste. Marie Weather Bureau for 0615 and 1815. Data were extracted from the 0615 rawinsonde record and included the following for the 850 mb., 500 mb., and 300 mb. surfaces: pressure heights, dew points, temperatures, and wind directions and velocities. The 0615 data were used because it was thought that lake breeze circulation would be affected by initial early morning conditions.

For the original 12-year sample 500 mb. wind directions for Sault Ste. Marie were also obtained on days of interior precipitation occurrences from daily Weather Bureau maps as a guide to tropospheric wave positions (16). Wind directions greater than 270° were regarded as reflecting a ridge upstream, whereas those less than 270° a trough upstream. The mean wind flow at 500 mb. for Sault Ste. Marie and Green Bay, Wisconsin, for June, July, and August was also obtained from upper-level flow charts (17) in order to compare wind flow during the 12-year sample with mean wind flow in the region. The maximum temperatures for all interior rain days during the 12-year period were also plotted against the mean monthly maximum temperature because it was hypothesized from the field survey that days of interior rain occurrence may be warmer than non-interior rain days. However, all data from the 12-year study must be regarded with caution because the data were obtained from a limited number of stations within the study area and without field verification.

CHAPTER III--REFERENCES

1. Fenneman, N. M. 1938. Physiography of Eastern United States. New York: McGraw-Hill.

2. Veatch, J. O., and others. 1927. Soil Survey of Chippewa County, Michigan. Washington, D. C.: U. S. Govt. Printing Office.

3. Trewartha, G. T. 1954. An Introduction to Climate. New York: McGraw-Hill.

4. Eichmeier, A. H. 1964. Climate of Michigan. In Readings in the Geography of Michigan. C. M. Davis (ed.). Ann Arbor: Ann Arbor Publishers. 41-49.

5. Defant, F. 1951. Local Winds. In Compendium of Meteorology. Boston: Amer. Meteor. Soc. 655-672.

6. Wexler, R. 1946. Theory and observations of land and sea breezes. Bull. Amer. Meteor. Soc. 27: 272-287.

7. Huff, F. A., and Shipp, W. L. 1969. Spatial correlations of storm, monthly and seasonal precipitation. J. Appl. Meteor. 8: 542-550.

8. Lyons, W. A. 1966. Some effects of Lake Michigan upon squall lines and summertime convection. Great Lakes Res. Div. Pub. 15: 259-273.

9. U. S. Weather Bureau. 1970. Local Climatological Data. Sault Ste. Marie: June, July, and August.

10. Moroz, W. J. 1967. A lake breeze on the eastern shore of Lake Michigan: observations and model. J. Atmos. Sci. 24: 337-355.

11. Wallington, C. E. 1959. The structure of the sea breeze front as revealed by gliding flights. Weather. 14: 263-270.

12. Pearce, R. P. 1955. The calculation of a sea breeze circulation in terms of the differential heating across the coastline. Quart. J. Roy. Meteor. Soc. 81: 351-381.

13. Water Temperature of Whitefish Bay. Personal communication from Dr. Arthur Pinsak, U. S. Army Corp of Engineers, Detroit. November 16, 1970.

14. Millar, F. G. 1952. Surface temperatures of the Great Lakes. J. Fish. Res. of Canada. 9: 329-376.

15. Reiter, E. R. 1963. Jet-Stream Meteorology. Chicago: Univ. of Chicago Press.

16. U. S. Weather Bureau. 1958-1969. Daily Weather Map. All dates of interior rain days.

17. Lahey, J. F., and others. 1958. Atlas of 500 mb. Wind Characteristics for the Northern Hemisphere. Madison: the Univ. of Wisconsin Press.

CHAPTER IV

RESULTS

Climatic Hypothesis

As stated initially, the Florida peninsula receives a considerable portion of its summertime precipitation from a convergence zone which develops when two sea breeze systems merge from the east and west coasts and subsequently augment convective motions (1). This interior convergence zone has been well documented.

Sea (lake) breeze convergence over peninsulas in the middle latitudes apparently has been less well studied. A 12-year survey was undertaken in eastern Upper Michigan to initially evaluate the possibility that convergence of sea breezes and subsequent interior precipitation may occur in the middle latitudes as well. The results indicated that interior precipitation occurrences were greater than coastal occurrences especially in the summer period when lake breeze development should be at a maximum.

The flow of air at upper levels favors the development of areas of divergence and convergence that are often compensated at the surface by opposite patterns of air flow (2). In areas east of an upper-level trough divergence occurs which is compensated at the surface by convergence and subsequent instability (3). Low-level convergence combined with high relative humidity during the summer months often favors convective motions and precipitation. These convective motions may be enhanced further by convergence of sea breezes over a peninsula which may favor a mean precipitation zone in the interior (4). Thus, the interior of Michigan's Upper Peninsula would be in an area where convective precipitation may be especially likely with the approach of an upper-tropospheric trough.

The hypothesis of this study is that lake breezes develop on both the north and south coasts of the Upper Peninsula of Michigan on warm summer days of general westerly flow, and advance inland. These lake breezes possibly converge over the eastern interior portion of the peninsula resulting in augmented convection and a number of interior precipitation occurrences that might not otherwise occur. It is also suggested that the presence of favorable air flow in the middle or upper troposphere may further encourage convective precipitation attending these lake breezes at certain times.

Results of the Surface Survey

During the three month study period ten days were identified as Group I days (days of apparent lake breeze convergence with subsequent interior precipitation), and 19 days were identified as Group II days (days of apparent lake breeze convergence with no associated precipitation). Twenty Group III days were identified in which no apparent lake breeze convergence occurred.

Precipitation. Interior precipitation occurred along or near the raingage network on ten sample days (Group I). The maximum width of a rainfall on a given day was 12 miles, the minimum width two miles, and the mean width was 4.80 miles (see Appendices for expansion of all data). The amount of precipitation and its location along the raingage network have been summarized in Table III. It is apparent from Table III that as the summer progressed each swath of interior precipitation occurred further northward toward Lake Superior. It can also be noted that, in general, the gage of maximum precipitation occurrence for each sample day was near the center of the swath even though, particularly in the case of the wider swaths, several different shower cells may have been involved. The amount of precipitation by gage ranged from a trace to 1.50 inches and the mean total per affected raingage was .19 inches (traces were not included in the calculation of the mean).

Correlation between the location of maximum precipitation occurrence by gage during each interior rainfall day and 300 mb., 500 mb., and 850 mb. wind direction

TABLE III

Precipitation Occurrences and Totals by
Gage for Group I Days

		6/22	6/29	7/11	7/28	7/29	7/30	7/31	8/7	8/11	8/12
Brimley	1.						T			.32	.01
	2.						.03			.60	.01
	3.						.04			1.10	.14
	4.						.06			1.35	.11
	5.						.13			1.50	.01
Vanderstar	6.						.33		*	.20	.01
	7.						1.05		*		
	8.						.62		*		
	9.					.05	.38	.01			
Hesselink	10.					.05	.18	T			
	11.		*			.02	.09				
	12.		*				.01				
	13.					T					
	14.										
Erfourth	15.	*			T						
	16.	*			.02						
	17.	*		.03							
	18.	*		.12							
	19.	*		.06							
	20.			.03							
Harrison	21.			T							
	22.										
	$\overline{X}$=			.06	.02	.04	.27	.01		.85	.05**

*Extrapolated occurrences.

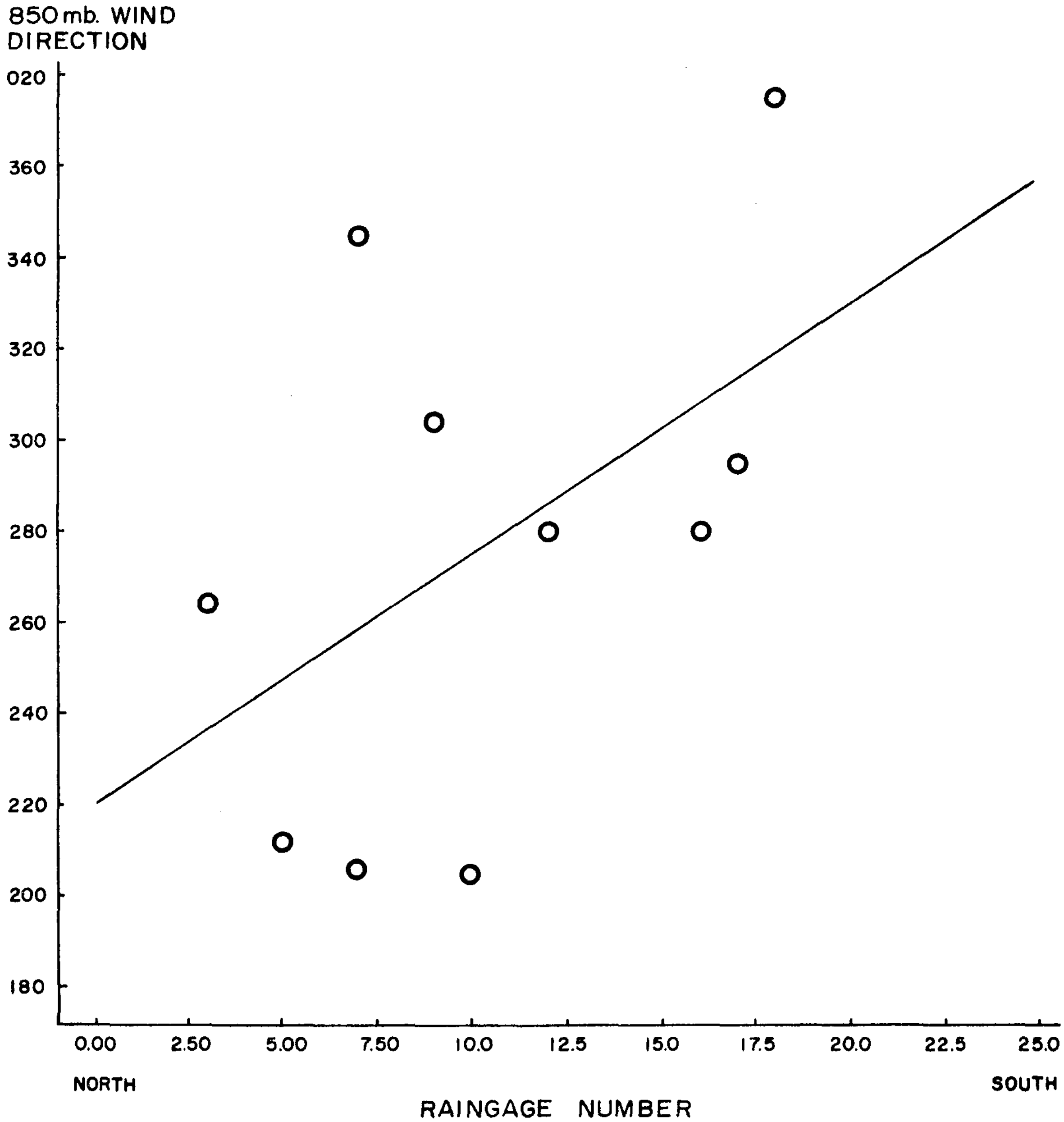
**Mean total per affected raingage was .19 inches. Traces were not used in this calculation.

revealed that variation of wind direction explained 65%, 31%, and 24%, respectively, of the variation of location along the network. Figures VII, VIII, and IX depict the relationships. A maximum of clustering was observed about the regression line when wind data for the 300 mb. level were used, suggesting that the direction of wind flow at this level substantially controlled the location of the shower clouds.

Cloud photography. On June 22, 1970, an unusually good sequence of apparent lake breeze development, convergence, and subsequent precipitation occurred and has been depicted in Figures X and XI. Additional photographs (Figures XII and XIII) provide a record of narrow cloud streets apparently associated with lake breeze convergence, possible lake breeze fronts with associated cumuli and a cloud-free zone just behind the front, and a narrow cloud street with apparent precipitation occurring just west of the raingage network. Tiros satellite photographs (Figures XIV and XV) depict narrow cloud streets oriented, in general, parallel to the long axis of the peninsula.

Temperature and relative humidity. Certain aspects of the hygrothermograph and mechanical weather station record have been summarized in Table IV. Some data were obtained from the Sault Ste. Marie Weather Bureau and include mean temperature and dew point values for 0615 and the daily maximum temperatures for all three sample groups.

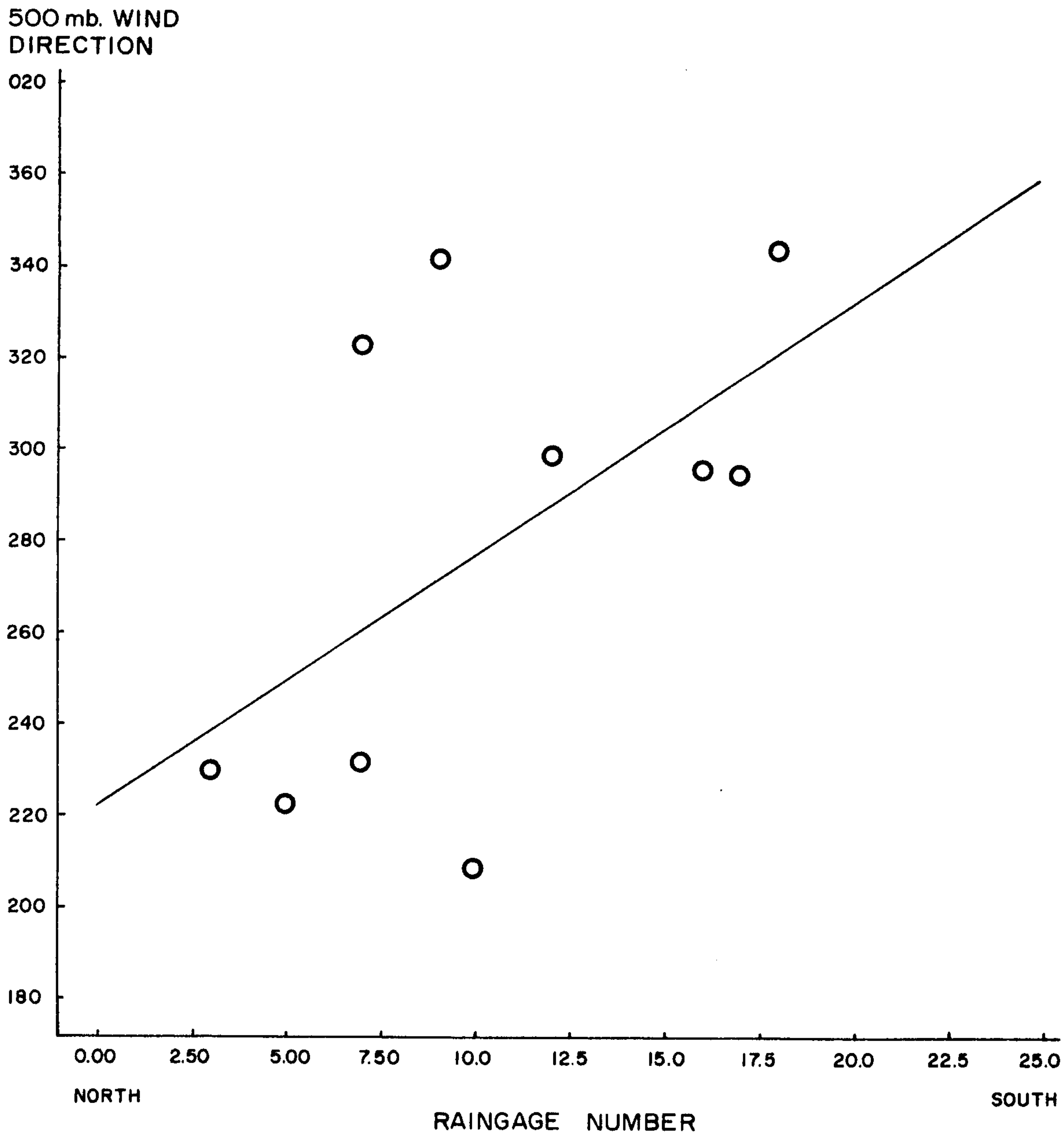
FIGURE VII
Regression of 850mb. Wind Direction Against Maximum Rain Occurrence Along the Raingage Network for Group I Days



r = 0.49
Sig. of F: 0.147

FIGURE VIII

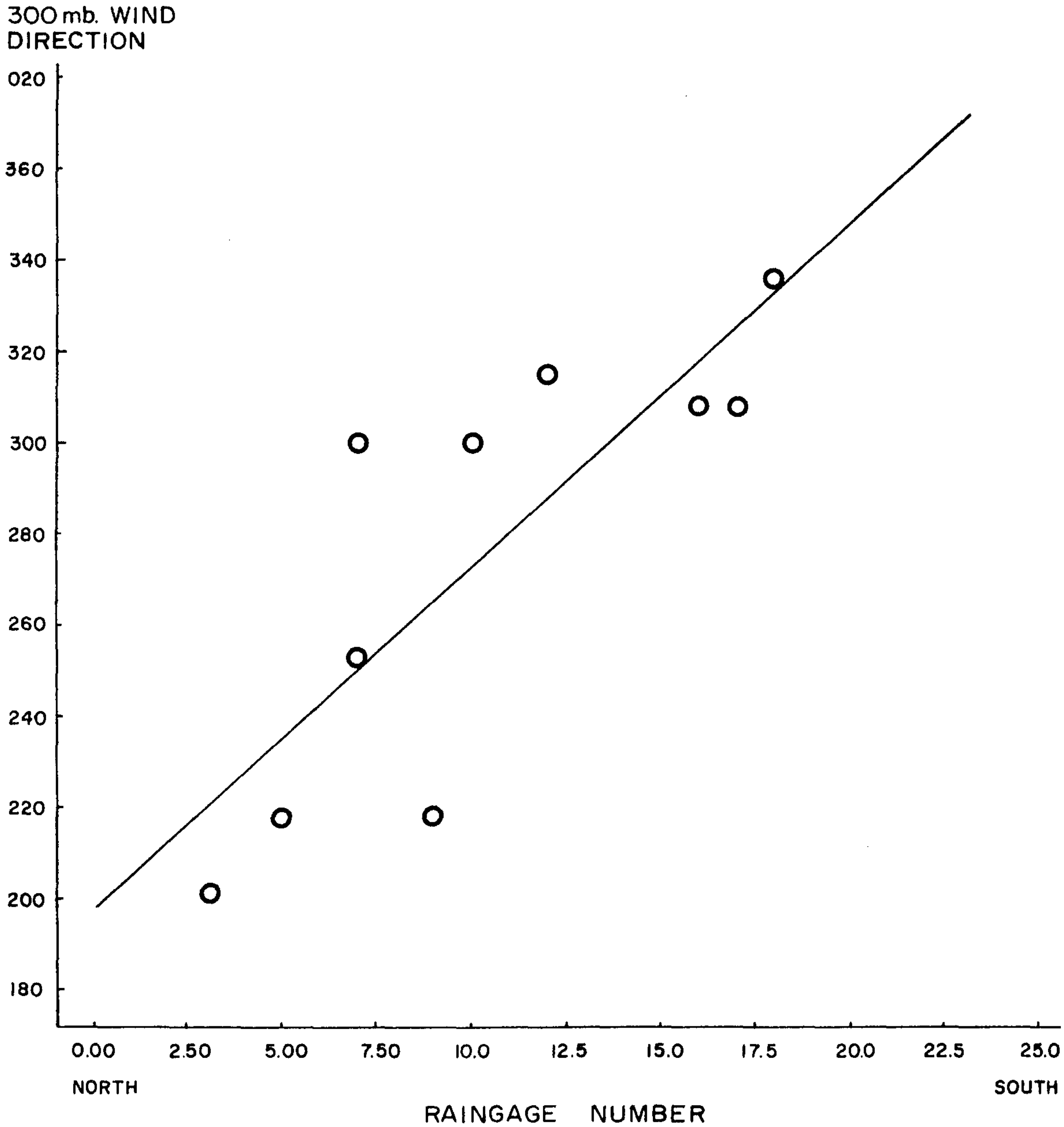
Regression of 500 mb. Wind Direction Against Maximum Rain Occurrence Along the Raingage Network for Group I Days



r = 0.56
Sig. of F: 0.094

FIGURE IX

Regression of 300 mb. Wind Direction Against Maximum Rain Occurrence Along the Raingage Network for Group I Days

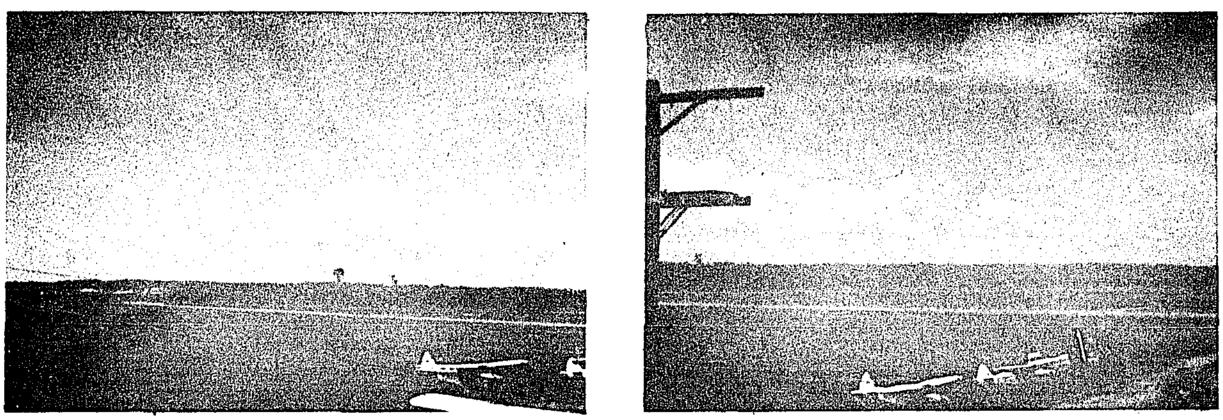


r = 0.81
Sig. of F: 0.004

FIGURE X

The Lake Breeze of June 22, 1970, Group I Day

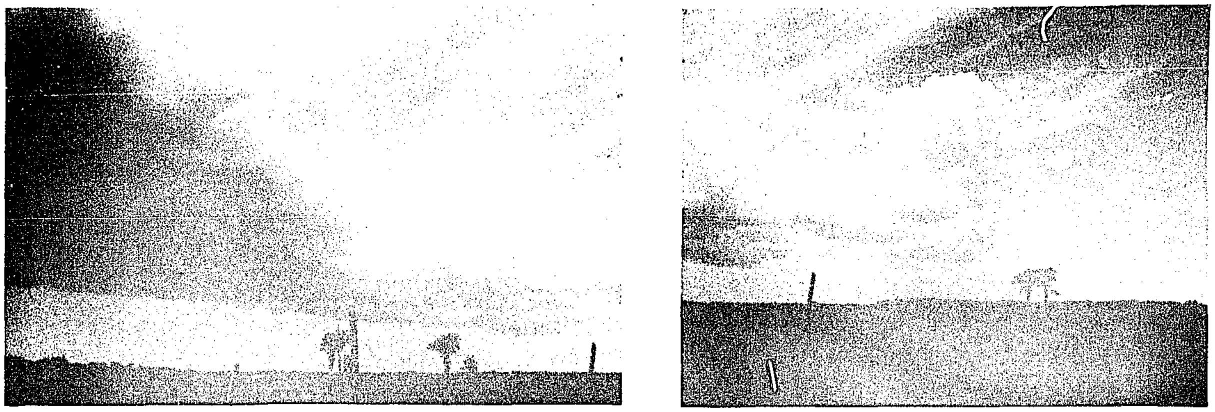
A. View southwest from Sault Ste. Marie at 1035 showing initial convective cloud development over the interior.



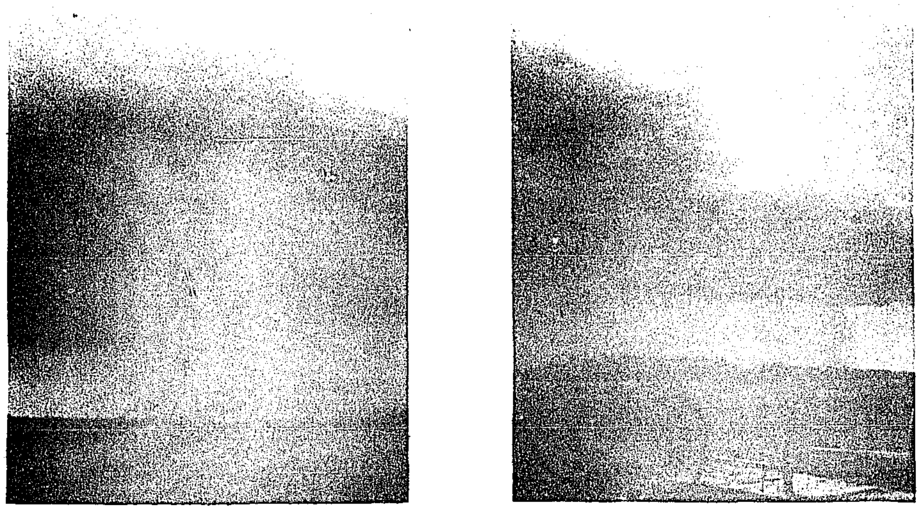
B. View southwest from Sault Ste. Marie at 1100 showing further cumulus development. The absence of convective clouds overhead suggests that a lake breeze front has already passed the observer and is advancing inland.

FIGURE XI

The Lake Breeze of June 22, 1970, Group I Day



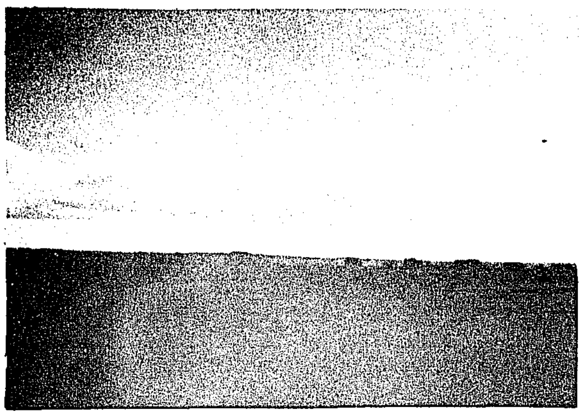
C. View west-southwest from the Hesselink site at 1400 showing a narrow band of building cumuli between two converging lake breeze systems. The absence of any convective clouds both north (to the right) and south (to the left) of the cumulus band is evidence of subsidence in the cooler lake breeze circulations.



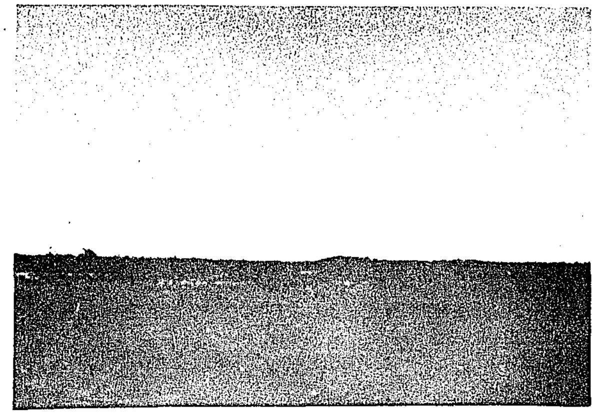
D. View southwest from the Hesselink site at 1420 of precipitation falling from the convective cloud band in the convergence zone. Note again the absence of low clouds beyond (to the south) of the zone.

FIGURE XII

Various Lake Breeze Views



A. View south-southwest from Pickford of cumulus along a narrow lake breeze convergence zone on August 1, 1970. Note the lack of vertical development and the absence of clouds on either side of the band. (Group II day)

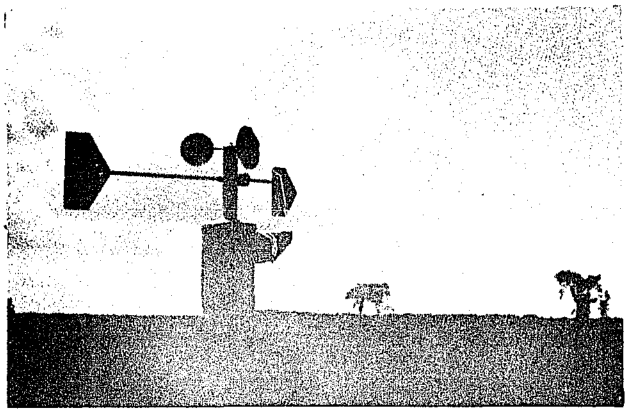


B. View south from Sault Ste. Marie of a cloud band along a lake breeze convergence zone on July 17, 1970. Note a slight increase of vertical development over A. (Group II day)

C. View west from Rudyard of a narrow cloud band along a lake breeze convergence zone on June 29, 1970. Precipitation appears to be occurring to the west; note the abrupt termination of the cloud band to the south (left). (Group I day)

FIGURE XIII

Various Lake Breeze Views

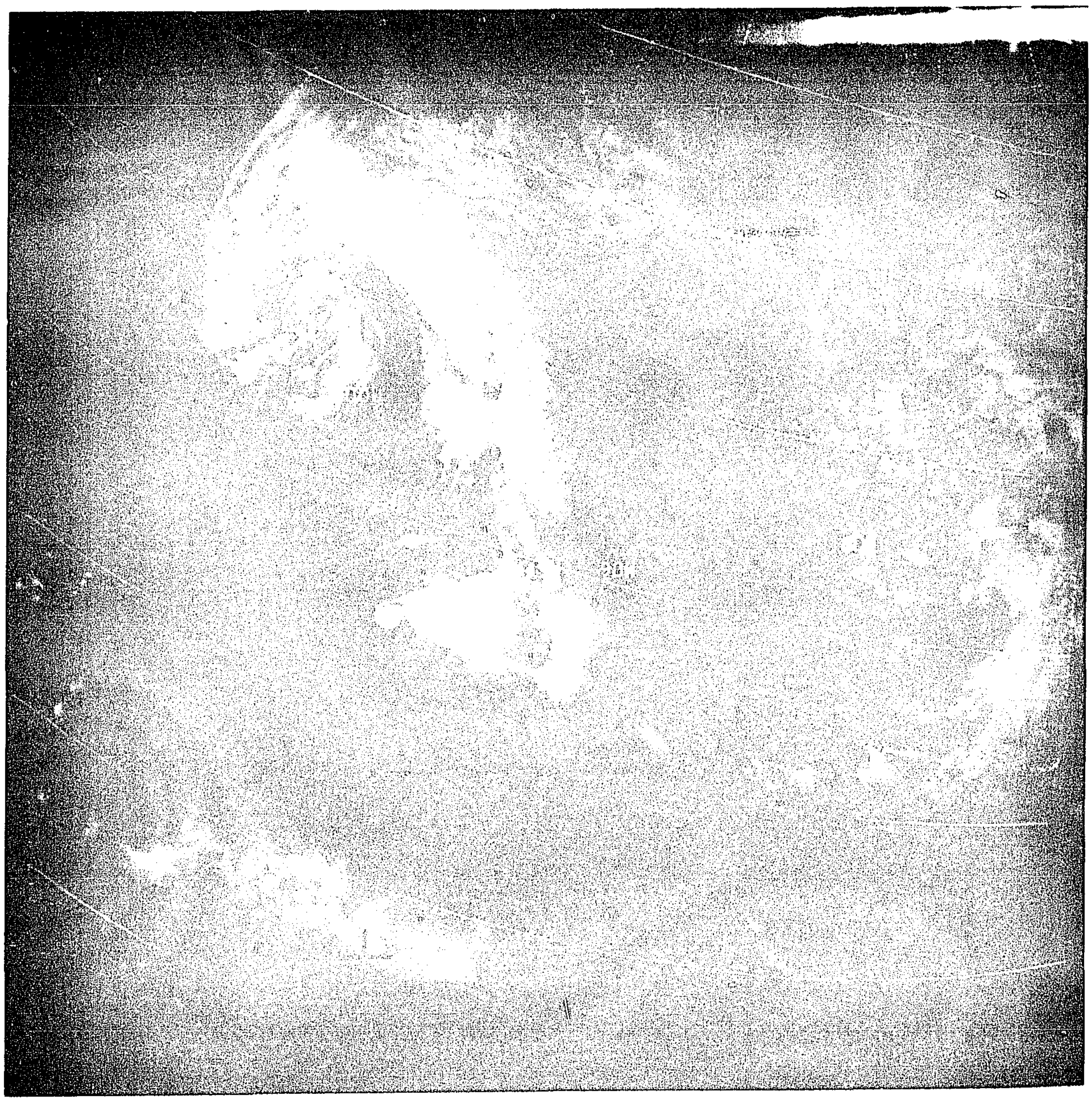


A. View west from the Hesselink site on July 26, 1970, showing a cloud band between two converging lake breeze systems. Note the absence of clouds to the north (right) of the band and the northerly wind indicated by the vane on the mechanical weather station; the advancing edge of the Lake Superior system had already passed the observer and the surface flow was toward the cloud band. (Group II day)

B. View west from the Erfourth site on August 6, 1970, showing cumulus forming along a lake breeze front which is moving south. Note the sharp boundary between the convergence zone and the stable lake air behind the front. (Group II day)

FIGURE XIV

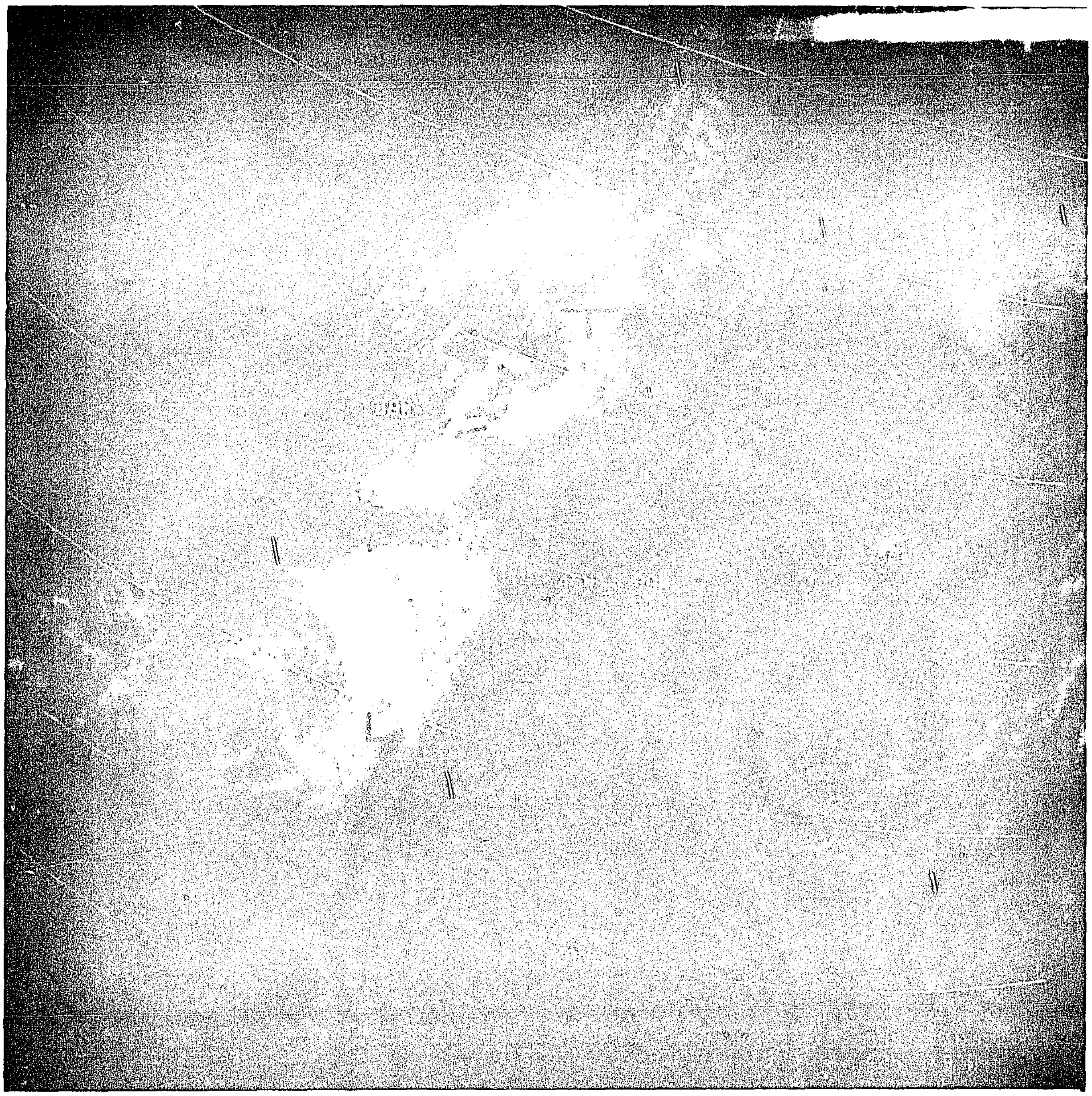
Tiros Satellite Photograph of the Great Lakes Region, July 26, 1969



A cloud street was oriented east-west through the eastern portion of Upper Michigan. Note the absence of clouds both north and south of the cloud street.

FIGURE XV

Tiros Satellite Photograph of the Great Lakes Region, July 30, 1969



A cloud street was oriented generally east-west through the central portion of Upper Michigan. Note the cloud free zone north-east of Lake Superior and Georgian Bay suggesting lake breeze formation.

TABLE IV

Selected Temperature and Humidity Data for the Instrumented Traverse and the Sault Ste. Marie Airport

	Instrumented Traverse					Sault Ste. Marie		
	Mean Max Daily Temp.	Mean Max Daily Humid.	Mean Drop in Temp.*	Mean Rise in Humid.*	Mean Max Humid After L.B. Pass.*	Mean Max Daily Temp.	Mean 0615 Daily Temp.	Mean 0615 Dew Point
Group I	79.95°F	70.00%	5.41°F	11.87%	70.00%	83°F	62°F	57°F
Group II	71.73°F	56.90%	2.45°F	7.83%	56.90%	75°F	53°F	49°F
Group III	72.93°F	60.12%				77°F	57°F	52°F

*All changes of these values were recorded within one-half hour after apparent lake breeze passage.

It is readily apparent from Table IV that temperature and relative humidity values vary considerably between Group I days and Group II and III days. On Group I days the mean maximum temperature and mean maximum daily relative humidity were 7.62°F and 11.49% higher, respectively, than the mean values for Group II and III days. Data from the Sault Ste. Marie Weather Bureau compare favorably with the instrumented traverse. The mean daily maximum and mean 0615 daily temperatures on Group I days were both 7.00°F higher than the mean values for Groups II and III. The Group I mean 0615 daily dew point was also 6.50°F higher than the mean value for Group II and III days.

Changes of temperature and relative humidity associated with lake breeze passage along the instrumented traverse were more extreme on Group I days than on Group II days. For example, the mean drop in temperature within one-half hour after apparent lake breeze passage was 2.96°F greater on Group I days, and the mean rise in relative humidity was 4.49% higher. The mean maximum relative humidity within one-half hour after apparent lake breeze passage was 13.10% higher on Group I days than on Group II days.

Insolation. Data concerning the amount of solar radiation reaching the earth's surface were collected at five instrument sites and have been summarized in Table V. These data indicate that afternoon insolation receipts for

TABLE V

Mean Percentage of Possible Sunshine,
Groups I, II, III

	a.m.	p.m.	daily total
Group I			
Brimley	64.32	70.44	67.77
Vanderstar	61.44	57.44	59.33
Hesselink	61.00	63.22	62.11
Erfourth	62.33	67.22	65.44
Harrison	60.00	72.00	66.66
	$\bar{X}$=62.80	$\bar{X}$=66.00	$\bar{X}$=64.20
Group II			
Brimley	74.52	81.76	78.52
Vanderstar	68.70	75.76	72.64
Hesselink	66.58	71.44	69.23
Erfourth	69.05	73.82	71.82
Harrison	64.47	69.76	67.35
	$\bar{X}$=68.60	$\bar{X}$=74.60	$\bar{X}$=72.00
Group III			
Brimley	71.44	76.23	74.11
Vanderstar	67.35	72.47	70.11
Hesselink	67.23	69.94	68.76
Erfourth	70.82	74.82	73.17
Harrison	67.47	71.23	69.82
	$\bar{X}$=68.80	$\bar{X}$=73.00	$\bar{X}$=71.20

Group I days were at a minimum in the interior and increased toward either coast. The afternoon receipts at the Vanderstar site of 57.44% and the Hesselink site of 63.22% of the mean percentage of possible sunshine were the lowest of the three sample groups, suggesting that the contrast between coastal and interior cloud development was greatest on Group I days. It should also be noted on Table V that the increase of solar radiation receipts on Group I days from morning to afternoon occurred at all sites except the Vanderstar site in the interior.

Group II days were characterized by higher mean afternoon and daily total solar radiation receipts than Group I days. In the afternoon period on Group II days the mean maximum receipt occurred at Brimley State Park on the north coast while the mean minimum was observed at the Harrison site on the south coast. On Group III days Brimley State Park also had the mean maximum insolation receipt. At all stations except the Vanderstar site, which was noted above, there was an increase of solar radiation receipts from morning to afternoon.

The mean percentage of possible sunshine for Group I and II days was plotted against 850 mb. wind direction at 40° intervals. Tables VI and VII summarize the results from this analysis. On Group I days, with a prevailing air flow from the west (260°-299°), maximum cloud development occurred in the central portion of the peninsula at

TABLE VI

Mean Percentage of Possible Sunshine as Related to Wind Direction at the 850 mb. Level by 40° Intervals, 180°-015°,* for Group I Days

	a.m.	p.m.	daily total
	Wind Direction 340°-015° Inclusive		
Brimley	74.13	75.32	74.83
Vanderstar	75.68	65.83	70.08
Hesselink	70.25	62.14	65.63
Erfourth	73.56	64.86	68.61
Harrison	73.43	64.10	68.12
	$\overline{X}$=73.41	$\overline{X}$=66.45	$\overline{X}$=69.45
	Wind Direction 300°-339° Inclusive		
Brimley	44.44	72.29	60.27
Vanderstar	31.75	65.06	50.69
Hesselink	44.44	72.29	60.27
Erfourth	46.03	61.45	54.80
Harrison	44.44	75.90	62.33
	$\overline{X}$=42.22	$\overline{X}$=69.40	$\overline{X}$=57.67
	Wind Direction 260°-299° Inclusive		
Brimley	70.84	80.74	76.36
Vanderstar	67.62	61.43	63.85
Hesselink	66.31	68.00	67.24
Erfourth	69.12	71.11	70.28
Harrison	59.94	77.68	69.92
	$\overline{X}$=66.77	$\overline{X}$=71.79	$\overline{X}$=69.53
	Wind Direction 180°-219° Inclusive		
Brimley	57.67	56.63	57.08
Vanderstar	56.08	45.38	50.41
Hesselink	55.03	56.23	55.71
Erfourth	53.97	67.47	61.64
Harrison	56.61	69.88	64.16
	$\overline{X}$=55.87	$\overline{X}$=59.12	$\overline{X}$=57.80

*There were no occurrences between 220° and 259°.

TABLE VII

Mean Percentage of Possible Sunshine as Related to Wind Direction at the 850 mb. Level by 40° Intervals, 180°-360°,* for Group II Days

	a.m.	p.m.	daily total
	Wind Direction 340°-360° Inclusive		
Brimley	88.32	81.49	84.49
Vanderstar	83.41	75.87	79.10
Hesselink	76.68	81.54	79.40
Erfourth	80.66	78.48	79.40
Harrison	79.62	70.82	74.72
	$\bar{X}$=81.74	$\bar{X}$=77.64	$\bar{X}$=79.42
	Wind Direction 300°-339° Inclusive		
Brimley	72.23	80.34	76.76
Vanderstar	64.90	75.29	70.79
Hesselink	62.48	67.72	65.43
Erfourth	65.87	70.51	68.53
Harrison	58.43	67.70	63.62
	$\bar{X}$=64.78	$\bar{X}$=72.31	$\bar{X}$=69.03
	Wind Direction 260°-299° Inclusive		
Brimley	67.73	86.35	78.10
Vanderstar	63.49	73.49	69.19
Hesselink	57.14	62.25	60.05
Erfourth	65.08	58.63	61.42
Harrison	58.73	58.63	58.68
	$\bar{X}$=62.43	$\bar{X}$=67.87	$\bar{X}$=65.49
	Wind Direction 220°-259° Inclusive		
Brimley	73.02	78.31	76.03
Vanderstar	73.02	78.31	76.03
Hesselink	74.60	85.54	80.82
Erfourth	69.84	92.77	82.88
Harrison	71.43	90.36	82.19
	$\bar{X}$=72.38	$\bar{X}$=85.06	$\bar{X}$=79.59

*There were no occurrences between 180° and 219°.

the Vanderstar and Hesselink sites, with minimum development occurring at Brimley State Park and the Harrison site. With a prevailing northerly flow (340°-015°) on Group I days maximum afternoon cloud development occurred in the central and southern portion of the peninsula, while on southerly flow days (180°-219°) the cloud zone shifted to the northern portion of the peninsula.

Group II days, in the mean, were characterized by higher percentages of possible sunshine, as noted in Table V. In all cases, excepting wind flow from 220°-259°, the Harrison site on Group II days had the minimum mean afternoon and daily insolation receipts, which was not the case for Group I days.

In general, on both Groups I and II days with a northerly flow of air maximum cloud development occurred toward the southern portion of the peninsula. The reverse was true with a southerly flow across the peninsula. In general, Brimley State Park had the mean maximum radiation totals. However, on southerly flow days, as noted above, for both Groups I and II, the sites toward the southern portion of the peninsula had the mean maximum insolation receipts. Thus, the zone of maximum afternoon cloud development appeared to have been displaced toward the leeward side of the peninsula during both groups of days.

Surface wind. Surface wind data were collected at five previously mentioned stations: Grand Marais (GRM), Whitefish Point (WHP), Sault Ste. Marie (SSM), Lansing Shoal (LAS), and the Hesselink site (HES) for 0630, 1230, and 1830. The results of this analysis are presented in Figures XVI through XXI utilizing modified wind roses to show direction and frequency for each time period for Groups I and II.

At 0630 on Group I days (Figure XVI) the pattern at the interior station, HES, was one of wind components from nearly all directions. The coastal stations, GRM, WHP, and SSM on the St. Marys River exhibited wind directions suggesting an offshore flow. By 1230 (Figure XVII) several patterns had developed. The stations along Lake Superior, GRM and WHP, showed a high frequency of onshore flow, while SSM showed varied wind directions. LAS at 1230 still exhibited a southwesterly onshore flow, while HES began to show important south-southwesterly influence, suggesting that the onshore flow from Lakes Michigan and Huron may have extended inland relatively frequently by this time. By 1830 (Figure XVIII), the Lake Superior stations, SSM, and HES were all showing a high frequency of northerly flow, while LAS still exhibited a predominantly west-southwesterly air flow. This pattern suggests that during the afternoon hours the Lake Superior onshore flow became relatively more important than the system from Lakes Michigan and Huron. With this surface flow pattern

FIGURE XVI

Directional Frequencies of Wind

GROUP I DAYS

0630
LOCAL TIME

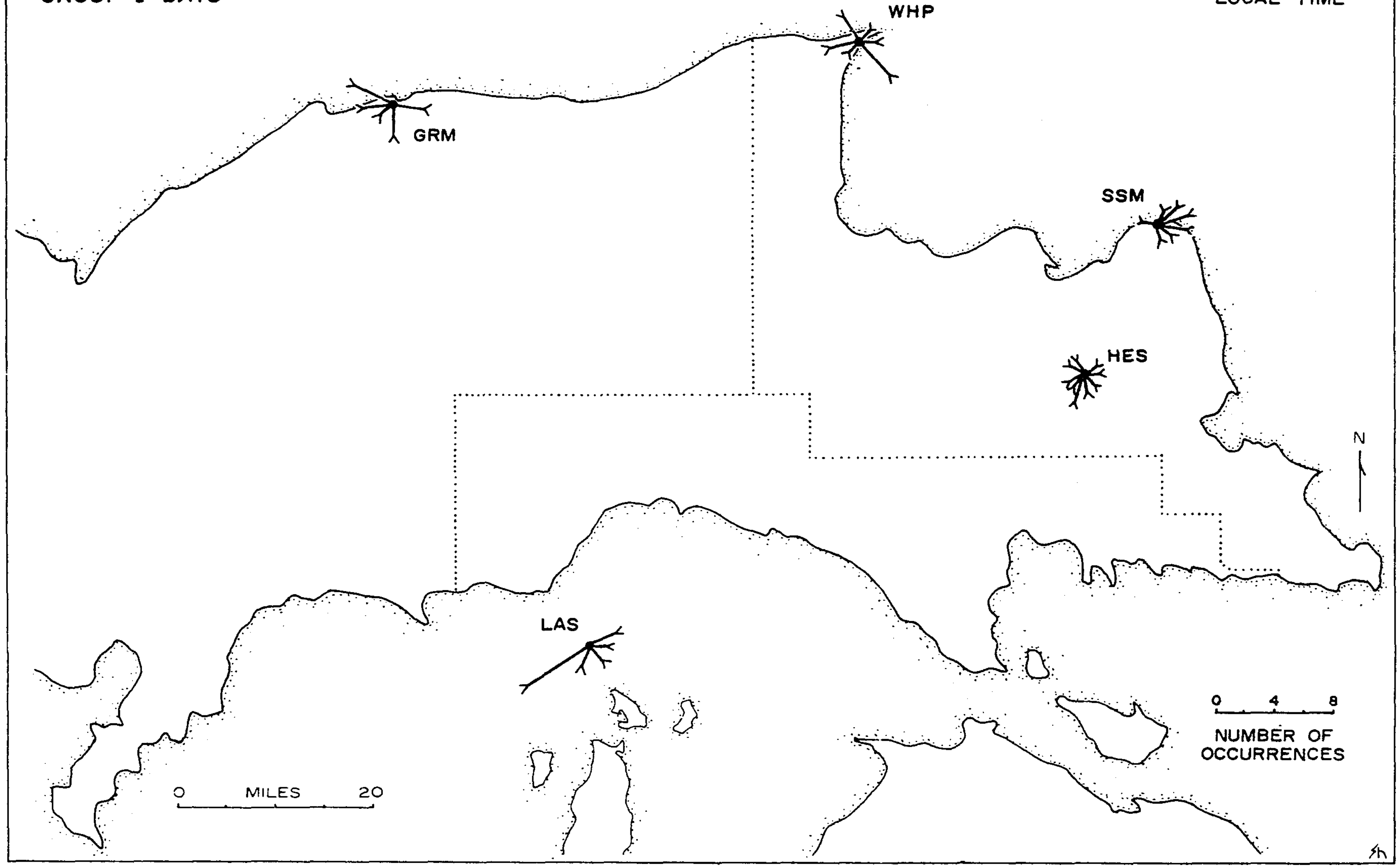


FIGURE XVII

Directional Frequencies of Wind

GROUP I DAYS

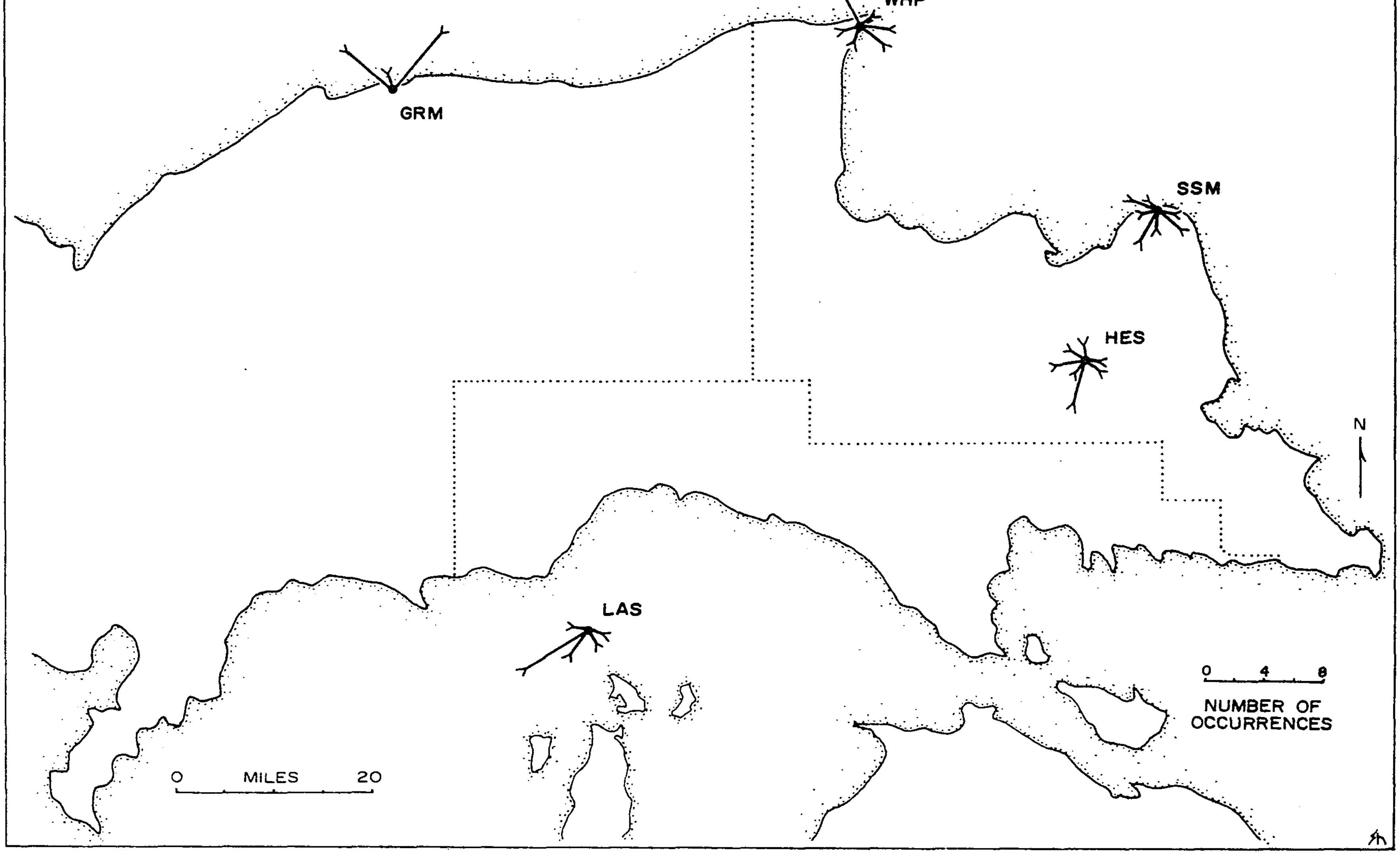
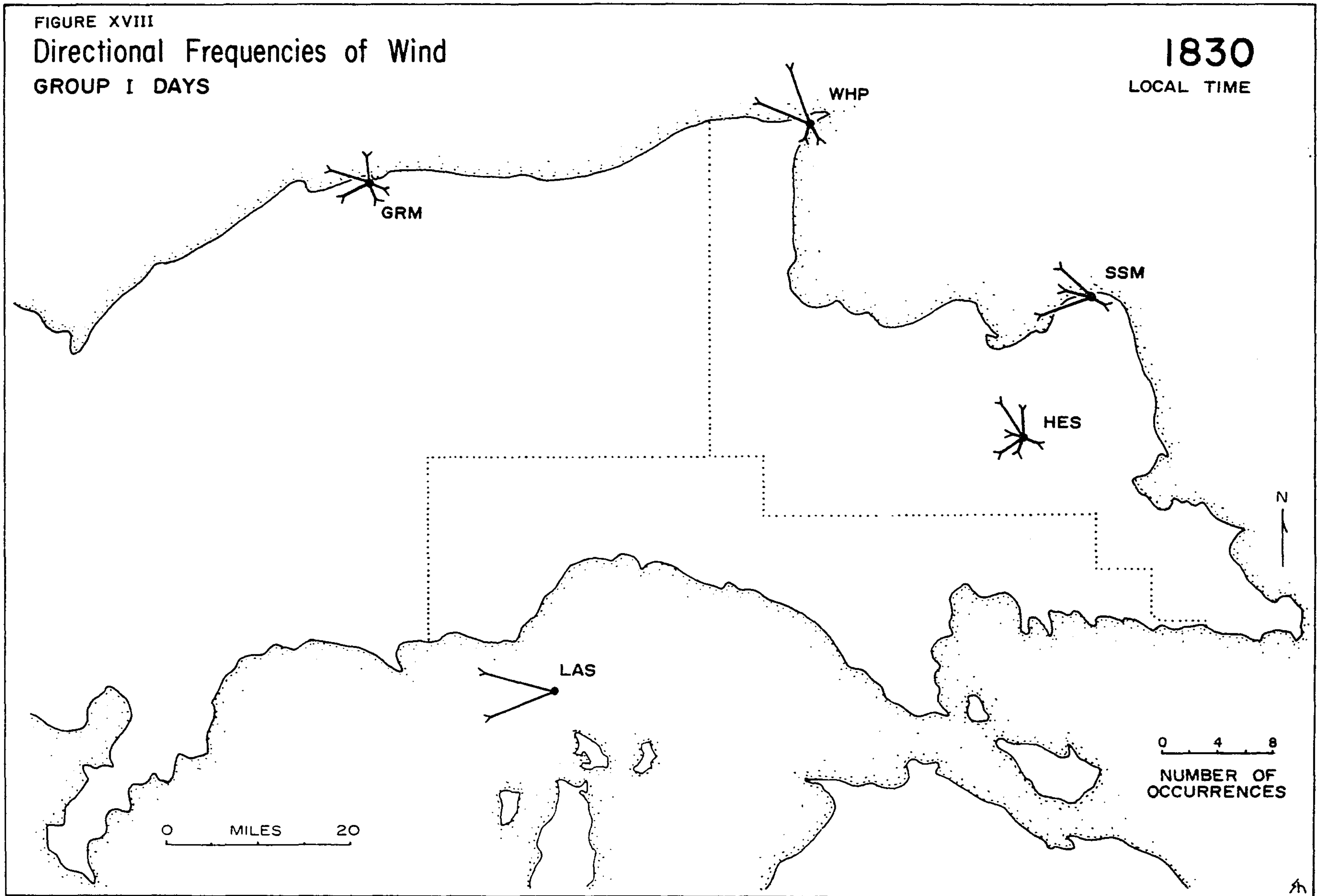


FIGURE XVIII

Directional Frequencies of Wind

GROUP I DAYS



apparently existing over the peninsula, a convergence zone may have been located between the HES site and the LAS site.

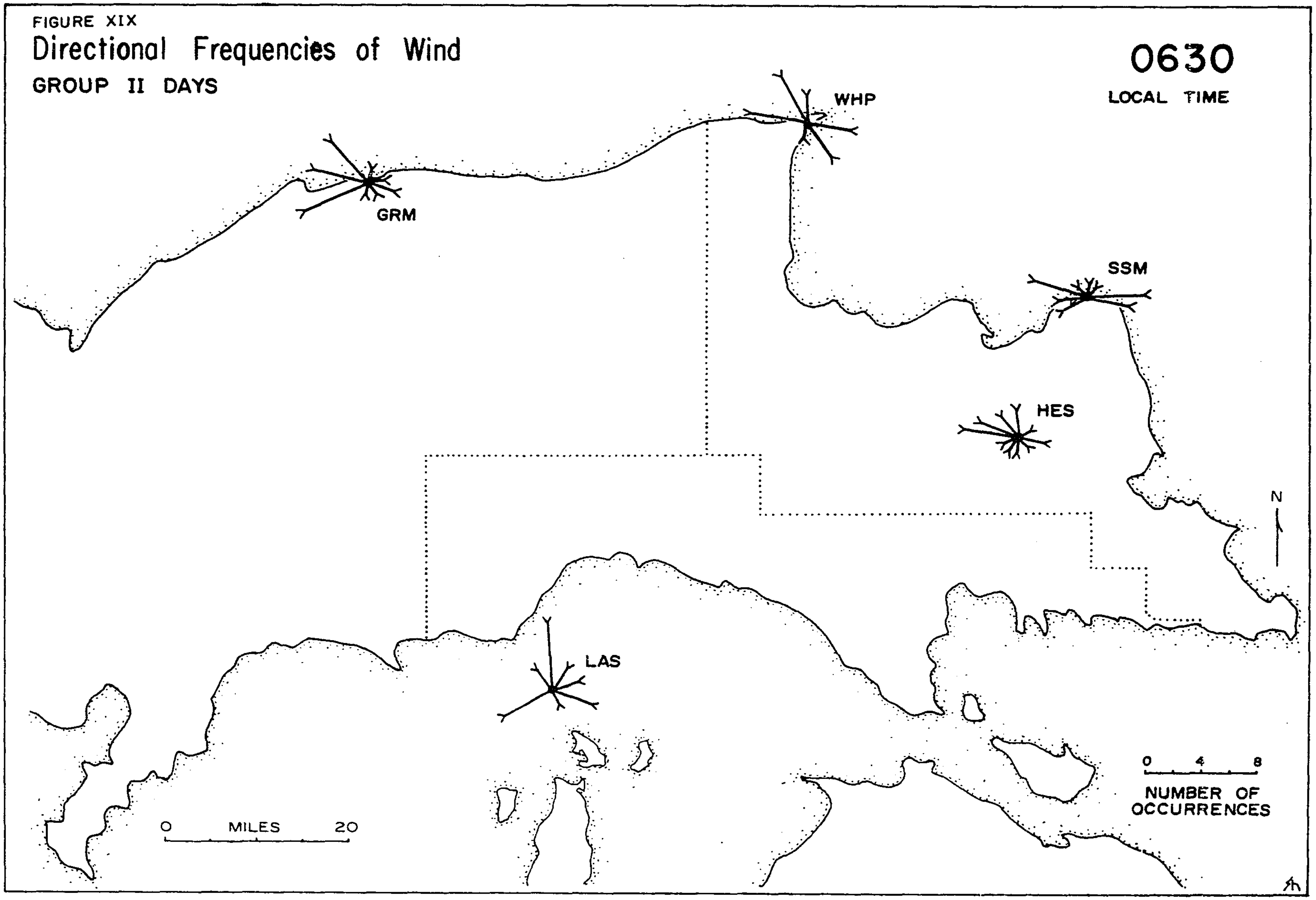
The 0630 patterns for Group II days (Figure XIX) were similar to those of Group I except that a higher frequency of offshore flows occurred at the coastal and offshore stations. The 1230 pattern on Group II days (Figure XX) differed from Group I days in that northerly flow patterns were more prevalent at the SSM and HES sites, indicating that the Lake Superior onshore flow often had advanced far inland by this time. At LAS at 1230 a prevailing southwesterly wind was evident. The 1830 pattern (Figure XXI) remained similar to that of 1230 with a northerly flow still prevailing at the GRM, WHP, SSM, and HES sites. The LAS site still exhibited a predominantly southwesterly flow.

Surface wind data taken from HES within one-half hour after apparent lake breeze passage for Groups I and II have been summarized in Table VIII. The data indicate that on Group I days onshore flow from Lakes Michigan and Huron reached the interior with higher frequency earlier in the day than did the Lake Superior systems, whereas the opposite occurred on Group II days. The prevailing flow before apparent lake breeze passage on Group I and II days was 221° and 267°, respectively. Wind flow after apparent lake breeze passage in both cases was northerly. On Group

FIGURE XIX

Directional Frequencies of Wind

GROUP II DAYS



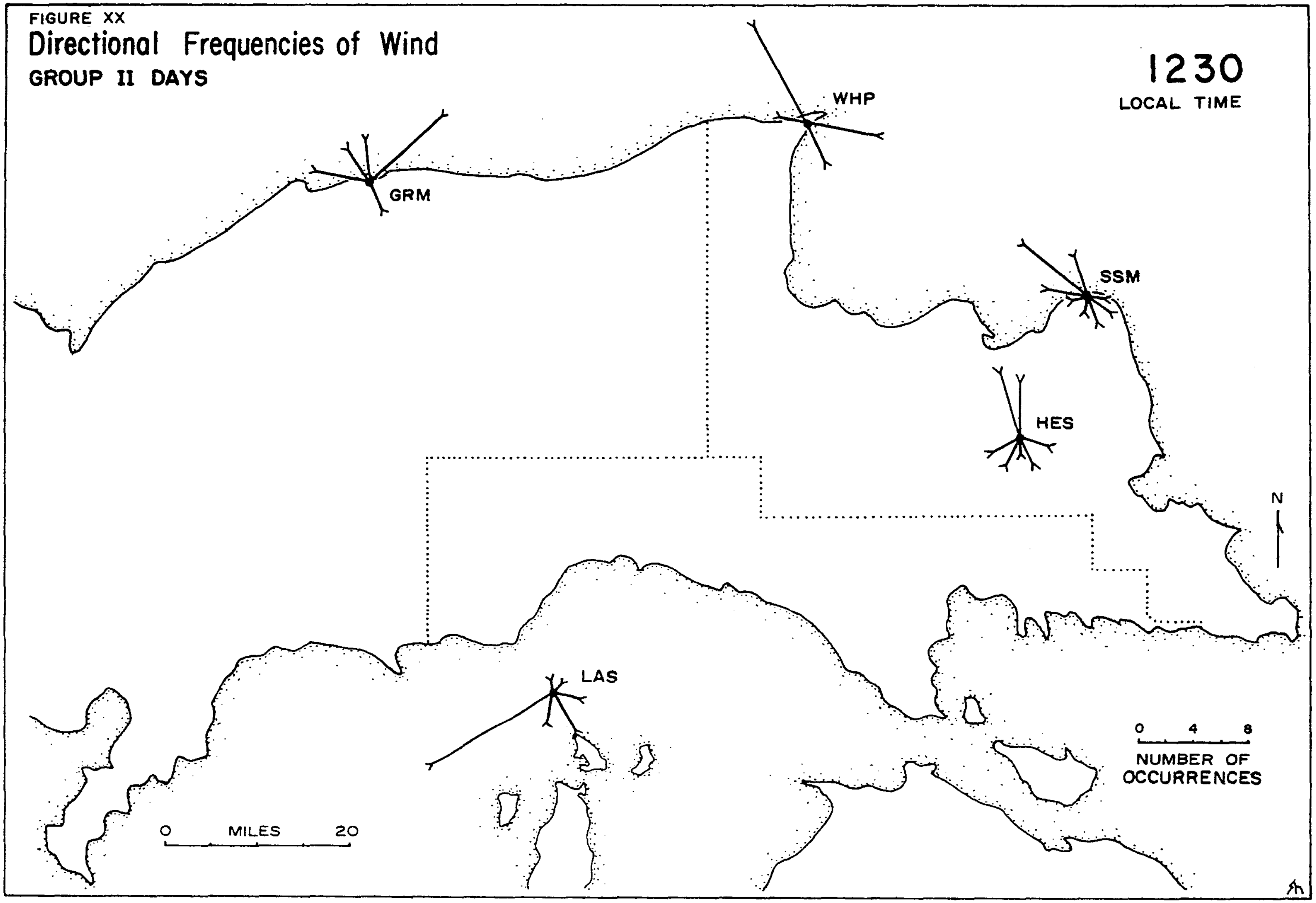


FIGURE XX
Directional Frequencies of Wind
GROUP II DAYS

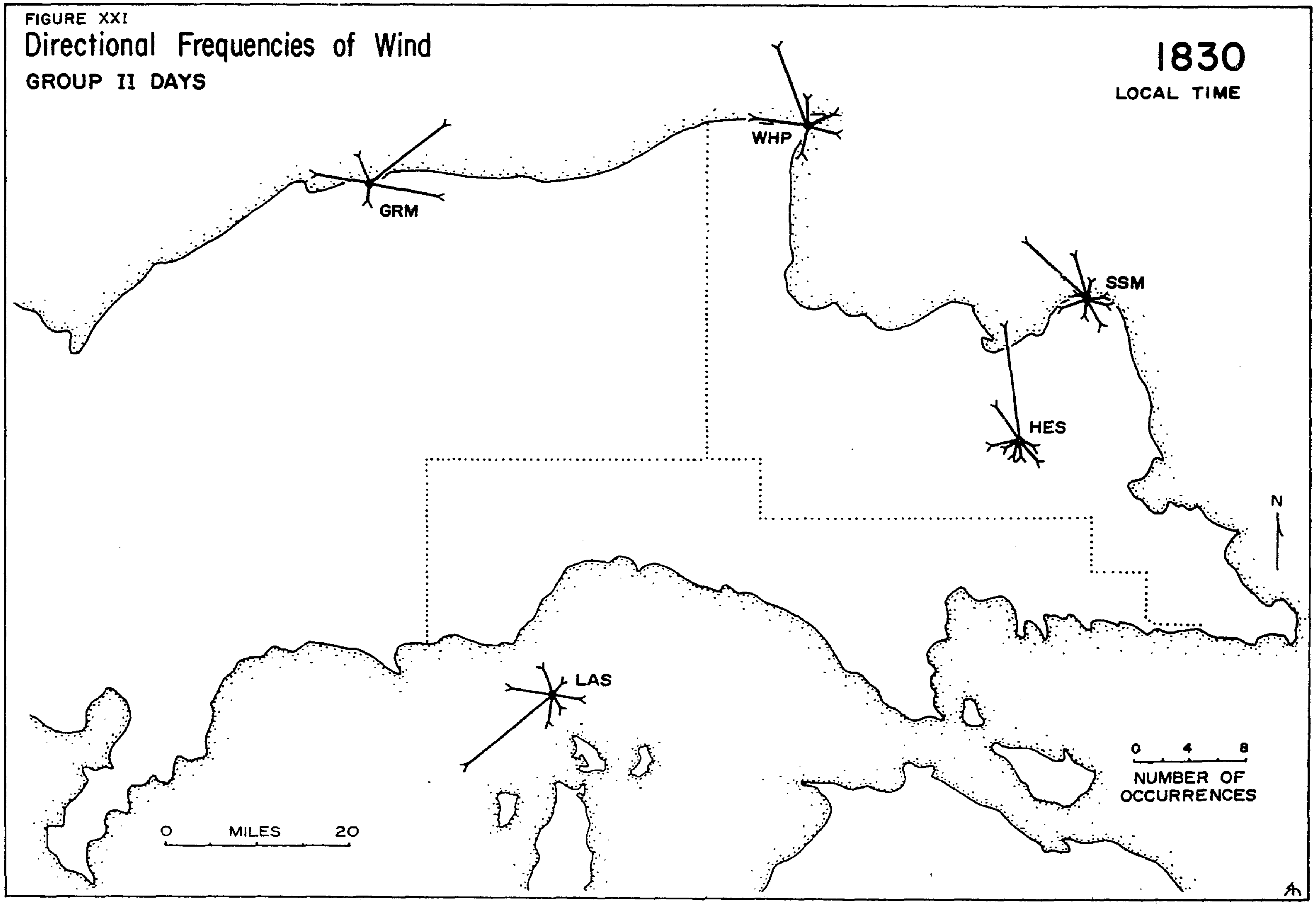


FIGURE XXI
Directional Frequencies of Wind
GROUP II DAYS

TABLE VIII

Selected Surface Windflow Data from the Hesselink Site During All Interior Lake Breeze Days

	Mean Time of Lake Breeze Passage	Mean Wind Change* Before	After	Change
Group I	Superior - 1410	221°	354°	133°
	Michigan Huron - 1335	**	226°	**
Group II	Superior - 1340	267°	360°	93°
	Michigan Huron - 1433	**	182°	**

*Within one-half hour of lake breeze passage.

**These wind directions were not computed because prevailing winds before lake breeze passage were both east and west of south.

I days the mean wind speed increase with apparent lake breeze passage was 4.00 mph while that of Group II was 3.33 mph.

Water temperature. Daily water temperature differences between the land and nearby water were compiled for all three sample groups. The mean temperature differential for Group I days was 24.63°F, whereas that of Group II and III was 17.13°F and 19.35°F, respectively. Thus, Group I days had a temperature differential that was 7.50°F and 5.28°F greater than Group II and III days, respectively.

Results of the Upper Air Analysis

Analysis of higher level air flow to infer the presence of upper-tropospheric divergence and convergence was carried out for Groups I and II. Trough distance and amplitude were expressed as a ratio of the distance to trough axis over the difference in pressure height surfaces so that increasing ratio numbers were indicative of less (upward) vertical motion. The ratio involving ridges west of Michigan was devised so that increasing ratio numbers were associated with more subsidence. Thus, in both cases, higher ratio numbers can be produced by changes of either wave amplitude or length and imply greater stability. Although relatively unsophisticated, this approach nevertheless provided a general estimate of the vorticity changes associated with upstream tropospheric waves. It should be noted that for a fixed wave length variations of wave amplitude and the strength of vertical atmospheric motions within the wave are positively related. For example, if the amplitude of a trough increases, vorticity changes and associated upper-level divergence ahead of the trough also increase, maximizing vertical motion. The opposite occurs if wave amplitude decreases (5). The results of this analysis are presented in Table IX with the results of an analysis of pressure height surfaces over the study area.

The data concerning troughs on Table IX indicate at each level being considered that Group I days had the smallest ratio number. This finding suggests that the upper-tropospheric environment on Group I days was characterized by substantial upward vertical motion, particularly at the 300 mb. level, where the ratio number was smallest. Group II days had relatively higher ratio numbers indicating greater stability, but again the 300 mb. level had the smallest ratio number. Thus, it appears that those features associated with vertical motion were most strongly developed at the 300 mb. level.

Data associated with ridges at the three levels being considered were generally similar. It should be noted, however, that at all levels Group I days were associated with less subsidence than Group II days, and

TABLE IX

Upper Air Index and Mean Pressure Heights over the Study Area

Upper Air Index*

	300 mb.	500 mb.	850 mb.
Group I Troughs	2.38	3.55	6.04
Group II Troughs	5.40	15.04	7.98
Group I Ridges	00.61	00.34	00.13
Group II Ridges	00.69	00.40	00.21

Mean Pressure Heights over the Study Area (ft)

	300 mb.	500 mb.	850 mb.
Group I	29511	18978	4947
Group II	30919	18811	4930
Group III	31001	18855	4916

*Higher ratio numbers denote increasing stability.

that the largest ratio numbers, suggesting stability, occurred at the 300 mb. level. The analysis of mean pressure heights over the study area was inconclusive and no patterns were evident.

Rawinsonde data were collected on all sample days and these data are summarized in Table X along with an analysis of the percentage of troughs and ridges at the 300 mb. level upstream from Michigan. Several interesting patterns are evident including the following: (1) at all levels temperatures were warmer on Group I days; (2) at the 850 mb. and 500 mb. levels the dew points were higher on Group I days; (3) at all levels wind directions were more southerly on Group I days; and (4) at all levels wind speeds were lower on Group I days. Specifically, 850 mb. temperatures were 10°F and 8°F lower on Group II and III days, respectively, and mean dew points were 14°F and 11°F lower, respectively. Wind directions at all levels on Group I days were more southerly. At the 300 mb. level on Group I days a high percentage of troughs occurred upstream from Michigan, whereas ridges prevailed on Group II days. The higher frequency of upstream troughs on Group I days probably explains the stronger southerly component of the mean wind for that sample group. Groups II and III, on the other hand, had mean northwesterly flows indicating a high incidence of ridges, as indicated for Group II days at the 300 mb. level, upstream from Michigan.

TABLE X

Rawinsonde Data from the Sault Ste. Marie Weather Bureau for 0615*

850 mb.

	Temp.	Dew Pt.	Wind Dir.	Wind Speed (mph)
Group I	58°F	49°F	266°	15
Group II	48°F	35°F	306°	17
Group III	52°F	38°F	296°	25

500 mb.

	Temp.	Dew Pt.	Wind Dir.	Wind Speed (mph)
Group I	14°F	-14°F	279°	21
Group II	7°F	-20°F	301°	31
Group III	9°F	-23°F	295°	39

300 mb.

	Temp.	Dew Pt.	Wind Dir.	Wind Speed (mph)
Group I	-33°F		276°	36
Group II	-39°F		304°	54
Group III	-38°F		295°	51

The Percentage of Troughs and Ridges Upstream from Michigan at 300 mb. for Groups I and II

	Troughs	Ridges
Group I	70	30
Group II	22	78

*Dew points are not available for the 300 mb. level.

Supplementary Data

Scatter diagrams have been constructed to indicate relationships and possible patterns of clustering among some of the data. These diagrams have utilized only Group I and II data to show contrasts between the two groups. Because Group I consists of only ten sample days, one must interpret the results with caution, and further statistical examination was not thought to be fruitful.

In Figures XXII and XXIII, Groups I and II have been plotted by 850 mb. temperature and wind speed and 500 mb. temperature and wind speed, respectively. On both diagrams it is apparent that Group I days are clustered toward higher temperature and lower wind speeds, whereas Group II days generally have lower temperatures. The data also appear to show more clustering on Figure XXII than Figure XXIII. These results suggest that within the Group I sample 850 mb. temperature and wind speed are positively related.

In Figures XXIV and XXV, Groups I and II have been plotted by the land-water temperature difference and the surface dew point and the land-water temperature difference and 500 mb. dew point, respectively. The results from Figure XXIV indicate that Group I days are clustered toward higher surface dew points and greater land-water temperature differences, whereas Group II days, in general, had both lower surface dew points and land-water

FIGURE XXII

Group I and II Days Plotted by 850 mb. Temperature and Wind Speed

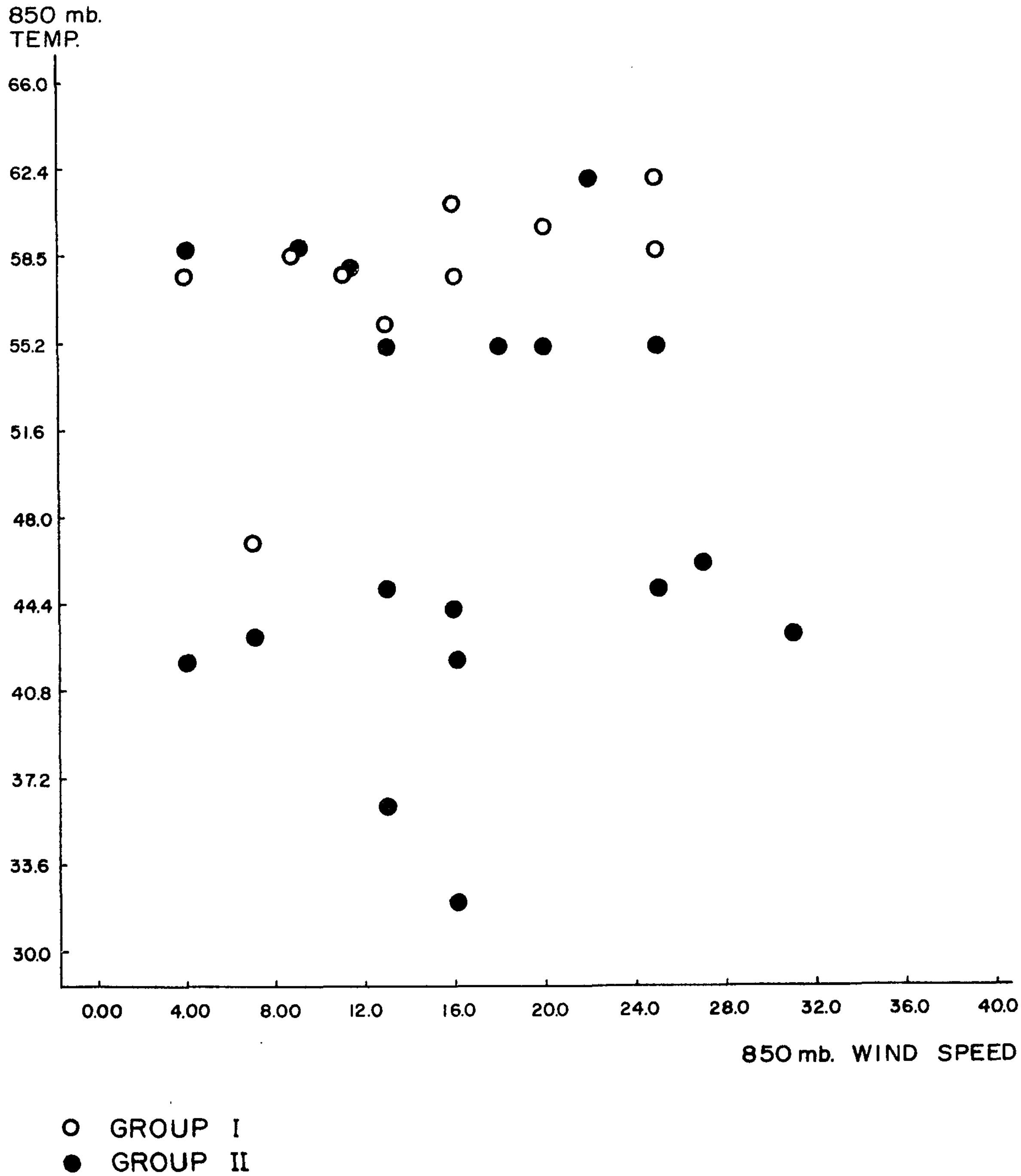


FIGURE XXIII

Group I and II Days Plotted by 500 mb. Temperature and Wind Speed

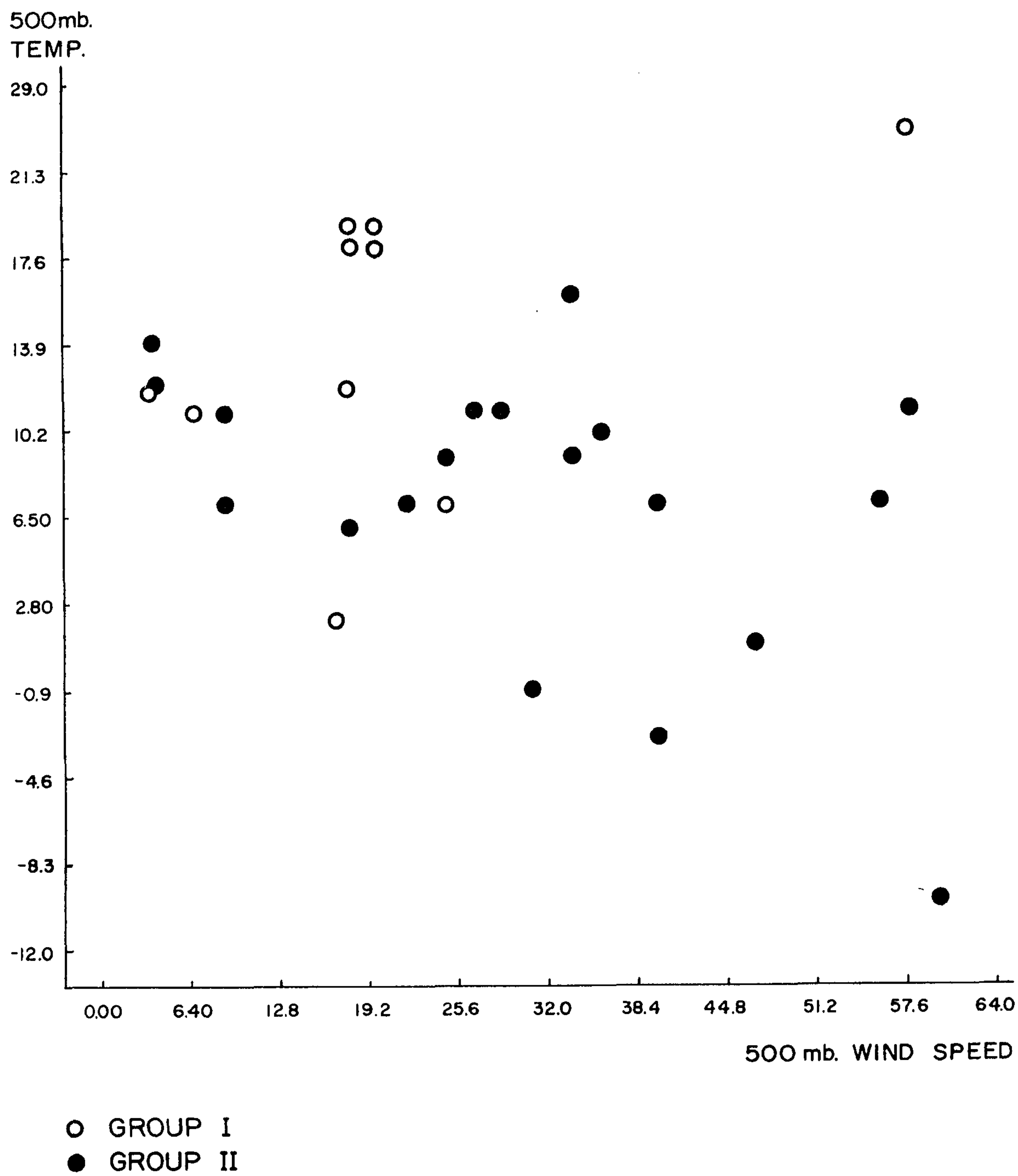


FIGURE XXIV

Group I and II Days Plotted by Surface Dew Point and Land-Water Temperature Contrasts

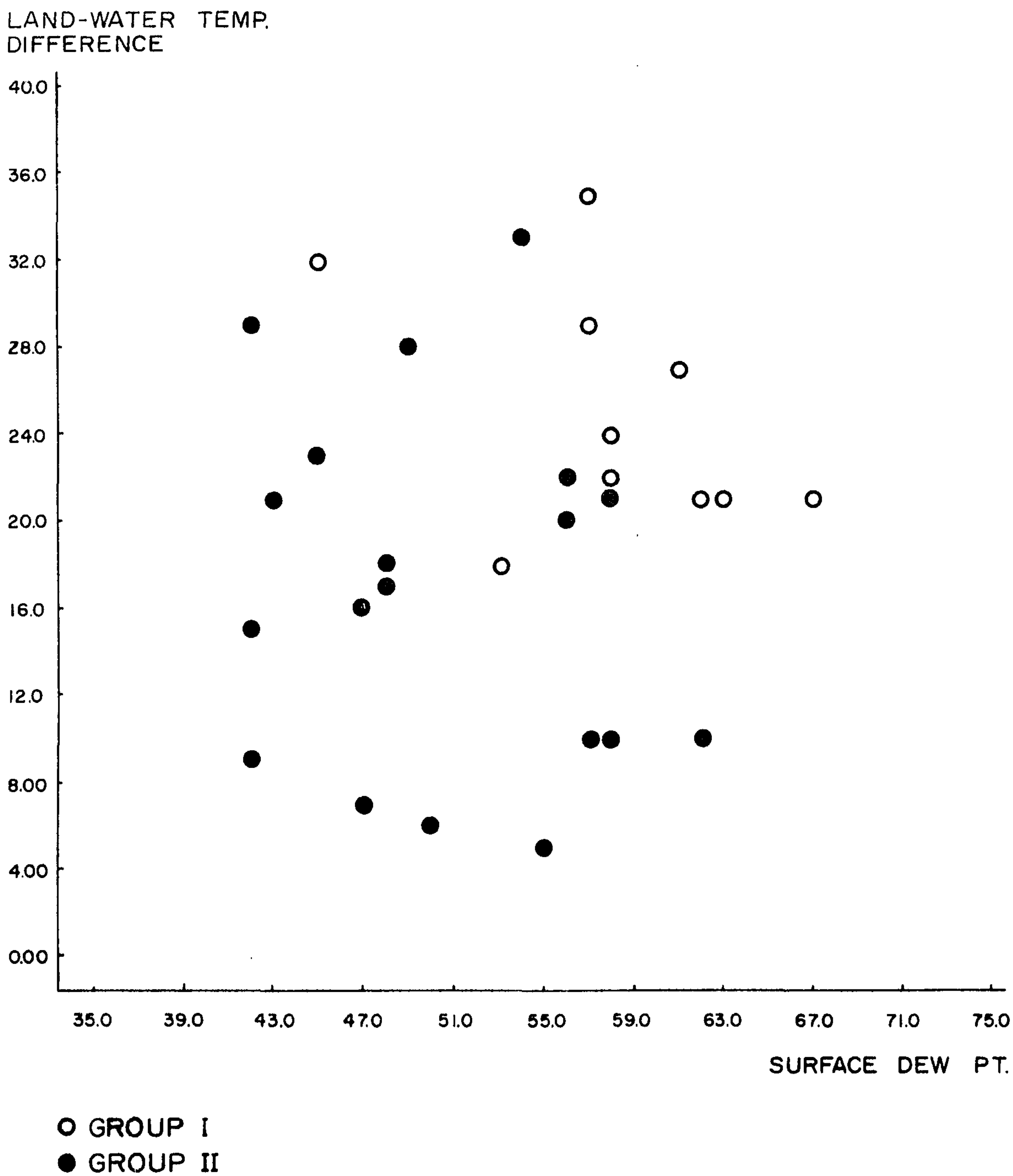
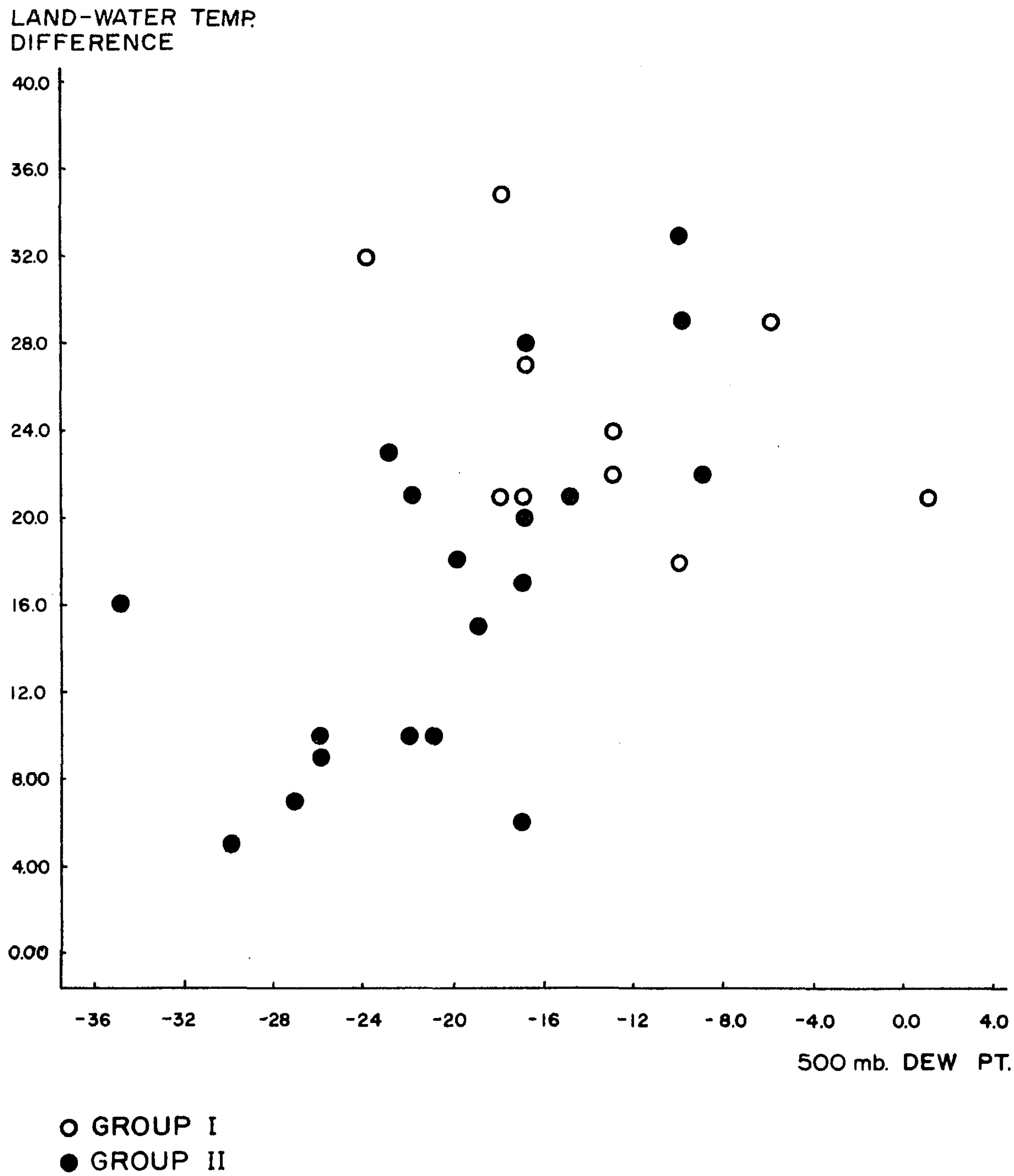


FIGURE XXV

Group I and II Days Plotted by 500mb. Dew Point and Land-Water Temperature Contrasts



temperature differences. The same general pattern was also present at the 500 mb. level as depicted in Figure XXV.

Group I and II days were plotted against the associated land-water temperature contrasts and the 850 mb. wind speed in Figure XXVI. Group I days generally were associated with high land-water temperature contrasts and relatively low 850 mb. wind speeds, whereas Group II days showed an opposite pattern. Figure XXVII, depicting the relationship between Groups I and II and daily maximum interior temperature and 0615 dew point at Sault Ste. Marie, further illustrates these patterns. Group I days were both relatively warm and humid, whereas Group II days were characterized by either lower interior temperatures or lower dew points, or both.

In summary, the three sample groups differed with regard to their various climatological variables. The notable differences between Group I and Groups II and III are as follows:

(1) Group I days at all atmospheric levels were warmer, more humid, and had lower wind speeds.

(2) Group I days had the largest mean maximum land-water temperature difference.

(3) Group I days had the greatest mean decrease in temperature, mean increase in humidity, and maximum humidity within one-half hour after apparent lake breeze passage in the interior of the peninsula.

FIGURE XXVI

Group I and II Days Plotted by 850mb. Wind Speed and Land-Water Temperature Contrasts

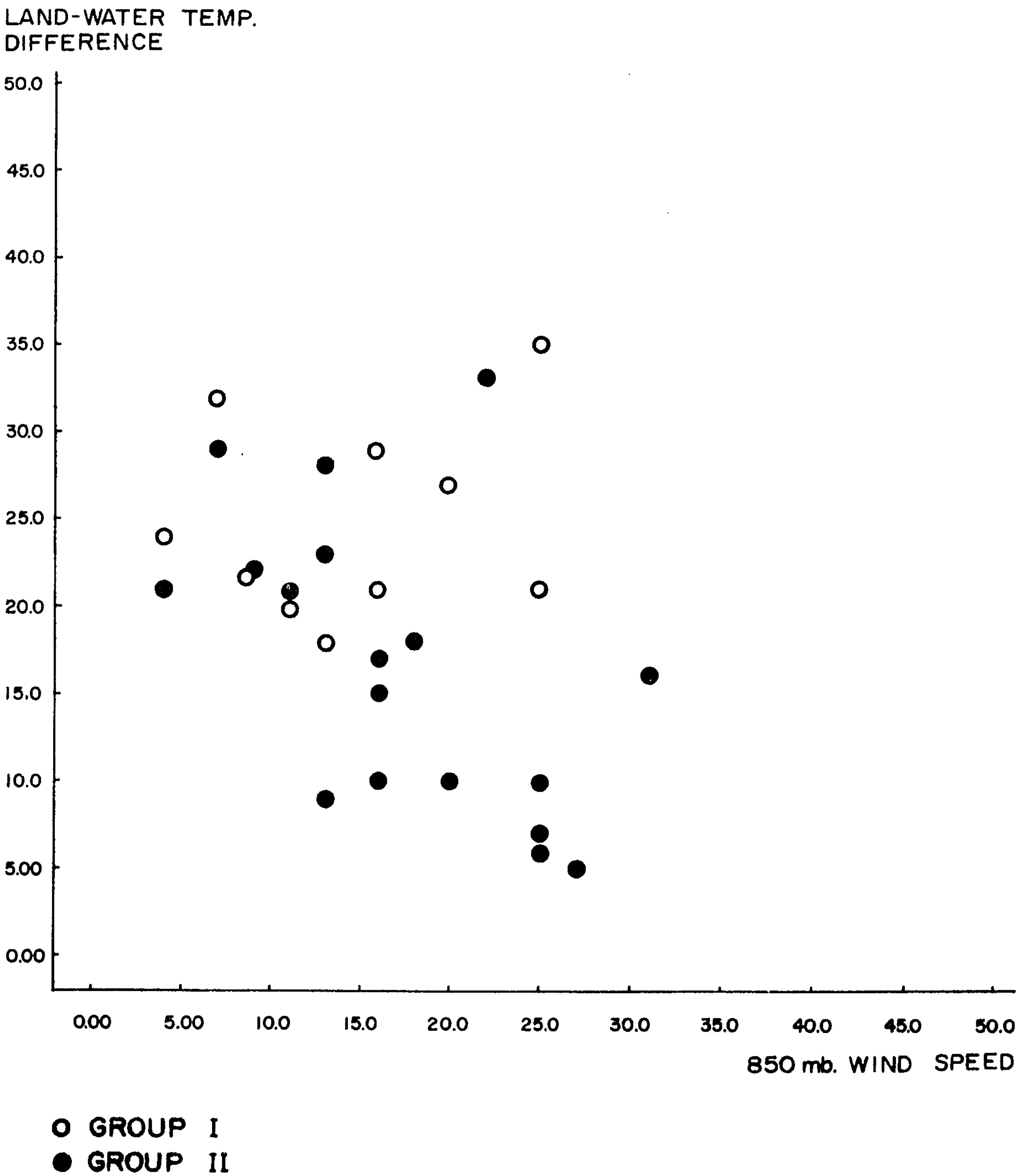
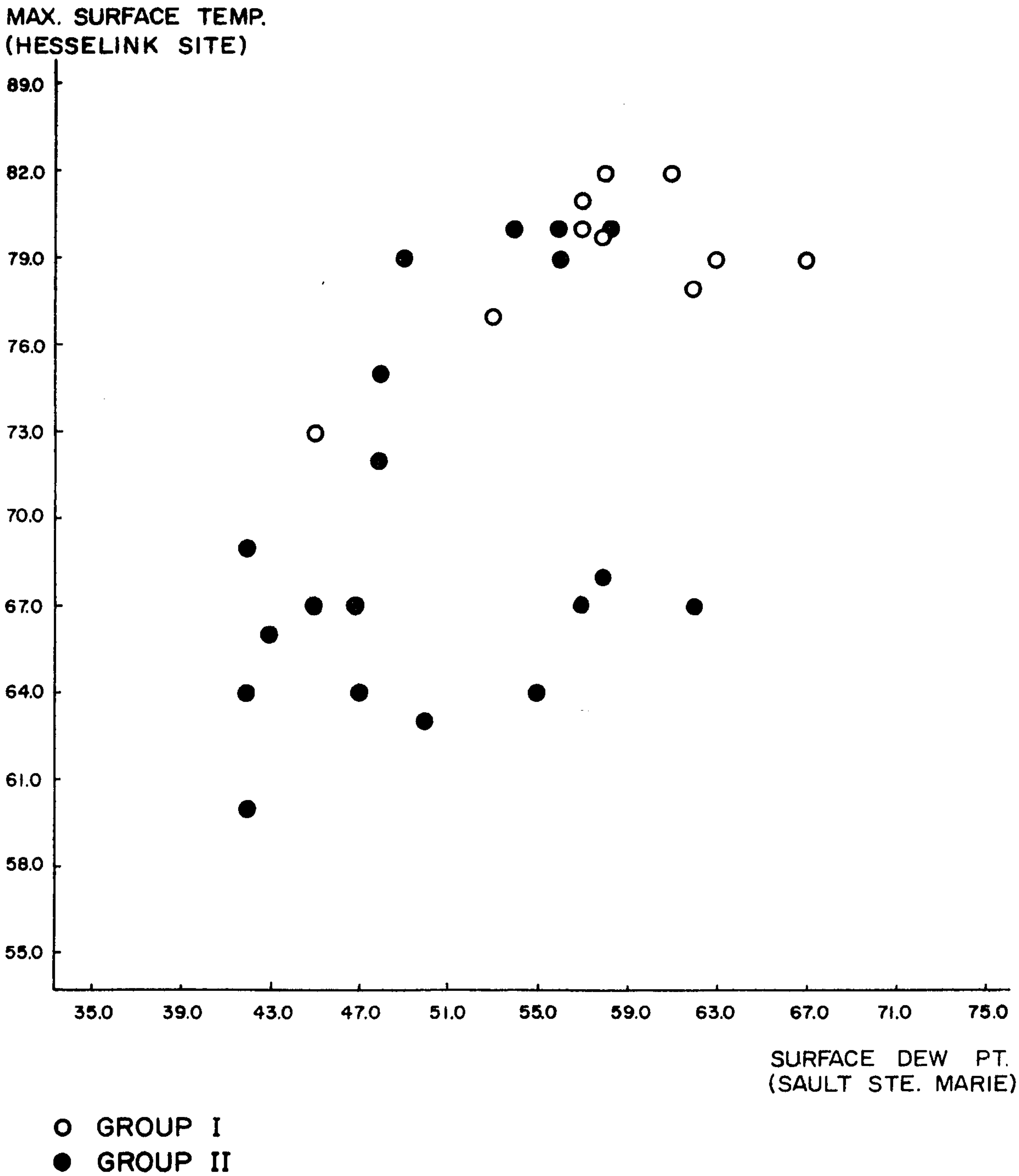


FIGURE XXVII

Group I and II Days Plotted by Maximum Surface Temperature at the Hesselink Site and 0615 Surface Dew Point from Sault Ste. Marie



(4) Group I days appeared to have the greatest amount of interior cloudiness.

(5) Group I days had a prevailing wind flow more southerly than Group II days suggesting that Group I days were associated with more (upward) vertical motion than Group II days.

CHAPTER IV--REFERENCES

1. Byers, H. R., and Rodebush, H. 1948. Causes of thunderstorms of the Florida peninsula. J. Meteor. 5: 275-280.

2. Jenrette, J. P. 1960. An objective application of vorticity principles to precipitation forecasting. Bull. Amer. Meteor. Soc. 41: 317-323.

3. Riehl, H., Norquest, K. S., and Sugg, A. L. 1952. A quantitative method for the prediction of rainfall patterns. J. Meteor. 9: 291-298.

4. Reiter, E. R. 1963. Jet-Stream Meteorology. Chicago: Univ. of Chicago Press.

5. Palmén, E., and Newton, C. W. 1969. Atmospheric Circulation Systems. International Geophysics Series, Vol. 13. New York: Academic Press. p. 325.

CHAPTER V

DISCUSSION

It was originally hypothesized that two lake breeze systems form over eastern Upper Michigan and subsequently move inland, where their convergence would augment convection and lead to interior rainfall under certain conditions. If this series of hypotheses is correct, the following patterns should be evident in the data:

(1) A drop in temperature, rise in relative humidity, and a change in wind direction and speed as the lake breeze passes a given sensor on all lake breeze days.

(2) A surface wind pattern showing onshore flow on both coasts during the afternoon hours but not at other times.

(3) The development of a line of cumulus and/or cumulonimbus clouds along the interior convergence zone, between the lake breeze systems, as depicted by a decrease in solar radiation receipts during the afternoon in the interior of the peninsula.

(4) The appearance of a cloud-free zone along both coasts in the stable air behind the advancing lake breeze fronts as depicted by an increase in solar radiation receipts as the front penetrates inland on a given day; repetition of this sequence in both Group I and II days should lead to higher mean afternoon receipts along the coast.

(5) A narrow precipitation pattern recorded along the raingage network resulting from augmented convection in a narrow convergence zone where two lake breeze systems merge.

<u>Temperature and relative humidity</u>. The results presented in Chapter IV indicated that on Group I and II days an abrupt decrease in temperature and increase in relative humidity were detected on most days of apparent lake breeze passage along the instrumented traverse, confirming the presence of well-developed lake breeze systems. On Group I days the mean temperature decline was 5.41°F and increase of relative humidity 11.87%, whereas on Group II days the mean temperature decline was 2.45°F and increase of relative humidity 7.38% within one-half hour of apparent lake breeze passage. These findings agree with studies by Wallington (1, 2), who found that sea breeze passage was associated with a rather sharp drop in temperature and rise in relative humidity, and thus seem to reflect the presence of lake breeze circulations over the peninsula during both groups of days. However, the use of 31-day recording charts on the hygrothermographs unfortunately reduced the accuracy of the record, and an exact time sequence of apparent lake breeze passage into the interior was not possible to determine.

The inland penetration of the lake breeze front normally is followed by an influx of somewhat cooler air, as noted above. Thus, Brimley State Park, a site normally exposed to onshore-moving lake breeze systems, would be expected to have had a lower mean daytime temperature than the interior stations. In agreement with this expected pattern, the maximum daily temperature was lower along the coast on 75% of the Group I days and 65% of the Group II days. This finding suggests that the lake breezes frequently modified patterns of maximum temperature across the peninsula. The frequent detection of lake breeze effects in the temperature record along the instrumented traverse (see Table IV) provides evidence of their relative resistance to thermal modification during overland movement, in contrast to lake breeze systems near Chicago (3). Thus, the initial supposition that the relatively colder waters of Lake Superior would produce a lake breeze system sufficiently strong to retain its thermal identity in the interior of the peninsula was found to be valid.

Surface wind. Surface wind directions compiled from the various stations in the study area confirmed that for both Groups I and II a convergenze zone existed somewhere in the interior of the peninsula during the afternoon hours when an onshore component was evident in the flow along both the north and south coasts (see Figures XVI through XXI). Further evidence of this convergence was presented from the data collected at the Hesselink site, where abrupt windshifts were frequent on both Groups I and II suggesting the passage of apparent lake breeze fronts (see Table VIII). In general, wind changes were from a westerly flow to a more northerly or southerly flow depending upon which lake breeze system reached the station.

These findings agree with Moroz (4), who found that the inland penetration of a lake breeze was associated with a change of wind direction.

Cloud photography and insolation. The development of cloud patterns over eastern Upper Michigan were recorded along the solar radiation traverse and by cloud photography. The solar radiation record indicated that on both Groups I and II cloud systems appeared to develop just inland from the shore in the late morning hours, and then move inland. For example, 64.22% and 60.00% of possible morning sunshine was received at the north and south coasts, respectively, on Group I days, while the Hesselink site had 61.00%. These patterns imply that morning cloud cover showed little spatial organization and was present along the coasts nearly as frequently as in the interior. During the afternoon, 70.44% and 72.00% of possible sunshine were recorded on the north and south coasts, respectively, while the Hesselink site received 63.22% and the Vanderstar site 57.44%. This pattern was especially evident along the north coast where Brimley State Park received 13.00% and 10.32% more afternoon insolation on Group I and II days, respectively, than did the interior site of minimum receipt. Thus, consistently more sunlight was received along the coasts, particularly the north coast, than in the interior during the afternoon when lake breeze strength should have been greatest. This pattern of solar receipts suggests that lake breeze development may have been stronger along the north coast, as originally inferred by an extension of the findings of Estoque (5).

As the band of cumuli apparently associated with a lake breeze front penetrated into the interior, the nearshore area became cloud-free, as evident from both the insolation record and cloud photography (see Table V). For example, this pattern is especially pronounced for Group I days when Brimley State Park, the Vanderstar site, and the Hesselink site had 64.22%, 61.44%, and 61.00% of possible morning sunshine, respectively, whereas the mean afternoon receipts for the three sites were 70.44%, 57.44%, and 63.22%, respectively. During the early afternoon the nearshore area became nearly cloud-free while cloud cover increased at the interior sites, apparently in association with lake breeze penetration. In general, the width of the cloud-free zone increased through the day as heating progressed, suggesting that the lake breeze systems were extending farther into the interior. For example, on August 9, 1970, cloud cover was absent at the Brimley State Park site, whereas the Vanderstar site recorded some cloud development near 1100 which continued only until 1500. The Hesselink site recorded cloud cover beginning at 1200 that remained overhead for the balance of the afternoon hours. On the south coast, convective cloud development was absent at the Harrison site, whereas inland the Erfourth site recorded cloud development starting at 1200 which continued until 1500. This pattern suggests that cumuli developed just inland on both the north and south coasts in association with lake breeze fronts and moved inland, forming a narrow cloud band in the vicinity of the Hesselink site that may have marked the zone of convergence between the two lake breeze systems.

The development of cumuli along the lake breeze fronts and their subsequent movement into the interior were especially evident from the cloud photography (see Figures X and XI) in which a line of cumuli may be seen which developed near the coast and subsequently moved inland, apparently in association with the lake breeze front.

As early as noon on some days of both Groups I and II the two lake breeze systems merged in the interior of the peninsula, forming a single band of cumuli. This band is particularly evident from the photographic record, which in several instances shows cloud bands oriented generally parallel to the long axis of the peninsula (see Figures X, XI, XII, and XIII). Tiros satellite photographs also provide evidence that isolated cloud bands are sometimes oriented in this manner (see Figures XIV and XV).

The cloud patterns described above appear to confirm that lake breeze systems moved inland from Lake

Superior and Lakes Michigan and Huron while convection along the mesoscale lake breeze fronts produced lines of cumulus and/or cumulonimbus clouds on both Group I and II days. These findings agree with studies by Wallington (1), Lyons (3), Moroz (4), and Wexler (6).

Precipitation. On Group I days precipitation occurred from the narrow bands of clouds that developed when two lake breeze systems appeared to merge in the interior. Precipitation was evident from both the rain-gage network (see Table III) and the photographic record which shows several views of rainfall occurring from the narrow cloud bands (see Figures XI and XII). This pattern is similar to that described by Leopold (7), who investigated the interaction of sea breezes and trade winds in Hawaii and found that a convergence zone often developed, subsequently leading to narrow bands of precipitation along the zone.

It appeared that the rain showers associated with Group I days were a result of the development and subsequent interior convergence of lake breezes. The following patterns suggest that lake breezes, rather than random convection or topographic influence, controlled rain showers associated with Group I days:

(1) The mean width of the ten rain swaths was 4.80 miles. The narrowness of the swaths and the fact that macroscale fronts were not in the study area imply that some mesoscale mechanism was controlling

the precipitation occurrences, and their continuous east-west extent suggests that they may have been closely related to the convergence of lake breeze systems from both coasts. It seems highly improbable that random convection alone could have accounted for the degree of spatial organization displayed by the rain shower systems on Group I days.

(2) The site of maximum rainfall along the raingage network was generally situated near the center of the swaths as, for example, on July 30, 1970 (see Table III), and a cloud-free zone existed north and south of the rain swaths (see Table V). Because convection between the merging lake breezes probably is strongest near the center of the convergence zone, the location of the heaviest rainfall appears to be further evidence of lake breeze control. The cloud-free zone on either side would also be expected because cool lake air and associated subsidence would suppress cloud development. Lyons (3), studying lake breezes along the Lake Michigan shoreline, also noted that subsidence associated with lake breeze subsidence resulted in a cloud-free zone behind the mesoscale front.

(3) The swaths of precipitation were generally oriented in an east-west direction parallel to the coasts as verified by automobile reconnaissance. When two lake breeze systems penetrate inland and subsequently merge over an east-west oriented peninsula, the resulting convergence zone and precipitation pattern would be expected to orient itself in the same general direction. It was also found that the cloud band was continuous and not broken into random cloud groups, while the rain showers usually moved from west to east along the zone. This pattern also suggests that convection along a rather long east-west oriented convergence zone, rather than random convection, controlled the narrow bands of showers.

(4) The location of each rain swath on Group I days generally developed farther north during the summer. The upper-level analysis revealed that 65% of the variation of rain swath location on Group I days was statistically explained by wind direction at the 300 mb. level. This finding implies that wind direction controlled rain swath

> location and that the two north facing scarps parallel to both the north and south coasts were of little importance in determining rain location (see Figure III).

As noted previously, much of the shift in lake breeze convergence zone location may be attributed to wind direction over the peninsula. During late July and early August all Group I days occurred when 300 mb. wind flow was southwesterly, a fact which may have accounted for the northward shift of rain swath location because vertical cloud development may have been great enough to reach that level. Features at the 300 mb. level appeared to be most important for vertical (upward) motion and subsidence in the Upper Air Index (see Table IX), as well.

Another factor that may have partially explained the northward shift of rain swaths during the summer was the decrease in the land-water temperature contrast as the summer progressed, which was accompanied by a gradual weakening of lake breeze systems. During the early part of the study period land-water temperature contrasts of over 30°F were common, whereas during late July and August contrasts of 20°F and less were characteristic. In addition, during late June and early July ridges prevailed west of Michigan on 67% of the interior rain days, a fact which suggests that upper-level support was not necessary to produce interior precipitation when the land-water temperature contrast was high. However, during late July and August, when land-water temperature contrasts were less, all of the interior rain days were associated with troughs upstream from the study area. Lake breeze convergence alone appears sufficient to produce interior precipitation only when the land-water temperature contrasts are exceptionally high; during times of weaker lake breeze development upper-level support may be more critical. The presence of troughs upstream on all interior rain days during late July and early August probably explains the more southerly mean wind flow of the entire Group I sample when compared with Groups II and III, and may have accounted for the progressively more northerly location of the rain swaths in the peninsula as the summer progressed.

The southwesterly flow at upper levels on Group I days during late July and August provided additional vertical (upward) motion because of vorticity advection and also transported moist air into the study area, resulting in higher dew points than were observed in June. The presence of moist air in the study area during occurrences of interior rain is in agreement with findings of Curtis and Panofsky (8), who noted that convective shower activity depends upon the existence of both vertical motion and high dew points. Thus, convergence of lake breezes, upper-level support, and high dew points appear to provide ideal conditions for interior precipitation.

The increase of interior rain occurrences in late July and early August also agrees with findings from the original 12-year study in which August generally had the largest number of interior rainfall days. Furthermore, as a result of southwesterly flow on Group I days during late July and early August an increase of convergence zones and cloud development was observed over the northern portion of the peninsula that probably accounted for the low solar radiation receipts at the Vanderstar site during the afternoon hours.

The location of convergence zones on Group II days also changed through the study period, but in this case flow at the 850 mb. level seems to have been the important control. The author noted that vertical cloud development was less on Group II days and estimated that cloud tops approached the mean level of 850 mb. which was approximately 5000 feet. With a northwesterly flow at the 850 mb. level, a condition that generally prevailed on Group II days, the convergence zones occurred toward the southern portion of the peninsula, a fact which probably accounted for the low solar radiation receipts at the Harrison site during the afternoon hours. On days of southerly flow the convergence zones occurred toward the northern portion of the peninsula, whereas on westerly flow days convergence zones formed generally in the central portion of the peninsula (see Table VII).

The time of lake breeze passage at the Hesselink site in the interior also appears to be related to upper-level wind flow. On Group I days, characterized by a greater mean southerly wind component than Group II days, the system from Lakes Michigan and Huron was first to arrive at the Hesselink site and the convergence zone usually occurred over the northern portion of the peninsula. On Group II days, which had a mean northwesterly component at upper levels, the Lake Superior lake breeze system was first to reach the Hesselink site and the convergence zone usually occurred over the southern portion of the peninsula. In some cases, however, one lake breeze system would displace another at the Hesselink site. For example, in several occurrences of southwesterly flow the system from Lakes Michigan and Huron penetrated to the Hesselink site before the Lake Superior system, only to be displaced later in the day. This finding suggests that even though supported by upper-level flow the system from Lakes Michigan and Huron was displaced by a relatively stronger Lake Superior system that probably developed from the colder surface waters of that lake.

Some controls can be envisioned which might govern the occurrence or non-occurrence of precipitation on a given convergence day. As previously noted, high temperatures and low wind speeds were characteristic of Group I days. Wind speed and temperature were especially useful in separating Group I days from Group II days when the 850 mb. level was considered (see Figure XXII), a finding which suggests that initial lake breeze development and its subsequent strength may be controlled largely by temperature and wind speed in the lower troposphere. Data from the instrumented traverse indicated that the drop in temperature and rise in relative humidity within one-half hour of lake breeze passage were of greater magnitude on Group I days, suggesting relatively strong lake breeze systems.

The direction of upper-level wind may also help determine whether lake breeze convergence leads to interior precipitation. At all atmospheric levels considered the mean wind flow for Group I days was more southerly than that of Group II days, as troughs prevailed upstream from Michigan during the Group I sample.

The Upper Air Index also indicated that Group I days may have been characterized by more vertical (upward) motion than Group II days. This vertical motion coupled with the high land-water temperature difference and the fact that mean relative humidity was highest on Group I days probably accounted for the increased cloud development on Group I days over that of Group II (see Tables IV, V, and IX). The author also observed that vertical cloud development was usually much greater on Group I days. The general differences between Group I and II days are as follows:

(1) The mean maximum temperature was higher at all levels on Group I days.

(2) The mean maximum relative humidity was higher at all levels on Group I days.

(3) The mean wind speed was lower at all levels on Group I days.

(4) The drop in temperature and rise in relative humidity associated with apparent lake breeze passage along the instrumented traverse was greater on Group I days, suggesting strong lake breeze development.

(5) Greater vertical motion occurred on Group I days as revealed by the Upper Air Index and the direction of mean wind flow.

The mean 500 mb. wind flow over the study area for the summer months is 286°, which implies that ridges are normally more frequent than troughs upstream from Michigan. After it became evident that interior rainfall during the summer of 1970 was associated with an anomalous southerly component to the mid-tropospheric flow, 500 mb. wind directions were calculated for the 448 days of interior rainfall occurrences in the original 12-year study to determine whether the same pattern would prevail through a longer sample period. Wind flow for 68% of this sample was less than 270°, suggesting that troughs were indeed relatively frequent upstream from Michigan. Therefore, it appears that more than two-thirds of the interior rain days from the original 12-year study were associated with some sort of upper-level support, a conclusion generally in support of the results of the present research.

Maximum temperatures from the original 12-year sample of interior rain days then were compared with the mean monthly maximum to determine whether the interior rain days were warmer than the normal, a pattern revealed by the 1970 study. The results from this analysis revealed no patterns and were inconclusive. These data must be examined with caution, however, because the precipitation data were obtained from a limited number of stations within the study area, and without field verification. Thus, the sample may be contaminated by days that were not "interior rain days" in the sense used in the present study.

Group III days were characterized by an absence of lake breeze convergence. It is interesting to note that the mean maximum temperature and relative humidity were higher at the surface and 850 mb. level on Group III days than on Group II days, and the land-water temperature difference on Group III days was several degrees higher than Group II days. It appears that Group III days should have had visible lake breeze convergence. However, the wind speeds at the 850 mb. and 500 mb. levels on Group III days were greater than both Groups I and II. For example, the mean wind speed at the 850 mb. level on Group III days was 25 mph, whereas on Groups I and II it was 15 and 17 mph, respectively. This finding suggests that wind speed was the factor, in this case, that prevented interior lake breeze convergence. Group III days often occurred just after macroscale fronts passed through the area when surface pressure gradients and thus wind speeds were still high.

The increase in the number of interior rainfall occurrences from the central portion of the Upper Peninsula to the eastern portion which was noted in the original 12-year study occurred presumably because the eastern portion is narrower. During the 1970 field survey and author observed that Whitefish Bay may have played an important role in permitting lake breeze convergence to occur over the eastern portion of the peninsula. On both Group I and II days lake breezes were observed to advance inland both west and south of Whitefish Bay (see Figure I). Southwest of Whitefish Bay vertical motions at the lake breeze front appeared to be especially strong, as inferred from increased cloud development at that point. This pattern agrees qualitatively with sea breeze studies by McPherson (9, 10), who also found that maximum vertical motions in a bay situation would be at the corners of the bay, in this case the southwest and southeast. The area of apparent maximum development southwest of Whitefish Bay was several miles west of the instrumented traverse and appeared to be the most westerly point of lake breeze convergence in eastern Upper Michigan (Figure XXVIII). This point of convergence between the system from Lakes Michigan and

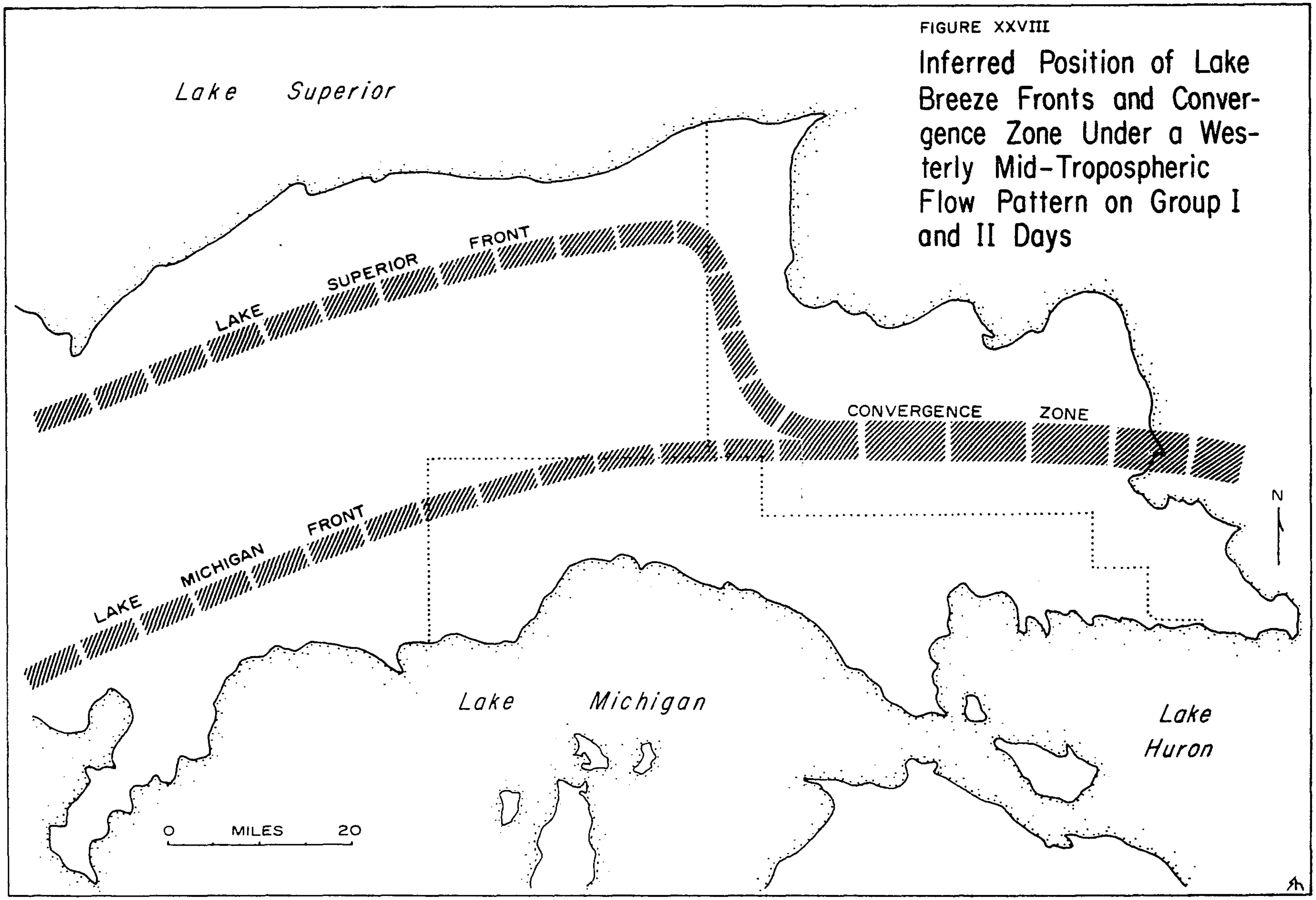


FIGURE XXVIII

Inferred Position of Lake Breeze Fronts and Convergence Zone Under a Westerly Mid-Tropospheric Flow Pattern on Group I and II Days

Huron and the Lake Superior system often developed daily in the same general area southwest of Whitefish Bay where cloud development appeared to have been greatest. The narrow convergence zone, suggested by a band of cumuli, extended eastward from this point (see Figure XXVIII). This pattern implies that convergence of lake breezes in the eastern portion of the peninsula occurs because the narrowness of the peninsula at this point may permit the lake breeze systems to penetrate sufficiently far inland. The apparent increase of vertical motion southwest of Whitefish Bay as depicted by increased cloud development and its role in increasing convection eastward along the convergence zone are difficult to assess in the present study.

Lake breeze development and convergence over eastern Upper Michigan and the occurrence of subsequent precipitation seem to depend upon a combination of conditions, each of which may vary in relative strength. For example, temperature differences between the land and water of 30° and 35°F were common in early summer; in these cases it appeared that upper-level support was not necessary for precipitation to occur if surface atmospheric moisture was not deficient. Thus, if one of the preconditions was well-developed, in this case an exceptionally strong thermal contrast, a lake breeze developed that was of such strength that precipitation resulted. From this study the general conditions responsible for lake breeze development and subsequent precipitation in eastern Upper Michigan appear to be:

(1) A land-water temperature differential sufficiently large to develop lake breeze flow. In this study the minimum temperature difference between land and water on Group I days was 18°F.

(2) A relatively low wind speed at all levels to permit lake breeze penetration over a peninsula. The maximum wind speed observed at the 850 mb. level on a Group I day was 24 mph at 0615.

(3) Southwesterly flow aloft so that large-scale upper-level divergence provides additional vertical motion along the sea (lake) breeze front or convergence zone.

(4) A relatively high dew point at all levels to provide moisture for cloud development and subsequent precipitation. The minimum surface dew point on a Group I day at 0615 was 45°F.

The original hypothesis of this study was that lake breezes develop on both the north and south coasts of eastern Upper Michigan and penetrate inland, where they often merge and subsequently produce precipitation. It was also suggested that large-scale low-level convergence produced by upper-level mid-tropospheric troughs situated west of Michigan may further encourage convective precipitation along the lake breeze convergence zones. The data gathered and analyzed in this study support the initial hypothesis.

Significance of interior precipitation. The occurrence of lake-breeze-associated rainfall appears to have played a significant role in the precipitation totals for the three month study period as depicted in Table XI. At several sites in the northern portion of the peninsula over 20% of the total rainfall was associated with lake breeze convergence. Such rainfall amounts, if they normally recur each summer, could conceivably affect agricultural activities in the region. For example, the rainfall amounts associated with lake breezes during 1970 could have increased substantially the yields of hay and corn in the northern portion of the peninsula where such rains were most frequent. Other types of land use, such as tourism or forestry, may also be affected by patterns of higher rainfall frequencies in the interior.

From data gathered during the study period it appears that the number of Group I days in 1970 may have been below the average summer frequency. The summer of 1970 was characterized chiefly by mid-tropospheric ridges west of Michigan, and a mean northwesterly flow prevailed over the region (11, 12, 13). This pattern suggests that the number of interior rain days may have been reduced because upper-level support was absent for most of the summer, although the more frequent occurrence of troughs west of Michigan in late July and early August was accompanied by a temporary increase of lake-breeze-associated precipitation. Therefore, it appears that yearly fluctuations of lake-breeze-associated precipitation occurrences

TABLE XI

Summer Precipitation Totals and the Percent Contribution of Lake-Breeze-Related Rainfall Along the Raingage Network, 1970

	Rain-gage	Summer Total	Lake Breeze Related Total	Percent Summer Total
Brimley	1.	7.08	.33	5%
	2.	7.08	.64	9%
	3.	7.54	1.27	17%
	4.	7.38	1.52	21%
	5.	7.84	1.64	21%
Vanderstar	6.	7.55	.54	7%
	7.	7.56	1.05	14%
	8.	7.10	.62	9%
	9.	6.14	.44	7%
Hesselink	10.	6.39	.23	4%
	11.	6.63	.11	2%
	12.	7.13	.01	--
	13.	7.06	--	--
	14.	6.10	--	--
Erfourth	15.	7.11	--	--
	16.	7.10	.02	--
	17.	6.42	.03	--
	18.	7.06	.12	2%
	19.	7.61	.06	1%
	20.	7.59	.03	--
Harrison	21.	7.18	--	--
	22.	7.15	--	--

may result from variations of flow at mid-tropospheric levels.

The occurrence of lake-breeze-related precipitation would be especially important during periods when mid-tropospheric ridges prevail upstream from Michigan, such as the summer of 1970. With a prevailing northwesterly flow over the study area negative relative vorticity advection would result in upper-level convergence, consequent subsidence, and surface stability, and general precipitation would be subnormal. Temporary shifts to a southwesterly flow with migrating short-wave troughs would import low-level moisture and provide the necessary upper-level support for convergence-associated rainfall if other conditions were adequate, although more general rains in association with the passing troughs may not occur.

During summer seasons when ridges prevail upstream from the study area and general drought develops, lake-breeze-associated rainfall might be expected to supplement precipitation, especially during June and early July when the land-water temperature differential is so large that upper-level support may not be necessary. During late July and August, on the other hand, weaker lake breeze systems resulting from the relatively lower land-water temperature contrasts appear to be insufficient in themselves to produce interior rain. Thus, only early-summer droughts may be alleviated by lake-breeze-related precipitation.

CHAPTER V--REFERENCES

1. Wallington, C. E. 1959. The structure of the sea breeze front as revealed by gliding flights. Weather. 14: 263-270.

2. ______. 1965. Gliding through a sea breeze front. Weather. 20: 140-144.

3. Lyons, W. A. 1966. Some effects of Lake Michigan upon squall lines and summertime convection. Great Lakes Res. Div. Pub. 15: 259-273.

4. Moroz, W. J. 1967. A lake breeze on the eastern shore of Lake Michigan: observations and model. J. Atmos. Sci. 24: 337-355.

5. Estoque, M. A. 1962. The sea breeze as a function of the prevailing synoptic situation. J. Meteor. 19: 244-250.

6. Wexler, R. 1946. Theory and observations of land and sea breezes. Bull. Amer. Meteor. Soc. 27: 272-287.

7. Leopold, L. B. 1949. The interaction of trade wind and sea breeze, Hawaii. J. Meteor. 6: 312-320.

8. Curtis, R. C., and Panofsky, H. A. 1958. The relation between large-scale vertical motion and weather in summer. Bull. Amer. Meteor. Soc. 39: 521-531.

9. McPherson, R. D. 1970. A numerical study of the effect of a coastal irregularity on the sea breeze. J. Appl. Meteor. 9: 767-777.

10. ______. 1968. A Three-Dimension Numerical Study of the Texas Coast Sea Breeze. Atmospheric Science Group. Rept. No. 15. Austin: Univ. of Texas.

11. Wagner, A. J. 1970. The weather and circulation of June 1970. Mon. Wea. Rev. 98: 717-722.

12. Green, R. A. 1970. The weather and circulation of July 1970. Mon. Wea. Rev. 98: 789-794.

13. Stark, L. P. 1970. The weather and circulation of August 1970. Mon. Wea. Rev. 98: 869-874.

CHAPTER VI

SUMMARY AND CONCLUSIONS

I

The present study was undertaken to evaluate the hypothesis that lake breezes develop on both the north and south coasts of eastern Upper Michigan and penetrate inland, where their convergence leads to augmented convection and subsequent precipitation under favorable conditions. From a survey of surface conditions conducted in late June, July, and August, 1970, to provide evidence for lake breeze convergence and interior precipitation in eastern Upper Michigan, three groups of days were recognized: (1) days of interior lake breeze convergence and associated rainfall (Group I days); (2) days of interior lake breeze convergence with no rainfall (Group II days); and (3) days with no apparent lake breeze convergence over the interior (Group III days). The following climatological patterns emerged:

Precipitation. A north-south traverse of 22 raingages was positioned across the peninsula and ten days of interior precipitation were recorded. The location of the rainfall swaths shifted northward as the summer progressed and 65% of the variation of rain swath location was statistically explained by wind direction at the 300 mb. level. The gage of maximum rainfall for each occurrence was generally near the center of the swath. Near the northern portion of the peninsula lake-breeze-associated precipitation accounted for 21% of the total rainfall during the study period.

Cloud photography. Cloud photography provided a record of lake-breeze-associated cumuli development, convergence of two lake breeze systems as depicted by narrow cloud streets, and interior precipitation resulting from augmented convection along the convergence zone.

Temperature and relative humidity. A series of three hygrothermographs and one mechanical weather station were positioned from the central portion of the peninsula to the north coast. The resulting data indicated that the highest mean maximum temperature and relative humidity among the three groups of days occurred on Group I days. The interior rainfall days also displayed the greatest mean decrease of temperature and increase of relative humidity within one-half hour of lake breeze passage along the instrumented traverse, indicating somewhat stronger lake breeze development. The highest land-water temperature differences occurred on Group I days, whereas Group III days had a slightly higher temperature difference than did Group II days.

Insolation. A series of five solar radiation recorders were positioned in a north-south traverse across the peninsula. Significant interior cloud development occurred on both Groups I and II, apparently in association with lake breeze fronts moving into the interior of the peninsula. A cloud-free zone developed behind the advancing lake breeze fronts which widened as the fronts moved inland. The location of the single cloud streets which developed when two lake breeze systems converged over the peninsula was modified appreciably by variations of wind direction in the middle and upper troposphere.

Surface winds. Surface wind data were collected from five stations including Grand Marais, Whitefish Point, Sault Ste. Marie, Lansing Shoal, and the Hesselink site in the interior of the peninsula. On both Groups I and II a convergence zone over the eastern portion of the Upper Peninsula was verified by onshore flow on both the north and south coasts during the afternoon hours. Lake breezes often reached the interior, as depicted by abrupt shifts in wind direction during the afternoon hours at the Hesselink site.

II

A survey of upper-level conditions was conducted in order to assess the assumption that conditions at mid-tropospheric levels would provide additional (upward) vertical motion in the study area and strengthen convection along the convergence zones. The following patterns appeared to be important in this respect:

Upper-level conditions. The data indicated that troughs prevailed west of Michigan on 70% of the Group I sample, suggesting increased vertical motion and surface instability, whereas ridges prevailed upstream on 78% of the Group II sample, suggesting subsidence and surface stability. As a consequence of these mean tropospheric wave positions, Group I days were associated with a more southerly wind component than Groups II and III; they also were characterized by lower mean wind speeds at all levels than Groups II and III. Rawinsonde data collected by the Sault Ste. Marie Weather Bureau also indicated that Group I days were warmer and more humid at all levels than Groups II and III.

III

The data gathered and analyzed during the three month study period support the initial hypothesis. It was also found that upper-level support was necessary for interior precipitation to occur, especially in late July and August when the land-water temperature difference and associated lake breeze systems were weaker.

IV

As stated initially, it was hoped that the brevity of the study period and the lack of instrumentation in part could be overcome by the careful placement of existing instruments. The findings which resulted from this study suggest that the available instrumentation was adequate. It was also apparent to the author, however, that additional instrumentation would have been desirable for more complete evaluation of the hypothesis. Further studies might incorporate the following modifications:

(1) The use of one mechanical weather station every mile to record surface wind changes associated with lake breeze penetration into the interior of the peninsula.

(2) The use of recording raingages to pinpoint the time of rain occurrence as well as to obviate the necessity of having to inspect the entire raingage network daily.

(3) The use of additional hygrothermographs with seven day recording charts to provide increased accuracy and a time-sequence of lake breeze penetration.

(4) The use of additional pyrheliographs to allow for more accurate identification of cloud streets associated with lake breeze convergence.

LIST OF REFERENCES

LIST OF REFERENCES

Angell, J. K., and Pack, D. H. 1965. A study of the sea breeze at Atlantic City, N. J. using tetroons as lagrangian tracers. Mon. Wea. Rev. 93: 475-493.

Atlas, D. 1960. Radar detection of the sea breeze. J. Meteor. 17: 244-258.

Baralt, G. L., and Brown, R. A. 1965. The Land and Sea Breeze: An Annotated Bibliography. Satellite and Mesometeorology Research Project. Chicago: Univ. of Chicago Press.

Bellaire, F. R. 1965. The modification of warm air moving over cold water. Great Lakes Res. Div. Pub. 13: 249-256.

Biggs, W. G., and Graves, M. E. 1962. A lake breeze index. J. Appl. Meteor. 1: 474-480.

Blust, F., and DeCooke, B. G. 1960. Comparison of precipitation on islands of Lake Michigan with precipitation on the perimeter of the lake. J. Geophysical Res. 65: 1565-1572.

Boyd, J. G. 1965. Observations of two intersecting radar fine lines. Mon. Wea. Rev. 93: 188.

Bungaard, R. C. 1956. Estimating vorticity advection. Bull. Amer. Meteor. Soc. 37: 465-472.

Butson, K. 1959. Climates of the States: Florida. Washington, D. C.: U. S. Govt. Printing Office.

Byers, H. R. 1959. General Meteorology. New York: McGraw-Hill.

Byers, H. R., and Braham, R. R. 1949. The Thunderstorm. Washington, D. C.: U. S. Govt. Printing Office.

Byers, H. R., and Rodebush, H. 1948. Causes of thunderstorms of the Florida peninsula. J. Meteor. 5: 275-280.

Changnon, S. A., Jr. 1961. Precipitation contrasts between Chicago urban area and an offshore station in southern Lake Michigan. Bull. Amer. Meteor. Soc. 42: 1-10.

_______. 1966. Effect of Lake Michigan on severe weather. Great Lakes Res. Div. Pub. 15: 220-234.

_______. 1968. Precipitation from thunderstorms and snowfall around southern Lake Michigan. Proc. 11th Conf. Great Lakes Res.: 285-297.

Craig, R. A., Katz, I., and Harvey, P. J. 1945. Sea breeze cross sections from psychometric measurements. Bull. Amer. Meteor. Soc. 26: 405-410.

Curtis, R. C., and Panofsky, H. A. 1958. The relation between large-scale vertical motion and weather in summer. Bull. Amer. Meteor. Soc. 39: 521-531.

Defant, F. 1951. Local winds. In Compendium of Meteorology. Boston: Amer. Meteor. Soc. 655-672.

Dixit, C. M., and Nicholson, J. R. 1964. The sea breeze at and near Bombay. Indian J. Meteor. and Geophy. 15: 603-608.

Eddy, G. A. 1966. The Texas coast sea breeze: a pilot study. Weather. 21: 162-170.

Edinger, J. G., and Helvey, R. A. 1961. San Fernando convergence zone. Bull. Amer. Meteor. Soc. 42: 626-635.

Eichmeier, A. H. 1964. Climate of Michigan. In Readings in the Geography of Michigan. C. M. Davis (ed.). Ann Arbor: Ann Arbor Publishers. 41-49.

Ellicott, A. 1799. Miscellaneous observations relative to western parts of Pennsylvania, particularly those in the neighborhood of Lake Erie. Amer. Philos. Soc. Trans. 4: 224-229.

Elton, W. M. 1970. Forest and Lake Breeze Patterns and the La Porte, Indiana, Rainfall Anomaly. Ph.D. Dissertation, Michigan State Univ., East Lansing.

Eshleman, C. H. 1922. Do the Great Lakes diminish rainfall in the crop growing season? Mon. Wea. Rev. 49: 500-502.

Estoque, M. A. 1961. A theoretical investigation of the sea breeze. Quart. J. Roy. Meteor. Soc. 87: 136-146.

_______. 1962. The sea breeze as a function of the prevailing synoptic situation. J. Meteor. 19: 244-250.

Fenneman, N. M. 1938. Physiography of Eastern United States. New York: McGraw-Hill.

Fisher, E. L. 1960. An observational study of the sea breeze. J. Meteor. 17: 645-660.

_______. 1961. A theoretical study of the sea breeze. J. Meteor. 18: 216-233.

Frank, N. L., Moore, P. L., and Fisher, G. E. 1967. Summer shower distribution over the Florida peninsula as deduced from digitized radar data. J. Appl. Meteor. 6: 309-316.

Frenzel, C. W. 1962. Diurnal wind variations in central California. J. Appl. Meteor. 1: 405-412.

Frizzola, J. A., and Fisher, E. L. 1963. A series of sea breeze observations in the New York City area. J. Appl. Meteor. 2: 722-739.

Fujita, T., Mendez, R., and Gargard, S. J. M. 1963. Cloud distribution over the Great Lakes Region as observed by Tiros meteorological satellite (Abst.). Bull. Amer. Meteor. Soc. 44: 704.

Gentry, R. C. 1950. Forecasting local showers in Florida during the summer. Mon. Wea. Rev. 78: 41-49.

Gentry, R. C., and Moore, P. L. 1954. Relation of local and general wind interaction near the sea coast to time and location of air-mass showers. J. Meteor. 11: 507-511.

Golden, J. H. 1971. Waterspouts and tornadoes over south Florida. Mon. Wea. Rev. 99: 146-154.

Green, R. A. 1970. The weather and circulation of July 1970. Mon. Wea. Rev. 98: 789-794.

Hall, C. D. 1954. Forecasting the lake breeze and its effects on visibility at Chicago Midway Airport. Bull. Amer. Meteor. Soc. 35: 105-111.

Harman, J. R. 1970. Forest types and climatic modification along the southeast shoreline of Lake Michigan. Annals Assoc. Amer. Geog. 60: 456-465.

Hass, W. A., and others. 1967. Tetroon flights over New York City. Quart. J. Roy. Meteor. Soc. 93: 483-493.

Haurwitz, B. 1947. Comments on the sea breeze circulation. J. Meteor. 4: 1-8.

Hsu, S. A. 1967. Mesoscale Surface Temperature Characteristics of the Texas Coast Sea Breeze. Atmospheric Science Group. Rept. No. 6. Austin: Univ. of Texas.

_______. 1969. Land and sea breeze fronts near 50 cm. on the Gulf Coast. Bull. Amer. Meteor. Soc. 50: 880-882.

_______. 1969. Mesoscale Structure of the Texas Coast Sea Breeze. Atmospheric Science Group. Rept. No. 16. Austin: Univ. of Texas.

Huff, F. A., and Shipp, W. L. 1969. Spatial correlations of storm, monthly and seasonal precipitation. J. Appl. Meteor. 8: 542-550.

Jenrette, J. P. 1960. An objective application of vorticity principles to precipitation forecasting. Bull. Amer. Meteor. Soc. 41: 317-323.

Johnson, D. H., and Daniels, S. M. 1954. Rainfall in relation to the jet stream. Quart. J. Roy. Meteor. Soc. 80: 212-217.

Kimble, G. H. L. 1946. Tropical land and sea breeze (with special reference to the East Indies). Bull. Amer. Meteor. Soc. 27: 99-113.

Lahey, J. F., and others. 1958. Atlas of 500 mb. Wind Characteristics for the Northern Hemisphere. Madison: Univ. of Wisconsin Press.

Lansing, L. 1965. Airmass modification by Lake Ontario during April-November period. Great Lakes Res. Div. Pub. 13: 257-261.

Leopold, L. B. 1949. The interaction of trade wind and sea breeze, Hawaii. J. Meteor. 6: 312-320.

Lyons, W. A. 1966. Some effects of Lake Michigan upon squall lines and summertime convection. Great Lakes Res. Div. Pub. 15: 259-273.

Lyons, W. A., and Wilson, J. W. 1968. The Control of Summertime Cumuli and Thunderstorms By Lake Michigan During Non-Lake Breeze Conditions. Satellite and Mesometeorological Research Project. Rept. No. 74. Chicago: Univ. of Chicago Press.

Malkus, J. S., Bunker, A. F., and McCasland, K. 1951. A formation of pileus-like veil clouds over Cape Cod, Massachusetts. Bull. Amer. Meteor. Soc. 32: 61-66.

McAuilffe, J. P. 1922. Cause of the accelerated sea breeze over Corpus Christi, Texas. Mon. Wea. Rev. 50: 581-582.

McPherson, R. D. 1968. A Three-Dimension Numerical Study of the Texas Coast Sea Breeze. Atmospheric Science Group. Rept. No. 15. Austin: Univ. of Texas.

_______. 1970. A numerical study of the effect of a coastal irregularity on the sea breeze. J. Appl. Meteor. 9: 767-777.

Millar, F. G. 1952. Surface temperatures of the Great Lakes. J. Fish. Res. of Canada. 9: 329-376.

Miller, E. R. 1917. The meteorological influences of lakes. Proc. 2nd Pan American Science Congress. Washington, D. C.: U. S. Govt. Printing Office. 189-198.

_______. 1939. The land and sea breeze of Door Peninsula, Wisconsin. Bull. Amer. Meteor. Soc. 20: 209-211.

Moore, P. L. 1963. A radar study of shower activity associated with the sea breeze. Proc. 10th Weather Radar Conference. Boston: Amer. Meteor. Soc. 8-12.

Moroz, W. J. 1965. The Lake Breeze Circulation Along the Shoreline of a Large Lake. Ph.D. Dissertation, Univ. of Michigan, Ann Arbor.

_______. 1967. A lake breeze on the eastern shore of Lake Michigan: observations and model. J. Atmos. Sci. 24: 337-355.

Moroz, W. J., and Hewson, E. W. 1966. The mesoscale interaction of a lake breeze and low level outflow from a thunderstorm. J. Appl. Meteor. 5: 148-155.

Munn, R. E., and Richards, T. L. 1964. The lake breeze: a survey of the literature and some applications to the Great Lakes. Great Lakes Res. Div. Pub. 11: 253-266.

Neumann, J. 1951. Land breezes and nocturnal thunderstorms. J. Meteor. 8: 60-67.

O'Dell, C. B. 1931. Influence of Lake Michigan on east and west shore climates. Mon. Wea. Rev. 59: 405-410.

Oliver, V. J., and Oliver, M. B. 1963. Cloud patterns, part I: some aspects of the organization of cloud patterns. Mon. Wea. Rev. 91: 621-632.

Olsson, L. E. 1969. Lake Effects on Air Pollution Dispersion. Univ. of Michigan, Dept. of Meteor. and Oceanography, Tech. Rept. Ann Arbor.

Olsson, L. E., Cole, A. L., and Hewson, E. W. 1968. An observational study of the lake breeze on the eastern shore of Lake Michigan, 25 June 1965. Proc. 11th Conf. Great Lakes Res.: 313-325.

Palmén, E. 1951. The aerology of extratropical disturbances. In Compendium of Meteorology. Boston: Amer. Meteor. Soc. 599-620.

Palmén, E., and Nagler, K. M. 1949. The formation and structure of a large-scale disturbance in the westerlies. J. Meteor. 6: 227-242.

Palmén, E., and Newton, C. W. 1969. Atmospheric Circulation Systems. New York: Academic Press.

Pearce, R. P. 1955. The calculation of a sea breeze circulation in terms of the differential heating across the coastline. Quart. J. Roy. Meteor. Soc. 81: 351-381.

_______. 1962. A simplified theory of the generation of sea breezes. Quart. J. Roy. Meteor. Soc. 88: 20-29.

Pearson, J. E. 1958. Influence of lakes and urban areas on radar observed precipitation echoes. Bull. Amer. Meteor. Soc. 39: 79-82.

Ramaswamy, C. 1956. On the sub-tropical jet stream and its role in the development of large-scale convection. Tellus. 8: 26-60.

Reiter, E. R. 1963. Jet-Stream Meteorology. Chicago: Univ. of Chicago Press.

Richards, T. L., and Loewen, P. 1965. A preliminary investigation of solar radiation over the Great Lakes as compared to adjacent land areas. Great Lakes Res. Div. Pub. 13: 278-282.

Riehl, H. 1948. Jet stream in upper troposphere and cyclone formation. Trans. Amer. Geophys. Union. 29: 175-186.

_______. 1949. Florida thunderstorms and rainfall. J. Meteor. 6: 289-290.

_______. 1962. Jet Streams of the Atmosphere. Dept. of Atmospheric Science. Tech. Rept. No. 32. Fort Collins, Colorado: Colorado State Univ.

_______. 1965. Introduction To the Atmosphere. New York: McGraw-Hill.

Riehl, H., Norquest, K. S., and Sugg, A. L. 1952. A quantitative method for the prediction of rainfall patterns. J. Meteor. 9: 291-298.

Riehl, H., and Teweles, S., Jr. 1953. A further study on the relation between the jet stream and cyclone formation. Tellus. 5: 66-79.

Schmidt, F. H. 1947. An elementary theory of the land and sea breeze circulation. J. Meteor. 4: 9-15.

Schroeder, M. J., and others. 1967. Marine air invasion of the Pacific coast: a problem analysis. Bull. Amer. Meteor. Soc. 48: 802-808.

Shenfield, L., and Thompson, F. D. 1962. The Thunderstorm of August 9th, 1961, at Hamilton, Ontario. Tech. Rept. 417, Meteor. Branch, Dept. of Transp., Canada.

Sourbeer, R. H., and Gentry, R. C. 1961. Rainstorm in southern Florida, 21 January, 1957. Mon. Wea. Rev. 89: 9-16.

Staley, D. O. 1957. The low level sea breeze of northwest Washington. J. Meteor. 14: 458-470.

Stark, L. P. 1970. The weather and circulation of August 1970. Mon. Wea. Rev. 98: 869-874.

Starrett, L. G. 1949. The relation of precipitation patterns in North America to certain types of jet streams at the 300 mb. level. J. Meteor. 6: 347-352.

Stout, G. E., and Wilk, K. E. 1962. Influence of Lake Michigan on squall line rainfall. Great Lakes Res. Div. Pub. 9: 111-115.

Strong, A. E. 1967. The overwater development of a lake breeze in an offshore gradient flow. Proc. 10th Conf. Great Lakes Res.: 240-250.

Sutcliffe, R. C. 1937. The sea breeze at Felixtowe. A statistical investigation of pilot balloon ascents up to 5,500 feet. Quart. J. Roy. Meteor. Soc. 63: 137-148.

_______. 1939. Cyclonic and anticyclonic development. Quart. J. Roy. Meteor. Soc. 65: 518-524.

Tannehill, I. R. 1921. Wind velocity and rainfall frequency on the south Texas coast. Mon. Wea. Rev. 49: 498-499.

Trewartha, G. T. 1954. An Introduction To Climate. New York: McGraw-Hill.

U. S. Weather Bureau. 1958-1969. Climatological Data, vols. 64-75.

_______. 1958-1969. Daily Weather Map. All dates of interior rain days.

_______. 1970. Local Climatological Data. Sault Ste. Marie: June, July, and August.

Veatch, J. O., and others. 1927. Soil Survey of Chippewa County, Michigan. Washington, D. C.: U. S. Govt. Printing Office.

Wagner, A. J. 1970. The weather and circulation of June 1970. Mon. Wea. Rev. 98: 717-722.

Wallington, C. E. 1959. The structure of the sea breeze front as revealed by gliding flights. Weather. 14: 263-270.

_______. 1965. Gliding through a sea breeze front. Weather. 20: 140-144.

Water Temperature of Whitefish Bay. Personal communication from Dr. Arthur Pinsak, U. S. Army Corp of Engineers, Detroit. November 16, 1970.

Watts, A. J. 1955. Sea breeze at Thorney Island. The Meteorological Magazine. 84: 42-48.

Weiss, L. W., and Kresge, R. F. 1962. Indications of uniformity of shore and offshore precipitation for southern Lake Michigan. J. Appl. Meteor. 1: 271-274.

Wexler, R. 1946. Theory and observations of land and sea breezes. Bull. Amer. Meteor. Soc. 27: 272-287.

Williams, G. C. 1964. Comparative rainfall study, 68th street crib and Chicago area, summer and fall 1963. Great Lakes Res. Div. Pub. 11: 311-320.

APPENDICES

APPENDIX I

GROUPS I, II, AND III DAYS FOR JUNE, JULY, AND AUGUST OF 1970

GROUPS I, II, AND III DAYS FOR JUNE, JULY, AND AUGUST OF 1970

Group I Days:

June 22, 29
July 11, 28, 29, 30, 31
August 7, 11, 12

Group II Days:

June 21, 25, 26, 27
July 2, 21, 22
August 1, 4, 5, 6, 8, 9, 10, 17, 21, 24, 26, 29

Group III Days:

June 23, 24, 30
July 5, 6, 10, 12, 16, 18, 20, 23, 25, 26
August 3, 13, 14, 15, 20, 28, 31

APPENDIX II

RAINFALL BY GAGE FOR JUNE, JULY, AND AUGUST, 1970

RAINFALL BY GAGE FOR JUNE, JULY, AND AUGUST, 1970

	Rain-gage	Date 6/28	7/1	7/2	7/3	7/7	7/8	7/11	7/13
Brimley	1.	.20	.10	--	.33	.02	.39	--	.89
	2.	.20	.04	--	.28	.02	.32	--	.81
	3.	.21	.04	--	.21	.02	.32	--	.70
	4.	.20	.04	--	.15	.02	.30	--	.57
	5.	.15	.05	--	.19	.01	.30	--	.60
Vanderstar	6.	.15	.03	--	.15	.03	.30	--	.68
	7.	.17	.05	--	.20	.04	.28	--	.68
	8.	.13	.04	--	.16	.05	.27	--	.67
	9.	.11	.04	--	.15	.04	.26	--	.82
Hesselink	10.	.10	.06	--	.14	.03	.28	--	.93
	11.	.06	.06	--	.10	.02	.23	--	.94
	12.	.05	.07	--	.07	.05	.22	--	.72
	13.	.05	.08	.03	.06	.15	.25	--	.62
	14.	.05	.09	.07	.07	.15	.25	--	.66
Erfourth	15.	.08	.10	.20	.05	.14	.26	--	.62
	16.	.07	.10	.28	.05	.11	.26	--	.84
	17.	.10	.10	.12	.08	.11	.30	.03	.78
	18.	.16	.12	.15	.16	.12	.30	.12	.66
	19.	.17	.12	.60	.07	.09	.30	.06	.68
	20.	.15	.09	.84	.07	.09	.28	.03	.66
Harrison	21.	.13	.06	.52	.05	.11	.29	T	.52
	22.	.11	.18	.50	.05	.11	.29	--	.46

Appendix II--Continued

	Rain-gage	Date 7/14	7/15	7/16	7/19	7/23	7/27	7/28
Brimley	1.	.32	.10	--	1.32	.68	.08	--
	2.	.48	.11	--	1.31	.69	.09	--
	3.	.37	.12	--	1.32	.74	.04	--
	4.	.29	.14	--	1.32	.73	.03	--
	5.	.42	.18	T	1.30	.73	.02	--
Vanderstar	6.	.44	.18	.03	1.35	.71	--	--
	7.	.50	.23	.01	1.37	.73	--	--
	8.	.46	.24	T	1.35	.81	--	--
	9.	.45	.24	.04	1.26	.86	--	--
Hesselink	10.	.40	.33	.05	1.33	.90	--	--
	11.	.35	.31	T	1.25	.94	--	--
	12.	.28	.35	T	1.35	.91	--	--
	13.	.31	.48	.01	1.40	.95	--	--
	14.	.32	.48	.02	1.40	.86	--	--
Erfourth	15.	.37	.45	.07	1.70	.73	--	T
	16.	.41	.62	.04	1.85	.69	--	.02
	17.	.62	.28	T	1.77	.70	--	--
	18.	.77	.37	--	1.70	.73	--	--
	19.	.86	.14	--	1.73	.78	--	--
	20.	.82	.03	--	1.62	.84	--	--
Harrison	21.	.75	.02	--	1.67	.83	--	--
	22.	.80	.03	--	1.67	.83	--	--

Appendix II--Continued

	Rain-gage	Date						
		7/29	7/30	7/30	7/31	8/2	8/11	8/12
Brimley	1.	--	--	T	--	.02	.32	.01
	2.	--	--	.03	--	.01	.60	.01
	3.	--	--	.04	--	.02	1.10	.14
	4.	--	--	.06	--	.01	1.35	.11
	5.	--	--	.13	--	.01	1.50	.01
Vanderstar	6.	--	--	.33	--	.02	.20	.01
	7.	--	--	1.05	--	T	--	--
	8.	--	--	.62	--	T	--	--
	9.	.05	--	.38	.01	.01	--	--
Hesselink	10.	.05	--	.18	T	.01	--	--
	11.	.02	--	.09	--	.01	--	--
	12.	--	--	.01	--	.02	--	--
	13.	T	--	--	--	.04	--	--
	14.	--	--	--	--	.02	--	--
Erfourth	15.	--	--	--	--	.01	--	--
	16.	--	--	--	--	.02	--	--
	17.	--	--	--	--	.03	--	--
	18.	--	--	--	--	.03	--	--
	19.	--	--	--	--	.05	--	--
	20.	--	.01	--	--	.05	--	--
Harrison	21.	--	.02	--	--	.05	--	--
	22.	--	.02	--	--	.05	--	--

Appendix II--Continued

	Rain-gage	Date 8/16	8/19	8/20	8/22	8/25	8/27	8/30
Brimley	1.	.38	.01	.67	.58	.01	.19	.46
	2.	.28	.02	.70	.51	.03	.13	.39
	3.	.19	.01	.77	.50	.01	.14	.32
	4.	.17	.02	.64	.53	.03	.18	.29
	5.	.14	.01	.84	.50	.07	.23	.30
Vanderstar	6.	.11	.01	1.66	.46	.02	.24	.29
	7.	.05	T	1.00	.44	T	.21	.38
	8.	.19	T	.41	.95	--	.22	.40
	9.	.05	T	.22	.50	--	.25	.34
Hesselink	10.	.03	.01	.17	.70	--	.21	.38
	11.	.06	T	.17	1.35	--	.18	.43
	12.	.11	T	.20	1.55	--	.20	.92
	13.	.13	.01	.36	1.20	--	.21	.67
	14.	.10	.01	.28	.70	--	.24	.28
Erfourth	15.	.05	.01	.34	1.47	--	.17	.21
	16.	.05	.02	.25	.84	--	.20	.30
	17.	.05	.02	.21	.33	--	.14	.55
	18.	.09	.03	.25	.20	--	.18	.66
	19.	.13	.03	.42	.25	--	.08	.88
	20.	.10	.03	.68	.20	--	.13	.73
Harrison	21.	.04	.03	1.08	.20	--	.10	.58
	22.	.09	.04	.86	.25	--	.10	.60

APPENDIX III

RAINFALL TOTALS FOR JUNE, JULY, AND AUGUST, 1970

RAINFALL TOTALS FOR JUNE, JULY, AND AUGUST, 1970

	Rain-gage	June	July	August	Total
Brimley	1.	.20	4.23	2.65	7.08
	2.	.20	4.18	2.70	7.08
	3.	.21	4.13	3.20	7.54
	4.	.20	3.85	3.33	7.38
	5.	.15	4.08	3.61	7.84
Vanderstar	6.	.15	4.38	3.02	7.55
	7.	.17	5.31	2.08	7.56
	8.	.13	4.80	2.17	7.10
	9.	.11	4.66	1.37	6.14
Hesselink	10.	.10	4.78	1.51	6.39
	11.	.06	4.37	2.20	6.63
	12.	.05	4.08	3.00	7.13
	13.	.05	4.39	2.62	7.06
	14.	.05	4.42	1.63	6.10
Erfourth	15.	.08	4.77	2.26	7.11
	16.	.07	5.34	1.68	7.10
	17.	.10	4.99	1.33	6.42
	18.	.16	5.36	1.54	7.06
	19.	.17	5.60	1.84	7.61
	20.	.15	5.53	1.92	7.59
Harrison	21.	.13	4.97	2.08	7.18
	22.	.11	5.05	1.99	7.15

APPENDIX IV

NUMBER OF OCCURRENCES OF WIND BY COMPASS DIRECTION

NUMBER OF OCCURRENCES OF WIND BY COMPASS DIRECTION,
GROUP I DAYS, 0630

Station	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm
Grand Marais						2				2	1	2		3			
Whitefish Point				1		1		3			1	2				2	
Sault Ste. Marie			1	2	2	1	2		1					1			
Lansing Shoal				2		1		1			1	5					
Hesselink Site				1	1			1	1	2	1	1			1	1	

Appendix IV--Continued

NUMBER OF OCCURRENCES OF WIND BY COMPASS DIRECTION,
GROUP I DAYS, 1230

Station	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm
Grand Marais				5										4		1	
Whitefish Point				1		2		2			1		1			3	
Sault Ste. Marie						1	2			1	2		1	2	1		
Lansing Shoal						1		1			2	5		1			
Hesselink Site						1	1			3	1	2		1		1	

Appendix IV--Continued

NUMBER OF OCCURRENCES OF WIND BY COMPASS DIRECTION,
GROUP I DAYS, 1830

Station	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm
Grand Marais	2			1		1		1				2		3			
Whitefish Point								1			1			4		4	
Sault Ste. Marie							1						4	2	3		
Lansing Shoal												5		5			
Hesselink Site	2						1				1	2		1		3	

Appendix IV--Continued

NUMBER OF OCCURRENCES OF WIND BY COMPASS DIRECTION, GROUP II DAYS, 0630

Station	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm
Grand Marais		1			1	2		1		1		5		4		4	
Whitefish Point	2					3		3		1				4		6	
Sault Ste. Marie		1	1	1	4	3						2	2	4	1		
Lansing Shoal	5		2	2		3		1				4				2	
Hesselink Site	2			1		2	1			1	1	1		4	3	2	

Appendix IV--Continued

NUMBER OF OCCURRENCES OF WIND BY COMPASS DIRECTION,
GROUP II DAYS, 1230

Station	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm
Grand Marais	3			7				2						4		3	
Whitefish Point				1		5		3						2		8	
Sault Ste. Marie						1	2	2		1			1	3	6	3	
Lansing Shoal	1		1			2		3		2		10					
Hesselink Site	4					2		2	1		2	2				5	

Appendix IV--Continued

NUMBER OF OCCURRENCES OF WIND BY COMPASS DIRECTION,
GROUP II DAYS, 1830

Station	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Calm
Grand Marais				7		5				1				4		2	
Whitefish Point	2			2		2				2				4	1	6	
Sault Ste. Marie	1					1	1	2		1		2	1	1	6	3	
Lansing Shoal			1			2		1		2		8		3		2	
Hesselink Site	8						1	2	1	1		1	2			3	

72-8691

HENNEGHAN, Kathleen Mary, 1931-
SCHOOL DROPOUT PROGRAMS IN SELECTED MICHIGAN
SCHOOL DISTRICTS: IMPLICATIONS FOR CURRICULAR
INNOVATIONS.

Michigan State University, Ph.D., 1971
Education, curriculum development

University Microfilms, A XEROX Company, Ann Arbor, Michigan

SCHOOL DROPOUT PROGRAMS IN SELECTED MICHIGAN SCHOOL DISTRICTS: IMPLICATIONS FOR CURRICULAR INNOVATIONS

By

Kathleen Mary Henneghan

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Secondary Education
and Curriculum

1971