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A SYNOPTIC CLIMATOLOGY OF WINTER SNOWFALL OVER THE
UPPER AND LOWER PENINSULAS OF MICHIGAN

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

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* * * * * * *

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ACKNOWLEDGMENTS

My interest in the persistent snow showers occurring along the lee shores of the Great Lakes dates from grade school days in south-western Michigan. The recurring sequence of brilliant sunshine alternating with periods of blinding snow borne by frigid northwest winds was a part of our daily lives and became embedded in our concept of Michigan winter weather.

This dissertation has grown out of a desire to learn more about both the mechanics of the storms, and the climatic effects of these lake snowfalls. Over the years, many persons have contributed, directly and indirectly, to the completion of the study.

Professor Guy-Harold Smith, of The Ohio State University, ably guided the work on the dissertation, and to him I am greatly indebted for much helpful aid and advice. In this final year of his service in the University, I am pleased that he has been able to serve as my mentor and see my research on snowfall in the Great Lakes area result in an acceptable dissertation.

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CONTENTS

ACKNOWLEDGMENTS ........................................... ii

VITA ............................................................ iv

ILLUSTRATIONS ............................................... vii

TABLES ........................................................ x

Chapter

I. INTRODUCTION AND ORIENTATION ......................... 1

Mesoscale Meteorological Influences on the
Snowfall of the Great Lakes Area
Definition of Lake-Effect Snowfall
Purpose of the Study
Organization of Material
Basic Methodology
Sources and Utilization of Data

II. THE SCOPE OF PREVIOUS STUDIES ....................... 21

Localized Snowfall in Areas Other than
the Great Lakes
Review of Literature on the Snowfall of
the Great Lakes Region

III. THE GENERAL CONTROLS OF WINTER CLIMATE ........ 39

Introduction
Effect of the General Circulation
Secondary Climatic Controls - Effects of
the Great Lakes

IV. THE WINTER WEATHER TYPES ............................ 71

Method of Analysis
The Weather Types
Cyclonic Types
Westerly Flow Types
Anticyclonic Types
Synoptic Type Frequencies
Sequence Probabilities
<table>
<thead>
<tr>
<th>Figure</th>
<th>Illustration Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Height Differences of Mean Monthly 500 Mb. Surface</td>
<td>46</td>
</tr>
<tr>
<td>2.</td>
<td>Frequencies of Anticyclones and Cyclones by</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>Grid Subdivisions</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Mean Great Lakes Surface Temperatures</td>
<td>60</td>
</tr>
<tr>
<td>4.</td>
<td>Relief of Michigan</td>
<td>68</td>
</tr>
<tr>
<td>5.</td>
<td>NW Synoptic Type</td>
<td>83</td>
</tr>
<tr>
<td>6.</td>
<td>NWs Synoptic Type</td>
<td>83</td>
</tr>
<tr>
<td>7.</td>
<td>W Synoptic Type</td>
<td>86</td>
</tr>
<tr>
<td>8.</td>
<td>Ws Synoptic Type</td>
<td>86</td>
</tr>
<tr>
<td>9.</td>
<td>SW Synoptic Type</td>
<td>88</td>
</tr>
<tr>
<td>10.</td>
<td>SWs Synoptic Type</td>
<td>88</td>
</tr>
<tr>
<td>11.</td>
<td>G Synoptic Type</td>
<td>89</td>
</tr>
<tr>
<td>12.</td>
<td>T Synoptic Type</td>
<td>89</td>
</tr>
<tr>
<td>13.</td>
<td>HB Synoptic Type</td>
<td>91</td>
</tr>
<tr>
<td>14.</td>
<td>WFm Synoptic Type</td>
<td>91</td>
</tr>
<tr>
<td>15.</td>
<td>WF Synoptic Type</td>
<td>93</td>
</tr>
<tr>
<td>16.</td>
<td>WFc Synoptic Type</td>
<td>93</td>
</tr>
<tr>
<td>17.</td>
<td>WFCm Synoptic Type</td>
<td>94</td>
</tr>
<tr>
<td>18.</td>
<td>CA Synoptic Type</td>
<td>94</td>
</tr>
<tr>
<td>19.</td>
<td>WA Synoptic Type</td>
<td>96</td>
</tr>
<tr>
<td>20.</td>
<td>NA Synoptic Type</td>
<td>96</td>
</tr>
<tr>
<td>21.</td>
<td>SA Synoptic Type</td>
<td>97</td>
</tr>
<tr>
<td>22.</td>
<td>R Synoptic Type</td>
<td>97</td>
</tr>
<tr>
<td>23.</td>
<td>Mean Annual Snowfall</td>
<td>115</td>
</tr>
<tr>
<td>24.</td>
<td>Great Lakes Snowbelts</td>
<td>115</td>
</tr>
</tbody>
</table>
25. November Snowfall .................................. 121
26. December Snowfall .................................. 121
27. January Snowfall .................................. 123
28. February Snowfall .................................. 123
29. Percentage Increase, January Snowfall over
    February Snowfall ................................ 125
30. March Snowfall .................................. 125
31. Number of Heavy Snows ............................... 128
32. Mean Seasonal Snowfall Occurring as Heavy Snow .... 128
33. Functional Relations, Heavy and Moderate
    Snowfall vs. Total Snowfall ...................... 130
34. Percent of Mean Seasonal Snowfall Occurring
    as Heavy Snow .................................... 131
35. Moving Ten Year Averages ............................ 137
36. Bar Graphs for Selected Stations .................... 143
37. Probability of Snowfall, WFM ........................ 147
38. Probability of Heavy Snowfall, WFM .................. 147
39. Probability of Moderate Snowfall, WFM .............. 148
40. Probability of Snowfall, WFGm ........................ 148
41. Probability of Snowfall, NW ........................ 150
42. Probability of Snowfall, NWs ........................ 150
43. Distribution of Snowfall, SWs ........................ 153
44. Percent of Mean Seasonal Snowfall, SWs .............. 153
45. Percent of Total Number of Heavy Snows, SWs ........ 155
46. Percent of Mean Seasonal Snowfall, Ws ............... 155
47. Mean Seasonal Snowfall, NW ........................ 158
48. Percent of Mean Seasonal Snowfall, NW ............... 158
49. Mean Seasonal Snowfall, All Cyclonic Types .......... 160
50. Percent of Mean Seasonal Snowfall, All Cyclonic Types .......... 160
51. Distribution of Snowfall, WFM ......................... 162
52. Mean Seasonal Snowfall, WFM ........................ 162
53. Percent of Mean Seasonal Snowfall, WFM .............. 165
54. Number of Heavy Snows, WFM ........................ 165
56. Percent of Total Number of Heavy Snows Resulting from WFM ............ 165
57. Percent of Total Number of Heavy Snows Resulting from WFM and SWs ........ 168
58. Mean Seasonal Snowfall, Westerly Flow Types ........ 168
59. Percent of Mean Seasonal Snowfall, Westerly Flow Types .............. 170
60. Location of Stations ................................. 187
TABLES

Table                                      Page
1. Trough Features                        43
2. Location of Trough Features            43
3. Percent of Time That Troughs or Ridges Were Located Within Ten Degree Longitude Intervals of Latitudes Within the Great Lakes 45
4. Mean Heights of 500 Mb Surfaces along Eighty-Fifth Meridian 47
5. Location and Speed of Average Maximum Westerly Wind Component - 500 Mb Surface 47
6. Average Number of Occurrences, Individual Synoptic Types, November Through March 99
7. Frequency of Synoptic Types by 15 Day Consecutive Intervals 103
8. Synoptic Sequences, SELP Subregion 108
9. Synoptic Sequences, WUP Subregion 109
10. Variability of Seasonal Snowfall, 1904-05 Through 1960-61 135
11. Variability of Moving Averages, 1904-05 Through 1960-61 139
12. Correlation Coefficients, January Snowfall vs. January Mean Temperature 1931-61 140
CHAPTER I

INTRODUCTION AND ORIENTATION

Mesoscale Meteorological Influences on the Snowfall of the Great Lakes Area

The distribution of snowfall in the Great Lakes region of the United States and Canada is a response to this area's location in relation to the features of the general circulation, and it reflects also the effect of secondary factors imposed by geographic structure, chiefly surface type and configuration. Latitudinal location and frequency of passage of moisture bearing cyclones during the winter are the dominant controls related directly to the general circulation. The areal distribution of snowfall is partially in accordance with these controls. Snowfall increases toward the north within the region as lower temperatures permit a greater percentage of the winter precipitation to occur in the form of snow. Snowfall is also heavier toward the east where well-developed low pressure centers pass with greater frequency.

Superimposed on this generalized distributional pattern are spatial and temporal characteristics which are the result of unique locational and meteorological factors. The presence in the area of extensive open water surfaces (The Great Lakes) has a profound effect on the climate of surrounding areas. These bodies of water cool less rapidly than the surrounding land and remain as heat sources throughout autumn and winter. Their dynamic effects on winter weather systems
occur mostly at the regional or meso-level and are manifested most mark-
edly within the winter weather complex by a high percentage of cloudi-
ness over the Lakes area, and by an increase in snowfall along the lee
shores of the Lakes.

**Definition of Lake-Effect Snowfall**

The precipitation resulting from these lake influences has been
generally known as "snow flurries." This term has been applied to snow-
fall, light or heavy, which occurs within a homogeneous air mass when
evidence of frontal activity is lacking.\(^1\) Snowfall of this nature has
also been referred to as "snowsqualls,"\(^2\) and when concentrated spatially
in narrow, slowly fluctuating bands, the term "snowbursts" has been
applied, particularly to the phenomenon when it occurs in New York State.\(^3\)

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\(^3\) B. L. Wiggin, "Great Snows of the Great Lakes," *Weatherwise*, III (Dec., 1950), 123. Recent refinements of these definitions have been supplied by Mr. Wiggin, Meteorologist in charge of the U. S. Weather Bureau, Buffalo, New York, and by Livingston Lansing, Research Affiliate, Atmospheric Sciences Research Center, State University of New York, Albany. Wiggin made the distinction between "snowflurries" (light snow showers within a homogeneous air mass) and "snowsqualls" (heavier snow showers). A generic term used by Wiggin including both of the above definitions was "lake-effect snow." (The Nature of Lake-Effect Storms in Western New York, opening address at Conference on Lake-Effect Storms, sponsored by Atmospheric Sciences Research Center, State University of New York, College of Fredonia, April 23, 1962.) Consideration of an additional terrain factor led Lansing to classify snowfall occurring in the absence of fronts and cyclones as "post-cold frontal." "Post-cold frontal" snow can either take the form of "general instability snow showers," which are caused by general lifting of a homogeneous air mass by terrain obstacles, or "lake-effect snows" caused primarily by modi-
fications induced by warm open water surfaces of the Great Lakes. cf "Field Observations of Lake Effect Storms to the Lee of Lake Ontario"
In order to avoid confusion, snowfall occurring on the lee shores of the lakes within a homogeneous air mass in the absence of fronts and cyclonic disturbances will henceforth be referred to as "lake-effect" snow. Several meteorological factors may combine to produce this lake-effect precipitation. The term will be used generically, therefore, to differentiate between snowfall which results primarily from the unique geographic structure of the area and that which results from factors largely independent of local geography -- the macro-scale features of the general circulation.

**Purpose of the Study**

The occurrence of lake-effect snowfall in the Great Lakes area presents a most singular example of the value of the relationship between the climatologist, attempting to discern the regional and local aspects of the atmosphere, and the meteorologist, analyzing the dynamic and synthetic function of weather processes. It becomes the purpose of

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*abstr Proceedings of the Conference on Lake-Effect Storms, Fredonia, New York, p. 2. Although theoretically valid, the distinction would be difficult to apply, as the effect of terrain obstacles on the lee shore of the lakes in inducing snowfall is obviously heightened when the air mass has already had its heat and moisture content altered by warm lake waters.*

The importance of this relationship in this case is paramount when it is considered that an entire atmospheric process at the macro-level, the evaporation, transportation, condensation, precipitation cycle, one of the most fundamental of atmospheric functions, may, through the influence of propitious geographic factors, be reduced in scale to the meso-level. In this sense, it is thought that the entire life cycle of some of the snowflakes from the time they leave the lake as water vapor, thence to be condensed and fall as snow, may take place within a very few feet above the lake and land surface (cf. E. G. Johnson and C. P. Mook, "The Heavy Snowstorm of January 28-30, 1953, at the Eastern End of Lake Ontario," *Monthly Weather Review*, XXVI (Jan., 1953), 30. Cf. also W. M. Culkowski, "An Anomalous Snow at Oak Ridge, Tennessee," *Monthly Weather Review*, XC (May, 1962), 194-196, citing just such a
the climatologist to depict and portray the details of element dis-
tributional patterns, which, in the interest of ascertaining the over-
all circulatory features, are of secondary interest to the meteor-
ologist. In order to be truly synthetic, explanatory-empirical methods
should be employed. A dynamic synthesis of the atmospheric processes
should be attempted as climate is no more than the sum of atmospheric
conditions in their usual succession and frequency. Thus the technique
of the climatologist should be "to utilize the aerological and synoptic
data (analysis of the daily weather situation) and then determine the
regional and local aspects as a function of geography." 6

Although the occurrence of lake-effect snowfall in the lee of
the Great Lakes has been recognized as a significant genetic factor in
the winter snowfall of the area, its relative role spatially and tem-
porally within the overall distributional pattern has not been deter-
m ined by means of quantitative weather parameters. Obviously a
substantial proportion of the winter snow occurs as a result of passage
of cyclonic storms and is quite independent of the existence of the
Lakes. It is the purpose of this study to analyze the climatological

meso-scale phenomenon involving snowfall. The snowfall was associated
with emission of water vapor by the Oak Ridge Gaseous Diffusion Plant.
The entire evaporation, condensation, precipitation mechanism was con-
fined within a five mile area. A semipermanent cumulus cloud was
formed and an intermittent and fairly light snow began falling three
miles downwind, and continued to be deposited noticeably on the
ground up to five miles.

5Arthur N. Strahler, "Empirical and Explanatory Methods in
Physical Geography," The Professional Geographer, VI (Jan., 1954), 4-8.

6Pierre Pedelahord, "Sur les Methodes de la Climatologie
Physique," La Meteorologie, IV (Jan.-Mar., 1959) 65 (writer's
translation).
characteristics of snowfall in the Great Lakes region, and to establish, by means of synoptic climatology, the relative role of the Lakes in the genesis of snowfall over surrounding areas.

Organization of Material

The materials of this investigation will be organized and presented in four major divisions or categories. First, through a review of the pertinent literature, a synthesis of the existing knowledge of the snowfall of the area will be presented, and the need for a quantified summarization of the climatological impact of lake-effect snows will be demonstrated.

Second, the general climatology of the region will be examined in relation to the characteristics of the general circulation, both at the surface and upper levels. The climatological and meteorological modifications induced by the open water of the Lakes and by the terrain factor will also be depicted, as well as the temporal and spatial aspects of these modifications.

Third, in order to ascertain the atmospheric factors in frequent combination over the area during the winter, genetic weather types will be defined. The frequency, sequence, and temporal variation of these types will be determined. The totality of winter weather occurring in the region will be expressed in a more meaningful and comprehensive manner and it is expected that a contribution to the methodology of climatological description will also be presented.

Fourth, the occurrence of snowfall with each defined weather type will be analyzed in terms of means, probabilities, and other climatological derivations. The lake effect will be shown by static
climatological methods, and then will be examined in relation to the mean distributional patterns evidenced by the individual weather types. At the same time, the feasibility of relating discrete distributional patterns to discrete atmospheric arrangements will also be investigated. Thus quantitative measurements of the lake effect with varying atmospheric situations may be obtained, and the impact of geography within the regional weather complex will not be confined to representation by the seasonal sum of atmospheric conditions.

**Basic Methodology Used in Formulation of Weather Types**

Utilization of weather typing in climatological work is predicated on the premise that a more realistic expression of the totality of weather can be obtained. A number of methods have been used in weather typing. Essentially, the different means of "totality expression" have fallen within the realms of dynamic, synoptic or complex climatology. All of these methods have a common opposition to static statistical presentation and their basic methodology has been discussed and summarized in the recent literature by Hare, Court, Calef, and Tucker.

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Hare's concept of dynamic climatology followed Conrad's translation of Bergeron's initial concepts and involves identification of flow patterns ... that represent distinctive combinations of weather with a definable circulation ... [these] must be isolated analytically ... [and] must be inserted into the general circulation to form the basis for a general dynamic climatology.\[^{11}\]

Synoptic climatology, in Hare's estimation, "deals specifically with regions small enough for recognized circulation types to be interpreted in terms of ordinary weather elements."\[^{12}\] Thus dynamic and synoptic climatology differ essentially in scope, according to Hare, with the former larger in scale, "a regional or global synthesis of daily circulation types."\[^{13}\]

Court sharpened the distinction between dynamic and synoptic climatology by contrasting the fundamental purpose of each. The goal of the original dynamic climatology was to describe the circulation of the atmosphere in terms of its various characteristic situations, rather than in terms of monthly, seasonal, or annual means of pressure, temperature, wind or precipitation ... none of [the original formulators] considered the climates of a specific place, or even of a region except as they were useful in synthesizing a picture of atmospheric energy.\[^{14}\]

Dynamic climatology sought to apply such treatment toward the hydrodynamic and thermodynamic explanation of the mean atmospheric circulation and


\[^{12}\]Hare, op. cit., p. 155.

\[^{13}\]Ibid.

\[^{14}\]Court, op. cit., p. 128.
its variations. The opposite approach, the description or explanation of local climates in terms of the large scale circulation . . . is the field of synoptic climatology.\textsuperscript{15}

Complex climatology was originally introduced by Federof in Russia, and was defined by Court as "analysis of the climate of a single place or comparison of the climates of two or more places by the relative frequencies of various weather types or groups of such types."\textsuperscript{16} The term "weather types" used in this context is not to be taken in the genetic sense, but refers to repeatable combinations of weather elements.

Calef used the term more broadly, and cited four distinct kinds of weather types: (1) types based on synoptic pressure patterns, (2) types based on air mass occurrence, (3) types based on conjunctions of elements, and (4) types based on standard time periods.\textsuperscript{17} Types one and two fall within Court's definition of synoptic climatology, whereas type three corresponds to Federof's complex climatology. Weather types based on standard time periods are bounded by arbitrary time units, and in this sense applicable to all three of the above types. In summary, dynamic climatology is disassociated from the weather complex, and, hence, does not offer a genetic explanation of surface weather. Weather types based on conjunctions of pure weather elements (complex climatology) are for the most part unrelated to the characteristic atmospheric situation and hence they, too, are not genetic.

\textsuperscript{15}Ibid., p. 129 (writer's underlining).

\textsuperscript{16}Ibid., p. 127.

\textsuperscript{17}Calef, \textit{op. cit.}, p. 3.
Weather types based on some aspect of the synoptic chart and related to the weather complex over given areas are obviously genetic (synoptic climatology) although there may not be a consistent correlation between the synoptic weather type and the associated element occurrence. The means of classification then rests largely with the purpose for which it is desired.

In this investigation the primary concern is in ascertaining the distributional patterns of a single weather element with varying atmospheric situations. An inherent assumption is made that certain similarities in the weather complex exist with differing synoptic patterns. The occurrence of snowfall assumes the existence of specific cloud, humidity, and temperature characteristics. Certain element combinations are also assumed to exist when no snowfall occurs. Thus a very broad two-fold classification of weather types based on conjunctions of weather elements is implicit. The problem then consists of obtaining varying genetic atmospheric patterns which may account for certain broad scale similarities of the surface weather complex. More specifically, the basic methodological problem is concerned with ascertaining the relationship between a single sensible weather element (snowfall), and regional atmospheric behavior with repeatable variations in the distribution of the element arising both from atmospheric contrasts and from local geographic factors.

Synoptic climatology would appear to best fulfill this purpose. Synoptic climatology was first defined by Jacobs and used as "a method for breaking down the purely ficticious mean climatic picture into the
actually occurring weather patterns of which climate is composed.\textsuperscript{18} C. S. Durst, of The Great Britain Meteorological Office, defined it succinctly as "description and analysis of the totality of weather at a single place, or over a small area, in terms of the properties and motion of the atmosphere over and around the place or area."\textsuperscript{19} Court interpreted the function of synoptic climatology as being essentially explanatory-descriptive, describing the "totality of weather resulting from, or at least physically related to the atmospheric circulation, as conveniently portrayed by a synoptic weather map."\textsuperscript{20} As such, synoptic climatology becomes the tool of the climatologist and the physical geographer.

In this study, synoptic climatology will be utilized (1) to portray in a more realistic fashion the prevailing structure of wintertime atmospheric conditions over the Great Lakes region as manifested by the synoptic chart, and (2) to determine the areal distribution of snowfall with each synoptic type, and to discover in quantitative terms the extent of geographic influence with each type.

**Region Selected for Synoptic Analysis**

Because of the labor of mathematical computations involving a large number of climatological stations, it appeared feasible to restrict the more intensive aspects of this investigation to a sample area within the Great Lakes region. The area selected for synoptic


\textsuperscript{19}Court, op. cit., p. 129, referring to personal communication from C. S. Durst.

\textsuperscript{20}Court, op. cit., p. 135.
analysis includes the Upper and Lower Peninsulas of Michigan. The reasons for this selection are the following:

1. The area is of ideal size for the formulation of a synoptic climatology.\(^{21}\)

2. Lake-effect snowfall may be expected to be of considerable importance within the area as it is surrounded by water on three quadrants.

3. Few studies have dealt with snowfall distribution in this area. The majority of studies dealing with lake-effect snows have been confined areally to the lee shores of Lakes Ontario and Erie.

4. The contrasting alignment of Lakes Michigan and Huron, as compared to Lake Superior, may result in differing distributional patterns with similar synoptic situations where contrasts in fetch and shore alignment are concerned.

5. A relatively dense net of recording stations is available within the area.

**Sources and Utilization of Data**

*Historical survey of development of snowfall observing stations in the Great Lakes area.* -- Organized meteorological observations, including the recording of snowfall days, began in the Great Lakes area during the early part of the 19th century.\(^{22}\) In 1818, the Office of Surgeon General was created within the newly organized Medical

\(^{21}\)Jacobs, *op. cit.*, Bull., *Amer. Met. Soc.*, p. 306, recommended an area no larger than 100,000 square miles for a synoptic climatology.

Department of the United States Army. From 1821 on, the Medical Department required surgeons to keep climatic records. The measurement of snows in their depth when first fallen received little attention, however, although the melting of the quantity and its measurement as water was very accurately and carefully given.

In 1847, additional stations manned by volunteer observers were proposed by Elias Loomis to be established and sponsored by the Smithsonian Institution. The Fifth Annual Report of the Secretary of the Board of Regents of the Smithsonian Institution contained instructions to volunteer observers for the measurement of snowfall. By 1851, seven volunteer stations had been established in Michigan under the jurisdiction of the Smithsonian Institution.

The meteorological records of the Smithsonian stations were

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24 **First Report of the Secretary of The Smithsonian Institution to The Board of Regents** (Washington: Ritchie and Heiss, 1848), p. 37.

25 **Fifth Annual Report of the Board of Regents of the Smithsonian Institute** (Washington, 1851), p. 18. Measurement of freshly fallen snow still was not taken. The snow gauge was described as "a cylinder of zinc of the same diameter as the mouth of the rain gauge. The measurement is made by pressing its mouth downwards to the bottom of the snow where it has fallen on a level surface. Then carefully inverting it, retain the snow by passing under it a thin plate of metal. The snow is afterward melted and the water produced is measured in one of the graduated glass cylinders of the rain gauge."

26 **Sixth Annual Report of the Board of Regents of The Smithsonian Institute** (Washington: A. Boyd Hamilton, 1852), p. 73. Michigan stations listed included Detroit, Battle Creek, Brest, Grand Rapids, Howell, Burr Oak, and Clinton. Additional stations established by The Smithsonian Institute in the Great Lakes area included Waterville, Buffalo, Oswego, Sackett's Harbor, and Lockport in New York, and Cleveland, Ohio.
published in 1861.²⁷ Depth of freshly fallen snow was still ignored, however. During the period preceding the transfer of the observation net to the jurisdiction of the Signal Service in 1873, the list of stations varied considerably. In 1872, the year prior to transfer, the Smithsonian Institution had stations at twelve locations in Michigan.²⁸ Weather records, including snowfall days, were also kept from 1859 to 1871 by the United States Army Engineer Corps.²⁹

Under the direction of the Army Signal Corps, the network of weather stations expanded rapidly until by 1890 one hundred and six voluntary and cooperative stations in addition to ten first and second order stations were making weather observations in Michigan.³⁰ In 1884, attention had been directed to the measurement of depth of freshly fallen snow at cooperative stations, and the observer was instructed to measure snow depths to the nearest tenth of an inch for the preceding


In 1891, the meteorological functions of the Signal Service was transferred to the Department of Agriculture, and the Weather Bureau remained under this jurisdiction until transfer, in 1940, to the Department of Commerce.

With an increased number of stations and a new emphasis on the recording of twenty-four hour snowfall depths, the first published snowfall records for the Great Lakes region began to appear. Scattered reports of monthly snow totals were published in issues of The Monthly Weather Review from 1873 through 1887, and beginning in 1890, totals were published for each month for stations which received ten inches or more, and for the heaviest station amount in states or territories where the maximum amount received was less than ten inches. Charts were also published showing the depth of snow at the end of the month, and after 1894, The Monthly Weather Review included monthly totals for cooperative stations.

Snowfall normals, totals for the 1891-1892 season, departures from normal, and maximum twenty-four hour amounts were published in 1893 for sixteen Great Lakes stations in the Annual Report of the Chief of the Weather Bureau. By 1898 the number of stations in Michigan for which annual snowfall totals was published in the Annual Report had

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increased by twenty-six. Supplementing these published records were the **Annual Reports of the Michigan Weather Service**, which had been organized as a climate and crop service in 1895. During that year, snowfall data for seventy-eight stations were summarized, including total monthly snowfall, snow on the ground on the fifteenth of the month, and snow on the ground at the end of the month. The Weather Bureau publication, **Climatic Summaries by District**, contained monthly and annual summaries, and descriptions of severe individual storms. This publication was superseded in 1931 by the Weather Bureau monthly publication, **Climatological Data by Sections**. Monthly and annual snowfall totals were published for a large number of stations from the inception of this series, and daily snowfall totals for selected stations, as well as snow on the ground, were published beginning in 1949.

**Selection of snowfall data for static analysis.** -- Data utilized in the construction of charts of monthly and annual snowfall of the Upper and Lower Peninsulas of Michigan were obtained from summaries of one hundred and fifty-three Weather Bureau First Order and Cooperative Stations for a thirty year period, 1931-1960. These unpublished data

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34Ibid., 6th Report, 1899.


are available at the East Lansing Office of the United States Weather Bureau.

**Selection of snowfall data for synoptic analysis.** — The selection and utilization of snowfall data in conjunction with the synoptic analysis were guided by three primary considerations. First, in order to obtain an accurate impression of the distributional patterns associated with each synoptic situation, a dense net of recording stations should be utilized. Second, a correlation of recorded snowfall with individual synoptic types requires a close correspondence of observational time for all stations. Third, the data used must meet tests of reliability and homogeneity.

Data from all available Weather Bureau First Order stations and from ninety-nine cooperative stations were selected. Daily snowfall totals were published for forty-eight of these stations. Data for the remaining stations were abstracted directly from the original Cooperative Observer Report, *Record of Climatological Observations*, WB Form 612-14, on file at the United States Weather Bureau Office, East Lansing, Michigan. Additional daily snowfall data were also obtained from the original records from ten gauges operated by the Michigan State Highway Department, in conjunction with County Highway departments. These gauges began operation in 1957 in selected locations in order to assist in determining state appropriations for the yearly allocation of funds to counties for snow removal. Data from these

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37 See Appendix A for complete list of stations, and Appendix A, Fig.60 for map indicating location of stations used with synoptic analysis.

gauges proved invaluable in determining snowfall patterns in certain critical areas.

Conformality of observation time. — Data used in conjunction with a synoptic analysis which is based on a standardized time period need to have conformance or near conformance to this time period. In order to correlate the weather element to the synoptic situation (as analyzed from the 1:00 AM and 1:00 PM E.S.T. sea level charts, and the 7:00 PM E.S.T. 500 millibar surface charts) only stations having late afternoon or evening observation times were selected.

Reliability and homogeneity of snowfall records. — The reliability of snowfall data involves the care and uniformity with which the measurement is taken, and the integrity with which the measurement is entered and reported. In dealing with a large number of Cooperative stations, wide variances in each of the foregoing aspects occurred. Stations with questionable or spotty records, as evidenced from the appearance of the observation form, were eliminated. The problem of obtaining uniformity in measuring procedures proved more difficult, however, as no measurement of a weather element is subject to such varying practices. In spite of the lack of standardization in snowfall measuring techniques, it was felt that the distribution patterns would not

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39 The problem of non-uniformity of snowfall measurement in Michigan was indicated by Mr. A. H. Eichmeier, State Climatologist, in a personal conversation. The literature is replete with discussions of snow measurement. For a summary, see C. F. Brooks, "The Need of International Standards in the Measurement of Precipitation, Snowfall, and Snow Cover," Transactions of International Committee of Snow and Glaciers (Sept. 1936), International Association of Scientific Hydrology, Bulletin 23 (1938), 7-55. The utilization of shielded and unshielded gauges in the area has been discussed by Leonard L. Weiss, "Relative Catches of Snow in Shielded and Unshielded Gauges at Different Wind Speeds," Monthly Weather Review, XXCIX (Oct. 1961), 397-400.
be obscured and that utilization of a large number of stations would offset measurement discrepancies at any one site.

A careful selection of stations was made to insure homogeneity of record. Most of the stations used for the static analysis, and many utilized with the synoptic analysis, had experienced changes in instrument location. The effect of site location on the recorded snowfall of New York state has been indicated by Muller, and the effect of exposure on gauge location was recognized in Michigan as early as 1904. The majority of site changes in Michigan entailed relocation of instruments within short distances with negligible elevation changes. In most cases, homogeneity of record was maintained. Where site changes resulted in interruption of record, the station or stations were eliminated.

A homogeneous record is one in which variation of a climatological element is caused only by variations of weather and climate, according to V. Conrad and L. W. Pollak, *Methods in Climatology* (Cambridge: Harvard University Press, 1950), p. 223.

Of sixty-four stations in Michigan where observations have been made for over fifty years, only nine stations have not experienced site changes. For nine stations with a forty-to fifty-year record, three have had continuous instrument siting, and for eighteen stations with a twenty-to thirty-year record, three have had the site unchanged.

Robert A. Muller, "Snowfall Patterns in the Eastern Lake Erie and Eastern Lake Ontario Snowbelts and their Relation to Snowfall in New York," *Proceedings of the Conference on Lake Effect Storms*, op. cit., pp. 18-27. Discontinuity in record occurred in New York State where gauges were translocated from valley to ridge or vice versa involving large altitude differences.

Annual Report *Michigan Weather Service*, op. cit. (Jan. 1903), p. 83. The observer at Ontonagon, Michigan, a station on the shore of Lake Superior, remarked "The wind blows the snow from the lake shore, and most of it is three or four miles away in the woods."
Derived data. -- Because of scale presentation, it proved extremely difficult to extract the desired synoptic information from microfilmed U. S. Weather Bureau Daily Weather Maps, or from the U. S. Weather Bureau's Daily Synoptic Series, Historical Weather Maps, Northern Hemisphere, Sea Level. Original copies of the U. S. Weather Bureau Daily Weather Map were used for the formulation of synoptic weather types. Back issues of The Daily Weather Map are on file at the East Lansing office of the U. S. Weather Bureau.

Time period selected for synoptic analysis. -- A synoptic analysis was completed for the five winter seasons, 1957-58 through 1961-62. Each day during the months of November through March, during which the majority of the snowfall occurs, was assigned a synoptic type. No attempt was made to select a "normal" period, and the selection was based primarily on the availability of weather and synoptic data. Namias has discussed basic circulational changes responsible for an increase in snowfall during the past decade for a number of stations in the Eastern United States. This tendency appears to be manifested in Michigan by a marked increase in snowfall in Southwestern areas near the shores of Lake Michigan, and will be further discussed in a later section. Hence climatological derivations in this thesis should be taken as normal only for the period of investigation and should not be construed as representing long term averages.

\[44\] Jerome Namias, "Snowfall Over the Eastern United States: Factors leading to its Monthly and Seasonal Variation," Weatherwise, XIII (1960), 238-247. Namias correlated the increase in snowfall for several eastern cities during the past decade with changes in the mean circulation as indicated by seasonally averaged maps at the 700 mb. level.
Arrangement of data for punch card entry. — The dense station network required to give validity to this study would require, for the five-season period, over twenty-eight thousand individual data entries. The statistical computations involving this mass of data necessitated the aid of a high-speed electronic computer. The IBM 1620 computer housed in the Computer Center, Western Michigan University, was used for the majority of the statistical computations.

All data were coded and entered on IBM punch cards. Each station was given a three-digit code number. The first digit of the identification code number referred to a geographical subdivision. Ten of these subdivisions were formulated in Michigan to aid in the synoptic classification where different synoptic situations may occur simultaneously over different sections of the state, and also to aid in station identification. Location of subdivisions, station code numbers, and observation times are listed in Appendix A. A location map is also included. The complete format arrangement for coded entry of data is indicated in Appendix B.
CHAPTER II

THE SCOPE OF PREVIOUS STUDIES

Localized Snowfall in Areas Other Than the Great Lakes

Introduction. — Localized or lake-effect snows occur on a significant scale only in world areas where a propitious combination of geographic factors is present. Latitudinal requirements must be met which insure adequate lowering of winter temperatures below the freezing point in order that precipitation will occur in the form of snow. A land mass of continental dimensions must be located to the windward, functioning as a source region for polar continental air. A body of water of sufficient areal surface extent to modify actively polar air must lie athwart the prevailing tracks of the air masses. This water body must remain ice free at least during the early months of the winter season. Other than in the Great Lakes region of the United States and Canada, these locational prerequisites are fulfilled only along the east shore of Hudson Bay in Canada and long the west coast of the Japanese islands of Honshu and Hokkaido.

Local snowfall along the east shore of Hudson Bay. — Disparate amounts of snowfall have been noted along the east and west shores of Hudson Bay. The effect of Hudson Bay on the distribution of snowfall in Eastern Canada and along the east shore has been investigated by Hare,¹

Hare and Montgomery, Burbridge, and Barry. Hare, and Hare and Montgomery substantiated the influence of Hudson Bay on snowfall during the early winter by a comparative analysis of monthly totals along the east shore of the bay. A chart of mean November snowfall indicated an excess of thirty inches, whereas on the March chart this belt of heavy snow had entirely disappeared. Hare estimated that from fifteen to twenty-five inches of the November snowfall in this area were directly induced by the open surface of the bay, while from mid-January on, with the bay completely frozen, little or no trace of this localized activity occurred. A similar effect on a smaller scale was noted by Hare on the west coast of Newfoundland, and later in winter, on the south coast of Labrador. This latter effect resulted from southerly currents of returning polar continental air which intensified the frontal precipitation.

Burbridge was concerned primarily with meteorological modifications within the lower layers of polar continental air during passage over the relatively warm water surface of the Bay during the early winter, and, also, with establishing the extent of ice formation in the Bay during the winter season. Snowfall data for the eastern shore was used in the deductive sense as indicative of a complete ice cover in


Hudson Bay during the late winter. Burbridge reasoned that the rapid decrease of monthly snowfall as the winter season progressed indicated a solid freeze-up of the Bay.  5

Barry investigated the average distributional patterns for several climatic elements occurring in conjunction with subjectively determined flow patterns adapted from trajectory models for the Labrador-Ungava area. He noted the high frequency of localized snowfall during the early winter at Port Harrison, and depicted the prevailing synoptic type with which it occurred. Although Barry's study was unique in indicating the synoptic aspects of this localized snowfall, the lack of availability of a dense network of recording stations in the area did not permit a detailed examination of the spatial and temporal distribution associated with the phenomenon.

Localized snowfall of the west coast of Japan. — The heavy monsoon snowfall occurring on the west coast of Japan has been described by Okada, who indicated the disparity between the west and east coasts of Honshu in total snowfall and of snowdays.  6 He noted also the influence of these snows on the cultural habits of the indigenous peoples, and on their architectural structures. The persistent and excessive snowfalls of this area were also noted by the Great Britain Meteorological Office.  7

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5 Burbridge stated that if Hudson Bay did not freeze, Port Harrison (on the eastern shore of the Bay) would receive nearly three hundred inches of snow during the winter (op. cit., p. 132).


Kitagawa classified the snowfall of western Japan as monsoon, depression, and medium, and noted the prevalence of monsoon snowfall in the center of the Nagata area. He also commented on the synoptic situation related to the first occurrence of monsoon snows in winter, and defined the meteorological mechanics involved with these snowfalls.

Review of Literature on the Snowfall of the Great Lakes Region

Early studies. --- Although meteorological observations in the Great Lakes area were confined to a few scattered army posts during the early years of the nineteenth century, the effect of the Great Lakes on weather processes, and on the climate of surrounding areas, had already been discerned. In his early account of the physical geography of the United States, Volney, although making no specific comment on the influence of the Lakes on the snowfall of adjacent shores, wrote that

the northwest wind is laden with moisture it sometimes imbibes from the lakes, rivers, and marshes it is obliged to pass over. Hence in places leeward to the lakes . . . this wind is distinguished as wet in winter and tempestuous in summer.

Forry recognized that the Lakes did not completely freeze over, and he described their climatic influences by comparing the mean annual range of temperature at Fort Brady (at the mouth of Lake Superior) with


Fort Hancock, Maine, at the same latitude. He was also aware of the heavier snowfall of the lakes region, and contrasted the number of snow days at Army posts near the Lakes with those in interior locations away from the Lakes.

Blodget's comprehensive climatology of the United States contained only a brief mention of the distribution of snowfall. Reference was made to the cursory attention that newly fallen snow had received in the medical records, and to the occurrence of excessively heavy snowfalls in the ice of the lakes from Buffalo eastward. Blodget stated that although the snowfall of the Lake Superior district was heavy, it was not equal to that which occurred in western New York State.

After the establishment of additional climatological stations, and with the new emphasis on the observation and recording of freshly fallen snow, the first tables of mean annual snowfall for the nation were published in 1893. Instruction for the uniform measurement of snow accompanied the tables, and a brief discussion of the distribution of snowfall in the lake area followed. With records available from the seven-year period ending in 1891, the Upper Peninsula of Michigan was cited as the area of greatest mean annual snowfall in the eastern United States. The average yearly amount within a circle of two hundred mile radius centering on Marquette, Michigan, was stated to be approximately

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one hundred and thirty-two inches, with a rapid dropoff to the west, southwest and south. To the southeast, a secondary center of maximum snowfall occurred in the northern part of the Lower Peninsula. The report noted the deficiency of snowfall on the southwest shores of the Lakes, and indicated the increase in annual snowfall as one progressed eastward along the south shores of Lakes Erie and Ontario.

Based on data appearing in The First Annual Report of the Chief of the Weather Bureau (1892), the initial chart of mean annual snowfall for the United States was published by Mark W. Harrington. A reproduction of Harrington's map was later published by Frank Waldo in his textbook. Although the heavier snowfall of the Upper Peninsula was shown on this map, the belts of heavy snow along the lee shores of Lakes Michigan, Huron, and Erie were not depicted, probably because of the paucity of recording stations in these areas.

Two years later, in 1898, a chart of mean annual snowfall utilizing data accumulated between 1884 and 1895 was published by A. J. Henry. Using more stations, Henry's map showed indications of the disparity in snow amounts between lee and windward shores. An additional snowfall map for the winter season 1897-98 showed a rapid decrease away from the Lake Superior shores, but apparently because of an unusually severe cyclonic storm of February 18 and 19 which dropped up

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15 A. J. Henry, Monthly Weather Review, XXVI (March, 1898), Chart XI.
to two feet of snow on both shores of Lakes Michigan and Huron, the heavier snow areas in the lee of the lower lakes were not depicted.

Two early studies attempted to ascertain the genetic aspects of snowfall around the Great Lakes. A. B. Crane investigated the synoptic features of heavy snowstorms in the Chicago area occurring between 1879 and 1890. Like most of the subsequent genetic studies involving some form of weather typing, Crane's study was beamed primarily toward the forecaster. About ten years after Crane's work, Weather Bureau Bulletin K was published, in atlas form. In the accompanying text, the synoptic situations accompanying severe lake storms were discussed. Subsequent Weather Bureau Bulletins Q and W made additional comments on the heavy snowfalls of the Lakes region.


16. A. B. Crane, "Snowstorms at Chicago," The American Meteorological Journal, IX (June, 1892), 63-66. Crane's analysis included an appreciation of the synoptic pressure situation and the trajectory of snow-bearing storms. He found that the location of the dominant high pressure system was invariably in the northwest, while eighty percent of the cyclonic systems approached from the west, with the majority of the rest of Gulf origin.

17. U.S. Weather Bureau, Storms of the Great Lakes, E. B. Garriot, ed. Bulletin K (Washington: Government Printing Office, 1903), p. 6. This study indicated that the majority of the cyclones bringing heavy snow approached the region from the southwest or west. Particular note was made of the lack of snow south of the track with the passage of cyclones from the northwest.

network of over 2200 stations to work with, Brooks' map accurately indicated for the first time the existence and extent of "snow belts" in Western Michigan, Northeastern Ohio, and Western New York state. On this chart, areas to the lee of Lake Ontario replaced Upper Michigan as the maximum snow areas of the eastern United States, and Brooks attributed the excessive snows of these areas to the lake influence.

In his doctoral dissertation, Brooks analyzed the snowfall of the Lake region from data furnished by approximately one hundred stations. Charts showing average annual, maximum and minimum annual, and extreme range of annual snowfall were presented, and snowfall amounts on windward and leeward sides of the Lakes were contrasted by means of histograms. Brooks concluded that cyclonic storms contributed perhaps thirty inches of the annual mean snowfall, and that the remainder was due to the effect of local topography on cold, moist northwesterly winds.

One chapter of Ward's regional climatology of the United States was devoted to the distribution of snowfall. Ward commented that the first snows of the season in the Lakes area often occurred with cold northwest winds which had been modified by the open water of the lakes. He stated that the heavier snow on the eastern shores of the lakes resulted "chiefly from the frequent occurrence of westerly snow squalls on the lee shores after cold winds have crossed warmer lake waters."  

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Day investigated the influence of the Lakes on the total amounts of precipitation (rain and snow) occurring in the area.\(^{21}\) A comparison of yearly averages for selected stations on the west and east shores of Lake Michigan revealed only negligible differences. Greater contrasts between the east and west shores of Lake Huron were attributed to the downslope of the land from interior Michigan to Lake Huron, and to the Canadian practice of using a uniform ten to one ratio in measuring the moisture content of snow. The increase in percentage of winter precipitation (October-March) on lee shores of the lakes was attributed to lake-effect snows and to a gradual transition to a Great Plains rainfall regime toward the west.

The climatological contrasts between the east and west shores of Lake Michigan were described by Odell.\(^{22}\) Snow days, number of clear and cloudy days, and prevailing wind direction were compared and contrasted. Odell found that the average number of snow days on the east shore nearly doubled those on the west shore during the months of January and December, while the disparity vanished during March.

Forry and Blodget recognized the influence of the unfrozen Lakes on the snowfall of surrounding lee shores, and Harrington completed the first map of mean snowfall for the United States. This map indicated the heavy snow in the vicinity of Lake Superior. The contrasts between windward and lee shores were not fully recognized until Brooks, with the availability of a large number of observing stations, compared mean


\(^{22}\)Clarence B. Odell, "Influences of Lake Michigan on East and West Shore," *ibid.*, LIX (Nov., 1931), 405-410.
annual and monthly totals occurring at selected stations. Brooks also stated that the lake influence accounted for the major portion of the annual snowfall in snowbelt areas. However, this was no more than an empirical estimate. Both Crane and Garriot attempted to indicate the synoptic characteristics accompanying severe snowstorms, although both studies were concerned with cyclonic storms of various origins and trajectories.

Review of literature on lake effect snows. — The localized nature of lake-effect snowfall was first noted in a published account by Henry J. Cox who reported a fall of eighteen inches on November 2, 1911, at South Bend, Indiana, while little or no snowfall was recorded at surrounding stations. 23

C. L. Mitchell, in an empirical attempt at greater understanding of the meteorological mechanics of lake-effect snows, corresponded with several vessel masters of Pere Marquette car ferries sailing between Ludington, Michigan, and Milwaukee and Manitowoc, Wisconsin. 24 Observations of the masters during west to east crossings pointed out the delicate relation between lake and air temperatures with temperature contrasts which produced steam (fog) on the west shore of the lakes generally producing snow on the east shores. These flurries began ten to twenty miles from the eastern shore.

Dole depicted for the first time the typical synoptic situation


accompanying lake-effect snows. He stated that a ripe condition for their occurrence was a strong low to the east or down the St. Lawrence Valley, with a north-south orientation of isobars over the lakes region. Dole commented on the difficulty of forecasting these snows, as they occurred with a rising barometer.

The synoptic and distributional aspects of a lake-effect snowstorm occurring at Chicago, Illinois, during December, 1935, were studied by Donnel. A rare occurrence on the west shore of the lake, Donnel recognized the narrow snowfall distributional pattern associated with this storm, and was also aware of the close relation to the gradient wind.

Brooks identified the genetic factors leading to a lake-effect snowstorm of unusually severe intensity occurring in western New York state during November 1930. The prevailing synoptic and air flow patterns were discussed, and a spell of warm bright weather which had occurred during the period immediately preceding the storm was recognized as a causation factor, as the surface temperature of the lake was raised. Lake-effect snowfalls in western New York during December 1937 were subsequently described by notation in the Bulletin of the American Meteorological Society.

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Modifications in the flow of polar continental air over Lake Erie during a four-day period when local snows were experienced on the lee shore of the Lakes were investigated by Sheridan.\(^29\) The sea-level synoptic situation associated with the continuous westerly flow over the lake was identified, and modifications occurring in the lower layers of the air were depicted by a comparison of soundings taken at Sault Ste. Marie and Buffalo during the period. Sheridan indicated the development of convective instability due to lake modification, and outlined several meteorological prerequisites necessary for the occurrence of these types of snows.

Sheridan's work was supplemented by a genetic study of winter precipitation in the western New York area by Remick.\(^30\) This study attempted to discern quantitatively the distributional aspects of lake-effect storms for one winter season in the western New York area. Remick analyzed synoptic charts for the winter and isolated the snowfall which occurred when no fronts or cyclonic disturbances were in the area, although he did not attempt to interpret the synoptic patterns or frequencies involved with either cyclonic or lake-effect storms. He examined lapse rates at Joliet, Illinois, and at Buffalo to ascertain the vertical extent of lake modification. His chart of the seasonal distribution of local snowfalls indicated some displacement inland of maximum totals, and also reflected the effect of local topography.

Wiggin discussed lake-effect snows in the western New York area

\(^{29}\)Laurence W. Sheridan, "The Influence of Lake Erie on Local Snows in Western New York," \textit{ibid.}, XXII (Dec., 1941) 393-395.

from his experience as Chief Forecaster at Buffalo, New York. He outlined the meteorological factors held tentatively by the Buffalo forecasting staff as necessary for the occurrence of local snowfalls, and listed a number of empirical observations pertinent to their occurrence. Wiggin contrasted the geographic characteristics of the Lake Erie and Lake Ontario snowbelts indicating the greater extent and seasonal persistence of the Lake Ontario belt due to the prevalence of open water throughout the winter in the lake. He noted the southwestward displacement of the Lake Erie snowbelt as winter progressed due to the formation of an ice cover in the eastern extremities of the lake. Wiggin subjectively estimated that lake-effect snows accounted for as much as 70 percent of the November snowfall in the Buffalo area, and at least 40 percent, and, possible, as much as 55 percent of all heavy snows at Buffalo throughout the winter.

The excessive snowfalls which occur on the Keweenaw Peninsula of Michigan were investigated by Eichmeier. Similar meteorological processes to those discussed by Wiggin for western New York state appeared to be in operation in the northern Michigan area. Eichmeier noted the topographic character of the peninsula and its exposure on three quadrants to winds of substantial lake fetch. He concluded that in contrast to the excessively heavy individual storms experienced in New York State, the heavy annual totals on the Keweenaw Peninsula were the result of persistent daily falls of light or moderate amounts.


Lansing described heavy lake-effect snows at the eastern end of Lake Ontario and noted the relation between the axes of the narrow distributional bands and the gradient wind. He also described the spraying effect which accompanies changes in the wind direction during periods of lake-effect snowfall.

The occurrence of fluctuating narrow cells of snowfall was further substantiated by Johnson and Mook. They investigated the synoptic wind patterns at the gradient level and the corresponding distributional effects accompanying an individual storm in the Lake Ontario region. The synoptic situation necessary for the existence of a storm of this type was identified. The shifting of the gradient wind was manifested by repeated micro-pressure troughs circulating around a great vortex of low pressure. The storm, after analysis, appeared to be four separate snowstorms, affecting different but partially overlapping regions which were determined by the direction of the gradient winds during each of the four periods. The necessary contrast between lake and air temperature and the required lapse rate through the five thousand foot level were also discussed.

Petterssen and Calabrese investigated the effect of the Great Lakes on the field of motion and on precipitation patterns during a cold spell of February 8-14, 1959. In general, the precipitation

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patterns caused by snow flurries from the Lakes revealed marked orographic influences, although a band of heavy snowfall occurred persistently over the flat plains of northern Indiana and southwestern Michigan. Evidence was produced to show that these patterns were related to non-adiabatic cooling and decrease in lapse rate of the air that moved from the open waters of Lake Michigan over the colder land.

Hodgins established "dynamic synoptic" types for the year for the Great Lakes region, and observed the effect of each type on temperature and precipitation for selected stations. Although his types were formulated for the entire year and did not include the specific synoptic conditions accompanying lake-effect storms, the increase in melted equivalent precipitation values on the lee sides of the lakes was noticeable with several prevailing synoptic types. The west to east decrease in melted equivalent precipitation over the lower peninsula of Michigan during the winter was also noted by Brunnschweiler, who compiled precipitation charts for the months of December, January, and February. Maximum winter precipitation amounts appeared concentrated in a triangle enclosed by Allegan, Paw Paw, and Kalamazoo in southwestern Michigan, and in the Traverse Bay area of northwestern Michigan.

Further observations on the nature of lake-effect snows at the


eastern end of Lake Ontario were made by Lansing,³⁸ Wiggin,³⁹ and Miller.⁴⁰ The average width, length, and inland extension of local snowstorms were established empirically by Lansing, who noted that commonly these storms appeared to be twenty to twenty-five miles wide, and extend roughly fifty miles inland. The areas of maximum snowfall ranged from fifteen to thirty miles inland from the lakeshore. The intensities of the storms were related to the length of fetch and the instability of the atmosphere, while the longitudinal axis of the storms apparently were controlled by the wind at the two thousand foot level. Lansing stated that with few exceptions, the storms occurred after the passage of a cold front. He also delineated the area most commonly affected by these storms, and indicated the need for researches to determine the impact of these storms on total amounts of winter snowfall.

The meteorological character of a snowstorm of December 28-30, 1961, at Buffalo, New York, as observed with the aid of WSR-57 radar, was described by Wiggin. The longitudinal cell of the meso-low center was observed in its formative stage, at its heaviest fallout stage, and immediately preceding its dissipation. Soundings and synoptic descriptions for the snowfall of December 29, 1961, were also introduced.

The impact of lake-effect snows on seasonal snowfall patterns in

³⁸Lansing, "Field Observations of Lake Effect Storms to the Lee of Lake Ontario," op. cit.


⁴⁰Muller, op. cit., pp. 18-25.
New York state was described by Muller. He found that the Lake Erie and Lake Ontario snowbelts were characterized by consistently deeper snowfalls than nearby areas, by a greater frequency of snowfall days, and by a complex pattern of very localized, but occasionally very intense, lake snowsqualls. These patterns suggested intimate relationships between surface features and characteristics of the lakes and lee shores, and heat, moisture and wind profiles at low levels of the atmosphere.

The distributional patterns associated with a lake-effect snowstorm at Chicago, Illinois, were discussed by Williams. The gradient wind relationship and the effects of shore alignment in the area were noted in terms of their influence on the distributional patterns.

Summary. -- The climatological impact of lake-effect snows has been indicated deductively in the literature by numerous studies of the relation between proximity to lee shores of the lakes and total annual snowfall, number of snowdays and mean snow cover. Wiggin, Remick, Sheridan, Johnson and Mook, Lansing, and Williams, have investigated the surface and upper air character of individual lake-effect storms. Petterssen and Calabrese have described macro-modifications in terms of changes in relative vorticity and pressure induced within the surface field of motion by the presence of a heat source. Associated precipitation patterns for a week-long period during which there was a continuous flow of arctic air over the lakes were also described and interpreted. The lack of a dense network of upper air soundings along

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the shores of the Great Lakes has prevented a more precise expression of the meteorological mechanics involved with lake-effect snows, and, as yet, data on the mechanical structure of these phenomena must be regarded only as indicative.

Remick has attempted to depict quantitatively and to compare distributional patterns resulting from cyclonic and lake-effect storms during a single winter season for a limited area in the Great Lakes region. No attempt was made at delineation of synoptic types occurring over the area within either broad classification. Hodgins formulated a number of weather types for the entire year for the Great Lakes area, but being based on sample months within each of the four seasons of the year, they lacked definitive acuteness for the winter season, and he was unable to depict the temporal variation in frequency and sequence as each season progressed. No attempt was made to isolate synoptic situations favorable to the occurrence of lake-effect snows, nor was there a correlation of snowfall to the defined types.

Although several subjective estimates have attempted to discern the climatological stature of lake-effect snows for specific areas, the need for a quantitative appraisal of the nature, frequency, and synoptic mechanics of these local snowfalls over a large area, involving a substantial sample period, is well indicated in the existing literature.
CHAPTER III

THE GENERAL CONTROLS OF WINTER CLIMATE

Introduction

The winter climate of the Great Lakes area mirrors the latitudinal and continental situation of the region and the relation of location to the characteristic perturbations of the atmospheric circulation, both aloft and at the surface. Secondary climatic controls are afforded by the open water surfaces of the Great Lakes. Topographic contrasts, although of relatively minor stature in determining composite climate, may be of major importance in resolving snowfall patterns within specific areas.

It is the purpose of this section to describe the chief controls of the cold season climate in the Great Lakes area imposed by temporal and spatial fluctuations of the general circulation, and to depict secondary modifications which result from the geographic structure of the area.

Effect of the General Circulation

The Great Lakes are situated within the zone of Ferrel westerlies and are dominated by westerly air flow at the surface and in the middle and upper troposphere throughout the year. However, marked seasonal contrasts in secondary flow patterns exist at the surface, and to a lesser extent, in the upper atmosphere.
Upper air circulation. — The salient characteristic of the circulation aloft over the Great Lakes and the eastern United States is the persistence in all seasons of the great meridional trough. This vortex extends equatorward over the east coast of North America from the Arctic to the lower mid-latitudes. Originally identified as an integral component of the hemispheric circulation by Rossby, the feature is statistically manifested by mean monthly charts of isobaric surfaces (700 millibar and higher) and by frequency representations. The presence of this trough has been attributed to non-adiabatic heating and baroclinic instability, although its persistence in summer is not easily understood. The quantitative relation between location and

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3. The mean position of the trough, as depicted on monthly charts, does not actually indicate frequency distributions. Mean frequencies of troughs and ridges over the eastern United States have been compiled for five day and thirty day periods by Wm. H. Klein and Jay S. Winston, "Geographical Frequency of Troughs and Ridges on Mean 700 Mb. Charts," *Monthly Weather Review*, LXXXVI (Sept., 1958), 344-358.

intensity of this circulation feature and surface weather parameters is beyond the scope of this investigation, although the relationship of abnormal circulational patterns to surface weather conditions constitutes a fertile field of meteorological research.\(^5\) Indications, however, of an existing link between mean seasonal location of the trough at the 700 millibar level and seasonal snowfall over the eastern United States have been noted by Namias,\(^6\) and the link between longitudinal location of the trough (as expressed by five day mean charts), and winter precipitation, has been investigated by Klein.\(^7\)


\(^6\)Namias, op. cit. Namias correlated seasonally averaged maps at the 700 mb level with snowfall totals for a number of cities in the eastern United States. He concluded that the increase in snowfall from the eastern Great Lakes to the Appalachians in the 1950's was associated with changes in the mean circulation aloft favoring increased marine influence and warmth along the east coast, but operating so as to increase snowfall well inland. Circulational features favorable to heavy snowfall included strong troughs over the east, with strong ridges over the west. Weaker than normal westerly circulation then prevailed (low zonal index) with cold air in the east. Associated with this pattern was steering of storms up the eastern seaboard, lighter than normal precipitation, with most of it in the form of snow. Circulational patterns conducive to snowless winters included strong troughs over the west with ridges over the Atlantic and Pacific. The eastern United States then received heavy precipitation, mostly as rain. Namias' conclusions regarding snowfall and mean circulation have been tested statistically by regression equations between consecutive monthly snowfalls by William E. Reifrynder and George M. Furnival, "Serial Correlation of Monthly Snowfall in New England," Proceedings of the Eastern Snow Conference, 18th and 19th Annual Meetings (1961-62).

Migrations in longitudinal location of meridional trough. --

Charts of mean monthly circulation at the 500 millibar level reveal contrasts in location of the trough, as well as in the latitudinal pressure gradient and isobaric surface height. Fluctuations in the mean monthly and seasonal circulation may be represented quantitatively by the construction of zonal and meridional flow indices. The difficulties of expressing the circulation mechanism by means of flow indices have been discussed in detail by Forsdyke.\(^8\) A non-mathematical expression of seasonal and monthly trough fluctuations may be obtained by representing various trough features in terms of geographic coordinates.\(^9\)

Measurements were taken from mean monthly charts for trough characteristics indicated in Table 1. The mean position of the trough for five winter months, November through March, and for a mid-summer location, is indicated in terms of these characteristics by Table 2.\(^10\)

The apex of the trough is convex to the east between latitudes 40 and 60 degrees north. Its longitudinal position in the higher latitudes is relatively stationary, drifting slowly eastward with the onset of the summer season, returning to a more westerly location during the winter. The mean November location is exceptional, being displaced westward almost to the eighty-fifth meridian.

In the lower latitudes, the longitudinal position of the trough apex is more variable. Its maximum westward extension at forty degrees


\(^10\) Trough locations are taken from mean 500 mb. charts compiled by Bryson et al., op. cit.
### TABLE 1

**TROUGH FEATURES**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Trough Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tw&lt;sub&gt;1&lt;/sub&gt;</td>
<td>amplitude of crest of trough from ridge to west at 60 N latitude</td>
</tr>
<tr>
<td>Tw&lt;sub&gt;2&lt;/sub&gt;</td>
<td>amplitude of crest of trough from ridge to west at 50 N latitude</td>
</tr>
<tr>
<td>Tw&lt;sub&gt;3&lt;/sub&gt;</td>
<td>amplitude of crest of trough from ridge to west at 40 N latitude</td>
</tr>
<tr>
<td>R&lt;sub&gt;1&lt;/sub&gt;W&lt;sub&gt;1&lt;/sub&gt;</td>
<td>longitude of crest of W. ridge at 60 N latitude</td>
</tr>
<tr>
<td>R&lt;sub&gt;2&lt;/sub&gt;W&lt;sub&gt;2&lt;/sub&gt;</td>
<td>longitude of crest of W. ridge at 50 N latitude</td>
</tr>
<tr>
<td>R&lt;sub&gt;3&lt;/sub&gt;W&lt;sub&gt;3&lt;/sub&gt;</td>
<td>longitude of crest of W. ridge at 40 N latitude</td>
</tr>
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<td>amplitude from crest of trough to ridge E at 60 N latitude</td>
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<td>amplitude from crest of trough to ridge E at 50 N latitude</td>
</tr>
<tr>
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<td>amplitude from crest of trough to ridge E at 40 N latitude</td>
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<tr>
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<td>longitude of trough crest at 40 N latitude</td>
</tr>
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### TABLE 2

**LOCATION OF TROUGH FEATURES**

<table>
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<tr>
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<td>19</td>
<td>x</td>
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<td>15</td>
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<td>15</td>
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<td>8</td>
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<tr>
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<td>10</td>
<td>8</td>
<td>11</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Re&lt;sub&gt;1&lt;/sub&gt;</td>
<td>10W</td>
<td>35E</td>
<td>5E</td>
<td>5W</td>
<td>4W</td>
<td>45E</td>
</tr>
<tr>
<td>Re&lt;sub&gt;2&lt;/sub&gt;</td>
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<td>5W</td>
<td>7W</td>
<td>15W</td>
<td>3W</td>
<td>45E</td>
</tr>
<tr>
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<td>24W</td>
<td>30W</td>
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<td>45W</td>
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<tr>
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<td>76W</td>
<td>76W</td>
<td>78W</td>
<td>72W</td>
<td>69W</td>
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<tr>
<td>T&lt;sub&gt;2&lt;/sub&gt;</td>
<td>86W</td>
<td>71W</td>
<td>72W</td>
<td>73W</td>
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<td>85W</td>
<td>95W</td>
<td>70W</td>
<td>72W</td>
<td>76W</td>
</tr>
</tbody>
</table>
north latitude is during January. In February, however, it is located off the east coast of North America. In summary, the mean location of the trough apex is thus east of the Great Lakes, except during November in the higher latitudes, and in January in the lower latitudes.

Both the amplitude and wave-length of the trough vary according to a seasonal pattern. Amplitude increases with the onset of the winter season at all latitudes, reaching maximum values during January and February. Fluctuations in wave length do not exhibit easily discernible patterns. The crest of the ridge to the west of the trough drifts slowly westward, reaching maximum displacement during January in the high latitudes, and in March in the middle latitudes. The crest of the easterly ridge does not exhibit progressive fluctuations. In general, however, its maximum eastward displacement is during the winter.

Frequency of troughs and ridges over the Great Lakes during the winter season. — Frequency charts for troughs and ridges at the 700 millibar level over the United States have been compiled for mean five- and thirty-day periods by Klein and Winston.¹¹ The high trough frequency over the east coast in all months except November corresponds to the mean location of the trough, while the November minimum is in accordance with the westward shift of the trough during that month. Peak trough frequencies also occur over the Mississippi Valley and the Plains states during the winter months. These troughs are

¹¹Klein and Winston, op. cit.
orographically induced. Eastward, in the central United States, the frequency of five-day mean troughs is somewhat greater than that of thirty-day mean troughs because of the tendency of troughs on the shorter period mean maps to develop in the lee of the Rockies, move rapidly eastward, and deepen near the east coast.

Trough and ridge frequencies over Michigan at the 700 millibar level were abstracted from mean frequency charts for the years 1947-1955 (five day means), and 1933-1955 (thirty day means). These are shown by Table 3.

**TABLE 3**

PERCENT OF TIME THAT TROUGHS OR RIDGES WERE LOCATED WITHIN 10 DEGREE LONGITUDE INTERVALS OF LATITUDES WITHIN THE GREAT LAKES AREA FOR THE MONTH AND PERIOD OF RECORD INDICATED

<table>
<thead>
<tr>
<th>Month</th>
<th>Troughs 5 day</th>
<th>Troughs 30 day</th>
<th>Ridges 5 day</th>
<th>Ridges 30 day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>15-20</td>
<td>15-20</td>
<td>5-10</td>
<td>0-10</td>
</tr>
<tr>
<td>Feb.</td>
<td>15-20</td>
<td>20-30</td>
<td>5-10</td>
<td>0-10</td>
</tr>
<tr>
<td>Mar.</td>
<td>15-20</td>
<td>10-20</td>
<td>5-10</td>
<td>0-10</td>
</tr>
<tr>
<td>July</td>
<td>10-15</td>
<td>0-10</td>
<td>15-20</td>
<td>0-10</td>
</tr>
<tr>
<td>Oct.</td>
<td>15-20</td>
<td>10-20</td>
<td>15-20</td>
<td>10-20</td>
</tr>
<tr>
<td>Nov.</td>
<td>25-30</td>
<td>30-40</td>
<td>5-10</td>
<td>0-10</td>
</tr>
<tr>
<td>Dec.</td>
<td>10-15</td>
<td>10-20</td>
<td>5-10</td>
<td>0-10</td>
</tr>
</tbody>
</table>

In general, troughs are more frequent during winter months and ridges more frequent in summer. The high November frequency is

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associated with the westward displacement of the mean trough. This high frequency is indicated for both five and thirty day mean periods. Otherwise, only minor variations occur during the winter season, with the exception of a high trough frequency in February.

**Variations in circulation intensity.** The speedup in circulation over the Great Lakes with the onset of winter is evidenced by changes in height differences of the mean monthly 500 millibar surface, measured at latitudes forty and sixty north along the eighty-fifth meridian (Fig. 1).

**FIGURE 1**

**HEIGHT DIFFERENCES OF MEAN MONTHLY 500 MB. SURFACE BETWEEN LATITUDES 40 AND 60N ALONG 85th MERIDIAN**

This speedup culminates in January, with a height contrast of 1650 feet. Circulation intensity decreases rapidly in the spring—(March 1300 ft., April 900 ft.), with little subsequent variation occurring during the summer months. Accompanying the increase in intensity is a general lowering of the pressure surfaces (Table 4).
Average monthly heights along the 85th meridian for the winter months were abstracted for latitude intersections at forty, forty-five, fifty, and sixty degrees north latitude. Lowest heights are attained in February for all latitudes, greatest heights during the summer months. The height differential increases toward the polar regions, attaining 1700 feet at sixty north latitude and 1100 feet at forty north latitude.

Variation in location and intensity of maximum westerly wind component. -- Table 5 indicates fluctuations in location and intensity of

### TABLE 4

**MEAN HEIGHTS OF 500 MB. SURFACE ALONG EIGHTY-FIFTH MERIDIAN**

(Hundreds of feet)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>40°</td>
<td>183</td>
<td>181</td>
<td>182</td>
<td>181</td>
<td>182</td>
<td>184</td>
<td>192</td>
</tr>
<tr>
<td>45°</td>
<td>179</td>
<td>176</td>
<td>177</td>
<td>176</td>
<td>180</td>
<td>182</td>
<td>190</td>
</tr>
<tr>
<td>50°</td>
<td>176</td>
<td>174</td>
<td>172</td>
<td>172</td>
<td>175</td>
<td>179</td>
<td>188</td>
</tr>
<tr>
<td>60°</td>
<td>172</td>
<td>169</td>
<td>165</td>
<td>165</td>
<td>171</td>
<td>174</td>
<td>182</td>
</tr>
</tbody>
</table>

### TABLE 5

**LOCATION AND SPEED OF AVERAGE MAXIMUM WEST-ERLY WIND COMPONENT - 500 MB. SURFACE**

<table>
<thead>
<tr>
<th>Month</th>
<th>Location of closed isotach</th>
<th>Orientation of axis of closed isotach, degrees east of north</th>
<th>Speed over Michigan (meters per sec)</th>
<th>Direction over Michigan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov.</td>
<td>39° 84°</td>
<td>70°</td>
<td>22</td>
<td>270°</td>
</tr>
<tr>
<td>Dec.</td>
<td>39° 74°</td>
<td>75°</td>
<td>26</td>
<td>300°</td>
</tr>
<tr>
<td>Jan.</td>
<td>42° 72°</td>
<td>70°</td>
<td>28</td>
<td>280°</td>
</tr>
<tr>
<td>Feb.</td>
<td>37° 75°</td>
<td>85°</td>
<td>26</td>
<td>300°</td>
</tr>
<tr>
<td>Mar.</td>
<td>35° 75°</td>
<td>90°</td>
<td>24</td>
<td>290°</td>
</tr>
<tr>
<td>April</td>
<td>40° 65°</td>
<td>90°</td>
<td>20</td>
<td>290°</td>
</tr>
<tr>
<td>May</td>
<td>44° 64°</td>
<td>85°</td>
<td>16</td>
<td>290°</td>
</tr>
<tr>
<td>June</td>
<td>47° 70°</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aug.</td>
<td>50° 50°</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
the maximum westerly wind component at the 500 millibar level (upper air polar front and jet stream) over the eastern United States during the winter season.\(^\text{13}\)

The center of the innermost closed isotach (jet axis) is off the east coast except during November when it moves far inland in conjunction with the interior displacement of the trough. The generalized progression during the winter season, however, is toward a more westerly location, accompanied by a slow equatorward migration. Maximum southerly position is attained in March (with the jet off the southeast coast of the United States). Westerly air flow at the 500 mb. level over Michigan attains greatest velocity during January, declining rapidly during April and May. Following a quick northward movement in April and May, by August the jet is located off the east coast of Labrador, with much reduced speed. Its seasonal migration brings it over the Lakes area during October on its southward migration, and during April on its northward shift.

**Summary of upper air circulation controls.** — The circulatory speedup accompanying changes in location and intensity of the meridional trough reaches a maximum in January over the Great Lakes. Latitudinal contrasts in the location of the maximum westerly wind component (jet stream) result in mean positions south of the Lakes during most of the winter, with maximum displacement in February and March. In its seasonal migration, the polar front is positioned over Michigan in

October and April. Frequency counts of troughs and ridges over the region indicate the dominance of trough situations, particularly when expressed in terms of five day means.

**Major features of surface circulational controls.** -- The Great Lakes region is positioned at a col between four major action centers. These centers are indicated by mean monthly charts of surface pressure distribution and include the Icelandic and Aleutian vortices and the North Atlantic and North Pacific highs. During the winter, the build-up of surface high pressure over northwestern Canada also becomes a major factor. The peripheral location of the Lakes region in relation to these features subjects it to weather changes accompanying the expansion and contraction or shift in location of one or more of these centers.

An examination of mean monthly charts of sea level pressure distribution discloses changes in location and intensity of these controls. During the winter, the Lakes region is marginal in location between the Azores High with a continental extension over Georgia, the continental high over northwest Canada which attains its maximum build-up during February, and the strong Icelandic vortex off the southeast coast of Greenland. This latter feature is most intense in January. Northwesterly air flow persists over the Lakes region. With the onset of spring, the Icelandic low weakens and moves westward to a position over the Davis Strait, while the Azores high intensifies and moves westward. By mid-summer, the Icelandic low is practically non-existent. In conjunction with the westward extension of the Azores High

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1\textsuperscript{4} U.S. Weather Bureau Technical Paper No. 21, op. cit.
over the Southeastern United States, and the disappearance of the con-
tinental high pressure area of northwestern Canada, a west-south-westerly
air flow is maintained over the Lakes region. In autumn, the Icelandic
vortex intensifies, moving eastward during November and December, while
high pressure appears once more at the surface over the interior of
northern Canada.

Representations of mean monthly positions of these centers of
action conceal the erratic short term fluctuations in their location
and intensity. Information, concerning mean five day pressures over the
Lakes area, and mean five day locations and intensities of the major
pressure controls, was abstracted from Northern Hemisphere Charts com-
piled by Lahey, Bryson, and Wahl.¹⁵

A comparison of mean summer and winter pressures over the Lakes
area shows only minor contrasts. Mean pressure slowly rises during the
winter season reaching maximum values during the latter two weeks of
January and the first week of February. Pressure readings during this
period averaged 1019.5 millibars. This pressure peak corresponds to
the maximum build-up and southward extension of the continental high
over northwestern Canada. The slow downward trend in pressure, subse-
quent to these dates, is marked by a rapid drop from the five day period
March 7-11 to the five day period March 12-16. At this time, a corres-
ponding rise in pressure of the Icelandic low can be noted as well as a
marked decrease in pressure over northwestern Canada. Similar rapid
changes in location and intensity of the Icelandic low during the winter

Normal Sea-level Pressure Charts for the Northern Hemisphere, Scientific
season appear singular when viewed within the framework of otherwise minor fluctuations over short term periods. Perhaps most conspicuous is the rapid deepening of the Icelandic vortex in mid-November and the quick movement of the center of the low eastward off the southeast coast of Greenland.¹⁶

Migratory pressure systems. — Representations of surface circulational features in terms of their mean monthly character fail to portray the impact of migratory and transitory cyclones and anticyclones. The fundamental role played by these atmospheric phenomena in terms of heat and moisture transfer and eddy transport of momentum has been emphasized by students of the general circulation. The influence of the Great Lakes on preferred tracks of moving surface pressure centers has been discussed by Cox.¹⁷ In terms of winter precipitation, the frequency and temporal variation of cyclones and anticyclones must be regarded as inherent genetic factors within the basic circulational structure. In addition, the frequency of pressure systems crossing the Great Lakes area is pertinent in relation to prevailing synoptic weather types. These types, as defined in Chapter IV, take their characteristics in part from certain repeatable trajectories of air flow or of surface pressure phenomena.

¹⁶The relationship of sudden changes in location of these pressure centers to weather singularities has been examined by R. A. Bryson, J. F. Lahey, The March of Seasons, Final Report, Contract AF 19 (604)-992. Dept. of Meteorology, University of Wisconsin (March, 1958).

¹⁷H. J. Cox, "The Influence of the Great Lakes upon the Movement of High and Low Pressure Areas," Proceedings of the Second Pan-American Scientific Congress, Vol. II, Section II (Washington: 1917), 432-459. Cox emphasized the attraction and steering control exhibited by heat sources such as the Great Lakes on cyclones during the winter, and the attraction of high pressure areas during summer, when the Lakes are cooler than the land.
Numerous studies have investigated the frequency and preferential tracks of migratory pressure systems over North America. Most of these have approached the problem by tabulating numbers of cyclones or anticyclones crossing designated grid boxes during specified time periods, although the classic study by Bowie and Weightman categorized pressure system crossings by their synoptic characteristics, as did an earlier investigation by Van Cleef.

Cyclone and anticyclone frequencies for the Lakes region were abstracted from frequency charts compiled from forty years of the Historical Map Series (January 1, 1899, to December 31, 1938). Frequencies were tabulated for five degree squares of latitude and longitude. Grid sub-divisions for the Lakes area and monthly frequencies of cyclones and anticyclones for these zones are indicated by Figure 2.

Cyclone frequency increases to the north within the region during all seasons of the year. August usually has fewest cyclones (sub-region A excepted), and maximum frequencies occur during December in sub-region B, in January in subregions A and C, and in March and April in subregion D. A secondary peak in most areas during March and April

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18 For an historical review of investigations of cyclone and anticyclone tracks and frequencies see William H. Klein, Principal Tracks and Mean Frequencies of Cyclones and Anticyclones in the Northern Hemisphere, U.S. Weather Bureau Research Paper No. 40.


21 Klein, Principal Tracks and Mean Frequencies of Cyclones and Anticyclones in the Northern Hemisphere, op. cit.
FIGURE 2

FREQUENCY OF ANTICYCLONES BY GRID SUBDIVISIONS
(AFTER KLEIN)
40 YEAR PERIOD

FREQUENCY OF CYCLONES BY GRID SUBDIVISIONS
(AFTER KLEIN)
40 YEAR PERIOD
corresponds to the northward progression of the polar front with the onset of the spring season. Northern subregions are visited by almost twice the number of cyclones as are the southern subregions during late fall and early winter (Oct. - Dec.). However, the disparity is reduced to a minimum during the late winter months. Low cyclone frequencies in July and August correspond to the northward shift in circulation and location of the axis of the hemispheric wind belt at fifty degrees north latitude in August, farther north than during any other month (Table 5). Cyclones, at this time, are infrequent in the United States but very frequent in central Canada. The southward swing of this storm track encroaches subregion A and accounts for the unusual frequency of low pressure centers there during that month. By October, the main belt of westerlies normally begins to move south accompanied by an increase in cyclonic activity. In November, high cyclone frequencies in subregions A and B are caused by a convergence of storm tracks of Alberta and Colorado lows, while the dominant paths of these storms are to the north of subregions C and D. During January, passage of Alberta lows gives peak frequencies to all but region B, while in February the upper air westerlies reach their maximum speed and the center of cyclonic activity is displaced southward over the United States with a peak of cyclogenesis off the east coast of Florida. This is the month of maximum cyclone frequency in the Gulf of Mexico. In conjunction with the southward displacement of the westerlies, February is characterized by depressions in the frequency curves for both western subregions. March is a transition month with near equal

\[22\textit{Ibid.}, \text{p. } 13.\]  \[23\textit{Ibid.}, \text{p. } 12.\]
frequency in all four subregions and an increase over February in the westerly areas. This frequency remains high during April in line with the continued low latitude of the jet stream and its movement northward at this time (Table 5). Insolation heating of the continental land surface then reverses the local temperature gradient in the Great Lakes area and the frequency of cyclonic action decreases in May and June.

Some indication of the origin and genesis of these cyclonic systems may be gained from the work of Bowie and Weightman, although their study dealt with a restricted time period. The cyclones were divided into nine types, according to origin, and frequency tabulations were made for similar five degree squares of latitude and longitude. The number of cyclones, having their origins in Alberta and traveling the familiar storm track across southern Canada and the northern sections of the United States, nearly exceeded the total of all other types identified in each zone. The increase in total frequency of cyclones in northern areas of the Great Lakes was due to location in the paths of these cyclones, although the Alberta low was also the most frequent type in southern subregions. This type is most frequent in subregions A and B during December and January, and frequencies drop rapidly in February and March with the southward displacement of the belt of maximum westerly winds. In subregions B and C, Alberta cyclones are only half as frequent as those in subregions A and B and a peak is attained during the early spring months.

As the winter season progresses, the frequency of cyclones increases, reaching a peak in northern areas during December and January.

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24 Bowie and Weightman, op. cit.
and in southern sections during January, February and March. The increased number of cyclones observed in northern areas may be attributed to closer proximity to tracks of Alberta cyclones. This type of storm has a maximum frequency during December and January, in the north, and then falls off rapidly during the late winter and early spring months with the southward migration of the polar front.

Anticyclones. — It might be expected that anticyclonic frequencies would exhibit characteristics inversely related to cyclone frequencies. In general, peak frequencies are reached in all subregions during the late summer and minimum frequencies occur during the mid-winter months. Because of the size and extent of the anticyclone, in comparison to the cyclone, contrasts in frequencies of anticyclones from subregion to subregion do not exist (Fig. 2). Frequency values for migratory highs over the area do not correspond to average monthly pressure trends (p. 50). The distinct minimum of anticyclonic activity, over the Great Lakes during the entire cold season, may be attributed to the effect of the warm surface water in inducing cyclonic vorticity. Most anticyclones, during the cold months of the year, form in northwestern Canada where anticyclonic frequency is greater in January than in any other time of the year. From this area, the polar highs travel southeastward, into a center of maximum anticyclonic frequency over the Dakotas, and then take a cyclonically curved path through the Missouri and Ohio Valleys to contribute to a zone of high frequency in the Middle Atlantic States. The polar highs which do not take a track to the south of the Lakes usually pass north of the area. These are

25Klein, Principal Tracks and Mean Frequencies of Cyclones and Anticyclones in the Northern Hemisphere, op. cit., Chart 13.
referred to as "glancing highs," which slip across southern Canada and Northern New England when strong westerlies prevent them from plunging southward.  

Frequencies of migratory highs over the Lakes remain low until April and May when the warm waters of the Lakes operate to increase the occurrence of cyclonic vorticity, thus forming a primary cyclone track through the area. During the summer months, the primary track of anticyclones in the United States passes across the Great Lakes where it is joined by another track consisting of polar highs from western Hudson Bay.

Summary of general circulation controls. -- The circulation at the upper levels over the Great Lakes region is dominated by the great meridional trough, which although located semi-permanently over the eastern United States, exhibits seasonal and temporal changes in amplitude, intensity, and location. The belt of maximum westerly component at the upper levels (jet stream) migrates southward reaching its greatest extension toward the tropics during February.

The Icelandic low, the Atlantic high, and the Continental High over northwestern Canada are mean controls of surface pressure phenomena. Weather changes resulting from expansion, contraction, or changes in location of these mean features are more realistically associated with migratory highs or lows. The frequency of highs and lows is strongly influenced by the presence of the Lakes as heat sources during the winter and cold sources during the summer. The area is thus characterized by a very high frequency of cyclones during the winter season, and low

frequencies of anticyclones, with the opposite pattern during the sum-
mer. This southward migration of the jet during the winter is mani-
fested at the surface by a decrease in the number of low pressure areas
affecting the more northerly regions of the lakes, and an increase in
the number of lows affecting the southern sections.

Secondary Climatic Controls - Effects of the Great Lakes

Although the dominant climatic controls of the Lakes region are
latitude and the perturbations within the general circulation, secondary
controls imposed by the marine influence of the Lakes are particularly
marked. These influences reach the components of the general circula-
tion itself by the attraction property of the Lakes for cyclones dur-
ing the winter season. The effect of these water bodies on the clima-
tology of winter snowfall is the subject of this investigation, and
modifications pertinent to the occurrence of snowfall will be discussed
in the following sections. It should be recognized, however, that the
influence of the Lakes is of considerable importance in affecting the
distribution of other observed weather elements in the Lakes area.27

Fluctuations in mean surface temperatures.— Modifications im-
parted by these water surfaces function throughout the winter as a
continuous ice cover seldom if ever forms, except over shallow Lake Erie.

March of Air Temperature in the Vicinity," Papers of the Michigan Acad-
emy of Science, Arts, and Letters, XXVII (1941), 377-414. Stanley A.
Changnon, "Precipitation Contrasts between the Chicago Urban Area and
Soc., XLII (Jan., 1961), 17-23. John E. Pearson, "The Influence of
Kresge, "Indications of the Uniformity of Shore and Off-Shore Precipi-
tation for Southern Lake Michigan," Journal of Applied Meteorology,
I (June, 1962), 271-274.
The surface temperatures and circulational patterns of the Lakes, and their changing seasonal character, have been the subject of several recent studies.\(^\text{28}\) The average surface temperatures of the Lakes are shown for the months of October, December, and April by Figure 3. Other factors besides latitudinal contrasts which affect the variation of surface water temperature include the depth of the lakes and the direction of the currents. Lake Superior, the deepest and at the same time the most northerly of the Lakes, has the lowest surface temperatures. Lake Erie, the shallowest and most southerly lake, has the highest temperatures. Cyclonic circulations are in evidence in Lakes Michigan, Superior, and Huron, resulting in the accumulation of warm surface waters in the southeastern portions and upwelling of cold waters along the northwestern shores. This gives rise to relatively cold waters in these sections during the warming period and during the early cooling period until the surface water has been cooled to the temperature of the bottom water.

The lag in the warming and cooling rate of the water surface in comparison with the adjacent land is the most critical factor as far as modification of the climate of the area is concerned. Observations were made of surface temperatures in the middle of Lake Michigan as represented by thermometers placed at the intakes of engine condensers on car ferries operating between Milwaukee and Ludington.\(^\text{29}\) Surface


FIGURE 3

MEAN GREAT LAKES SURFACE TEMPERATURES
(after Millor)
temperatures evidenced a pronounced lag during the spring warm-up period, and did not go above 40 degrees until after June first. In the fall, however, the water cooled almost as rapidly as the land until mid-October when the water began to cool more slowly than the land. By early December, an average disparity of thirteen degrees existed. Surface temperatures then fell slowly from means of forty-two degrees in early December to thirty-six degrees in late February and March. By April, the land temperature again became higher than the water temperature.

The greatest surface temperature contrasts thus exist from late October to January and from late April to late June. These contrasts increase with latitude. December surface temperatures in Lake Superior average 38 degrees, affording greater contrasts with temperatures of surrounding shores than do the surface temperatures of Lake Michigan (only two degrees higher than Lake Superior).

Modifications of polar air masses. — The heat and moisture exchange from the lake surface into over-passing Arctic air between Green Bay and Ludington was calculated by Willett to extend upward to the two and one-half kilometer level. Temperature increases of ten degrees centigrade and moisture increases from a normal 0.5 gr. to 2.0 gms. were involved. During a cold air outburst of March 16-19, 1941, comparisons of soundings, taken at Sault St. Marie and Buffalo, indicated modifications extending to four kilometers. Both temperature


31 Sheridan, op. cit., p. 393.
and specific humidity increased in passage over the lakes. Equivalent potential temperature increased with elevation before passing over the Lakes and decreased with elevation after crossing the lakes, indicating development of convective instability.

Burbridge, in investigating the modification of polar continental air during passage over Hudson Bay, recognized the meteorological variables involved. These included the original temperature, the water temperature, the original lapse rate, the length of fetch over the water, and dynamic factors. The flux of heat and water vapor from the warm water surface theoretically would rapidly modify the air, creating a superadiabatic lapse rate in the lower layers, dry adiabatic above the turbulent layer to the condensation level, and saturated adiabatic until equivalent conditions were reached in the stable continental polar air above. Radiosonde observations examined by Burbridge tended to substantiate these theoretical modifications.

Further substantiation of these theoretical modifications was furnished by fifty-four ship soundings taken during cold polar air outbreaks in the Atlantic Ocean off the east coast of the United States. During the transformation of the air, lapse rates approaching the dry adiabat were observed to the level of condensation above a turbulence zone extending upward to a height of fifteen meters. Saturated adiabatic lapse rates were observed to the limit of convection.

Along with the basic exchange processes leading to the addition of heat and moisture in the lower layers of cold polar air, certain

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32Burbridge, op. cit.

dynamic modifications of the field of motion are induced by these water surfaces. The modifications of the frictional layer by the change in surface characteristics encountered by air moving from a relatively rough land area over the smooth surface of the lake may be of climatological significance. This frictional change in the lower layers results in increased velocity and a directional change toward the gradient wind. A piling up of air at the opposite shore occurs where friction again slows the air motion and once more broadens the angle between the surface and gradient wind. The height of the layer of frictional influence has been found to be directly proportional to the wind velocity at the anemometer level and inversely proportional to the sine of the latitude.\textsuperscript{34}

Mesoscale circulational changes also result from the addition of heat in the lower atmospheric layers. With surface heating, the air undergoes a decrease in density. This density decrease results in an increase of speed and Coriolis force. The observed effect is to increase the angle between both the surface lake and land wind, and the gradient lake and land wind, thus supplementing frictional effects.

The heat exchange involved in a theoretical model has been examined by George and would operate to create a thermal circulation in the upper air, with a reversal of flow along the right side and an enormous increase along the left side.\textsuperscript{35} When the speed of the airflow reached


a given value, a tendency would be present for the creation of pseudofronts, parallel to the direction of the main air stream, and for the development of a shallow thermal cyclone. The geographic and meteorological conditions involved in actual air passage over the Lakes create marked differences in the observed modifications. George however, concluded that a marked increase in surface wind velocities in the right portion of the lee shore of the Lakes was discernible and that it was probable that an increase in velocity at the top of the convective layer is found to the downwind left of large warm lakes, and a decrease to the right. The observed results of these modifications may vary from lapse rate steepening to the creation of pseudo-fronts and thermal cyclones.

The dynamic effect of heat transfer from the Lakes, at the synoptic or macro-level, is manifested by modifications of the pressure field during cold spells of considerable intensity. These modifications include development of cyclonic vorticity and a decrease of sea level pressure. These effects appear to be due entirely to differential heating and are separate from modifications involving frictional and orographic factors. The pilot investigation by Petterssen and Calabrese suggested that the maximum relative vorticity that can be produced during a prolonged cold spell is likely to be checked by frictional dissipation before a value of $1 \times 10^{-4} \text{ sec}^{-1}$ is reached and that the largest drop in sea-level pressure from the rim to the center of the low-pressure system is unlikely to exceed about six or seven mb.

Summary. -- The effects of the Lakes on atmospheric properties

\[^{36}\text{Petterssen and Calabrese, op. cit.}\]
during the winter may be summarized as follows: (1) influences at the synoptic level including controls of motions and paths of weather systems and modifications of the circulational field (these factors are reflected in attraction of low pressure areas during the winter, by creation of a region of cyclogenesis over the Lakes, and by the development of cyclonic vorticity and lowering of sea level pressure in overpassing Arctic air), and (2) meso-level or regional modifications including heat and moisture transference and changes in air motion because of frictional effects. Conditions favorable for the production of snowfall resulting from these modifications include steepening of the lapse rate, raising of the inversion, addition of moisture, convergence on lee shores, and the formation of thermal cyclones and pseudo-fronts under given conditions. Lack of a detailed sounding net surrounding the Lakes renders these factors chiefly theoretical, although measurements taken during cold air outbreaks tend to substantiate them.

Recognition of theoretical factors, plus empirical observations, has led Wiggin to summarize the meteorological prerequisites involved in the creation of lake-effect snows. These include large temperature differentials and long fetch in order to produce a lapse rate of dry adiabatic or greater up to 5000 ft. in the polar continental air, cyclonic curvature of the air flow, and a favorable shear aloft to increase the possibility of forming longitudinal thermal convection cells. Observations by Wiggin and his staff indicated that a 20 degree temperature differential was most favorable for the occurrence of the

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foregoing. Anticyclonic curvature may produce brief blinding falls of snow but no great snowfalls. With a marked shear of the wind aloft, only a few flurries develop. With a favorable shear aloft, a longitudinal cell may form which can perpetuate itself for hours, varying in width from three to five miles and extending inland for fifteen miles or more.

**Topographic Controls**

Topographic contrasts in the Great Lakes area are minimal and the effects of terrain on composite climate are small. However, snowfall distributional patterns are rather strongly influenced by landform arrangement, particularly where terrain obstacles lie athwart air streams which have crossed lake surfaces. Cold air, laden with moisture acquired from the surface of the lakes, needs only a slight rise to lower temperatures below the dew point, with condensation and instability snow showers resulting.

The effects of local topography on the distribution of snowfall in New York State have been pointed out by Muller and empirical formulae have been devised relating seasonal snowfall totals to altitude for the Southern Appalachians and New England. In New York, the terrain factor was enhanced by proximity to the lakes. Muller found that snowfall increased much more rapidly with elevation on the Tug Hill plateau,

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38 Muller, *op. cit.*

exposed to winds having considerable fetch over Lake Ontario, than in
the Adirondacks, protected from winds blowing directly off the lakes.
Terrain description will be confined here to the peninsulas of Michigan,
the region for which the synoptic analysis was formulated, with the
purpose of depicting elevated areas which may become terrain controls
for the distribution of snowfall.

Figure 4 indicates the chief features of the surface configura-
tion of the upper and lower peninsulas of Michigan by means of general-
ized two-hundred foot contours. Elevated areas in southern Michigan
occur within an elongated zone approximately one hundred miles in
length, extending from the Michigan-Ohio border northeastward to the
lower thumb area. This is an area of glacial deposition, and included
within the region are the Irish Hills of southeastern Michigan and the
Pontiac Hills of eastern Michigan. Elevations are nowhere great, ex-
ceeding 1100 ft. at several scattered points in the Pontiac area and
in the Irish Hills.

The valleys of the Grand and Saginaw rivers bisect south-central
lower Michigan and substantial areas of low elevation are located at the
mouths of both rivers. Northward from the Grand-Saginaw col, elevations
increase gradually to the high plains of north-central Michigan, cul-
minating in a node located to the east of the Grand Traverse Bay which
encompasses a considerable area of outwash plain over 1300 ft. in ele-
vation. A second node, of near equal elevation, occurs in the Cadillac
region. In both instances, ascent to these higher areas is marked by

40 Abstracted from Topographic Map of Southern Peninsula of Mich-
igan (1956), and Topographic Map of Northern Peninsula of Michigan
(1957), compiled by James M. Campbell, Geological Survey Division,
Department of Conservation, State of Michigan.
FIGURE 4

RELIEF OF MICHIGAN

ELEVATION IN FEET
rather steep west-facing scarps which lie athwart west and northwest winds of substantial lake fetch. The more northerly of the highland areas lies closer to the lake, and the fetch of northwest and west winds is augmented by the configuration of the shore line which swings inland and to the east in the Traverse Bay area. A third area of relatively high relief is located just to the north of Little Traverse Bay in Emmet County, where sand dunes border the lake and present a steep escarpment on the west facing slope.

In the Upper Peninsula, the higher elevations are determined by exposures of pre-Paleozoic rocks in the western half of the area. The linear trend of ancient volcanic rocks along the south shore of Lake Superior, from the Wisconsin border to the tip of the Keweenaw Peninsula, culminates in the high plateau and mountain ranges of the Keweenaw Peninsula where elevations exceed 1800 ft. at several points. Abrupt rises from the Lake Superior shore to the plateau occur on the west, north, and east, and in places the land rises over 1000 ft. above the lake within a horizontal distance of several miles. Another abrupt scarp is also presented by the Porcupine Mountains, to the southwest, where an elevation of 2000 ft. is exceeded within three miles of Lake Superior.

Toward the interior of the western half of the Upper Peninsula, elevation increases on the Superior Upland, and a plateau along the Wisconsin-Michigan border encompasses a large area over 1600 feet above sea level. A northward extension of this upland includes the Huron Mountains to the west and north of Marquette, with elevations above 1600 feet. This region is exposed to NE winds but is protected by the Keweenaw highlands from winds from the west and the north.
The eastern half of the Upper Peninsula is underlain by Paleozoic rocks, mantled by glacial materials, and exhibits much less vertical relief. Eastward from Marquette, the drainage divide is within ten or twenty miles of the Lake Superior shore, and an east-west ridge, exceeding 800 ft. in elevation, extends parallel to the shoreline.

The configuration and relief of the Michigan Peninsula, although of relatively small dimensions, in several instances afford rather substantial rises to air currents of lake fetch. These are most noticeable along the Lake Superior shore in the western part of the Upper peninsula, particularly on the Keweenaw Peninsula, where an area of high elevation is exposed to winds of lake fetch from several quadrants. In the lower peninsula, highland areas to the east and south of Grand Traverse Bay offer obstacles to west and northwest winds blowing off Lake Michigan. The highland areas in the southeastern part of the state are some distance from the lake. However, it may be expected that they exert some influence on the distribution of snowfall.
CHAPTER IV

THE WINTER WEATHER TYPES

Method of Analysis

Introduction. — The atmospheric and terrestrial controls in the Great Lakes area combine to create the infinite variety of weather responses which collectively constitute the winter climate of the region. An examination of the controls, however, does not make it possible to express the climate of the region, nor to determine the degree to which each of the controls may individually influence the climate.

Climatic descriptions in the Great Lakes area, for the most part, have been confined to static representations. Objections to static depictions have been voiced in the first chapter, and were raised years ago by both Henry and Ward. It will be the chief purpose of this


section to describe the winter weather of the area in terms of characteristic weather types based on repeatable circulational patterns.

Static climatology also fails to convey the precise effect of individual weather controls on the resultant climate. In this study, concerned primarily with the effect of geographic controls on the distribution of a single weather element, the utilization of static climatology may create an implicit assumption that geographic controls interact equally with each and every atmospheric arrangement. The meteorological mechanics involved with heat and moisture transfer processes from the lakes appear to refute this assumption. However, it may be equally erroneous to assume that geographic controls interact with a very limited number of atmospheric situations. The truth is suspected to lie somewhere between the two extremes—a particularly marked and sharp imposition of geographic controls with certain atmospheric situations and lesser, although still viable, interactions with other types. In both cases, whether to obtain a more realistic description of climate, or to ascertain the role of a climatic control in weather genesis, a summary of weather needs to be made in reference to the prevailing atmospheric conditions of the region.

**Synoptic climatology.** — Synoptic climatology involves the classification of circulational patterns either on a large or secondary scale. Most synoptic classifications in the past have been used for two purposes: (1) for identification of the prevailing circulational patterns and depiction of these by means of frequency diagrams and probability analysis, which in turn provide the basis for future prediction of circulational patterns (in most cases the associated element complex has been disregarded or relegated to a position of secondary importance),
(2) for correlation of the related weather element, but with the

element expressed as a prediction factor, or a probability based upon

the momentary atmospheric state. The climatology of weather accom­
panying circulational patterns has been largely overlooked, although

recently there has been renewed interest in weather element distri­
bution occurring with synoptic types. These studies become, in essence,

Cf. U.S. Weather Bureau, Office of Forecast Development, Clima­
tological Snowfall Patterns and the Synoptic Climatology of Precipita­
tion of Winter Storms in the Central United States, Heavy Snow Project, Part I, Manuscript of the U.S. Weather Bureau (1962), 33 pp.; H. K.
Saylor and E. B. Fawcett, "A Study of the Distribution of Weather Accom­
panying Colorado Cyclogenesis" (unpublished paper given at the Annual
Meeting of the American Geophysical Union in Joint Session with American
Meteorological Society, Washington, D.C., April 22, 1964); Donald L.
Jorgensen, "A Computer Derived Synoptic Climatology of Precipitation
from Winter Storms," Journal of Applied Meteorology, II (April, 1963),
227-234; Roger G. Barry, op. cit.; idem, "A Note on the Synoptic Cli­
matology of Labrador-Ungava," Royal Meteorological Society, Quarterly
Journal, LXXXVI (Oct., 1960), 557-565; Clarence A. Carpenter, "The
Relation Between Cloudiness Over the Greenland Icecap and Synoptic
Weather Types," Bulletin, American Meteorological Society, XLI (Feb.,
1960), 68-78; P. Pedelaborde and H. Delannoy, "Recherches sur les Types
de Temp et le Mecanisme des Plieus en Algerie," Annales de Geographie,
LXVII (May-June, 1958), 216-244; Homer W. Hiser, "Type Distributions
of Precipitation at Selected Stations in Illinois," Transactions, Amer­
ican Geophysical Union, XXXVII (Aug., 1956), 421-424; Phil Williams Jr.
and Eugene L. Peck, "Terrain Influences on Precipitation in the Inter­
mountain West as Related to Synoptic Situations," Journal of Applied
Meteorology, I (Sept., 1962), 343-347; D. L. Farnham and R. C. Gould,
Weather Patterns and Local Forecasting at the Naval Ordnance Test Sta­
tion, China Lake, California, Naval Ordnance Report 5267 (USNOTS, China
Lake, 1956), 36 pp.; Nina Zikeen, Surface Temperature Regime in Green­
land, U.S. Weather Bureau Contract DA 3-99-00-500, Quarterly Report
(July, 1960), 53-95; Charles Ray Dickson, Synoptic Climatology of Diurnal
Inversions in the Jordan Valley, Utah, Contract DA 19-129-399,
Technical Report No. 2, University of Utah, Dept. of Meteorology (Aug.,
1957), 82 pp. No attempt is made to list all the recent studies at­
tempting to correlate surface weather to circulation patterns. Only
articles and publications appearing in the more accessible literature
were consulted and are cited. A check of the authoritative Meteorolog­
ical and Geoastrophysical Abstract for the past five or six years in­
dicated an active interest by foreign meteorologists and climatologists,
particularly in the Soviet Union and Eastern European areas, in synoptic
studies. Most of these were read only in abstract form, and have not
been listed. Earlier studies, although not plentiful by any means, are
Problems of synoptic climatologies. -- The problems inherent in utilization of synoptic classifications are numerous. The advantages appear, however, to be paramount. The typical atmospheric patterns may be identified and investigated, and correlations between the weather complex, or a weather element, may be made. The problem of a selection basis for the synoptic types has presented one of the biggest obstacles to utilization of synoptic climatology, and the literature is replete with classification schemes and methods.

Classification of synoptic types. -- Practically all synoptic classifications involve some aspect of the pressure distribution. As the pressure pattern is a changing entity and no two patterns are the same, the problem is one of expression of certain characteristics of the pressure field and categorizing these according to similar types. These characteristics may consist of the arrangement of the dominant highs and lows (and, hence, an effort is made to describe the pressure pattern itself), or they may be derived characteristics, such as the gradient wind, which may be expressed more objectively.

Classifications based upon interpretations of the entire pressure field usually involve some degree of subjectivity. A purely objective method of expressing pressure distribution, however, has been developed

listed in the footnotes accompanying the studies by Court, op. cit., Hare, op. cit., and Calef, op. cit. The realization of the significance and potential of the synoptic approach to both meteorological and climatological research, and of the value of electronic data processing equipment along these lines, was expressed by Mr. Saylor in his recent paper (see above footnote).

For a detailed discussion of these problems, cf. Wesley Calef, op. cit.
by Wadsworth \(^5\) and utilized by the Massachusetts Institute of Technology school of synoptic meteorology. \(^6\) The sea level pressure is approximated by a linear combination of Tschebyscheff orthogonal polynomials. The coefficients of the polynomials are used as circulation indices, and the surface weather related to these indices through the use of a linear operator. These studies have been used chiefly in the prediction and specification of several weather elements while the climatological aspects have been largely overlooked. Several shortcomings of these numerical specification methods as means of analysis of the pressure field have been outlined by Horn, Essenwanger, and Bryson. \(^7\) The advantages of these purely objective classification schemes are that statistical analysis can be undertaken from the objective and numerical values obtained. The disadvantages are that numerical values may fail to depict the salient aspects of the synoptic field, and that several arrangements of the pressure field may approximate similar numerical values. It was not felt that these purely objective methods of classification would be suitable for this study, nor that utilization of numerical specification procedures would meaningfully express varying atmospheric conditions over the area.


Objective criteria may more easily be applied to derived values than to the entire pressure field. On this basis, Jacobs abandoned attempts to classify the large scale aspects of pressure distribution and concentrated on a manifestation of the circulation over a limited area. Jacobs used the gradient wind, which could be represented by means of a single vector, and thus formulated an objective genetic climatology which would be amenable to computations aided by high speed electronic computers. It was felt, however, that for purposes of this study, partial manifestations of the pressure field, although more objectively defined, would not be sufficient to represent adequately the totalities and vagaries of the winter circulation. It was also felt that these could not be definitive enough to isolate effectively genetic situations leading to contrasting snowfall distributional patterns.

Synoptic classification schemes involving various degrees of subjectivity have been rather numerous. Basically, two classification methods have been utilized. First, classifications can be based on the pattern of air flow over the region either at the surface, or in the upper levels. With this approach, the character of the air flow over the area is primary. However, the pressure patterns determining the air flow are also interpreted in the analysis. This attempt to relate to large scale circulational features contrasts this approach with more objective methods based upon the gradient wind, or some other derived value. The air flow patterns may be classed according to a

8W. C. Jacobs, op. cit.
directional characteristic, or by the trajectory of the flow.¹

Synoptic classifications based on air flow analysis are effectively utilized for the upper atmosphere where the pressure pattern and air motions are more stable. They may also be utilized with the surface chart to characterize periods of stable air flow which are dominant in most regions. They may fail, however, to represent accurately atmospheric conditions associated with rapidly moving pressure systems, where air flow at the surface level changes with rapidity. In regions where rapidly moving fronts and pressure systems are the rule and not the exception, some means of representing periods of perturbed flow are imperative. This difficulty of generalizing the effects of frontal passages with air flow classification schemes reduces their value in unstable areas. The frequency of cyclonic and frontal passage in the Great Lakes area, plus the direct association of winter precipitation with cyclones and fronts, made it undesirable to utilize a system derived strictly from air flow parameters in this study.

Secondly, classification schemes may be based on the locations of dominant high and low pressure areas, either migratory or semi-permanent. These may categorize mean pressure over large areas with

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correlations of short term weather to the mean circulation of the same period, or classify pressure patterns over smaller areas, with efforts at relating weather on a day to day basis to the pressure patterns. Classifications over smaller areas may be related to an arbitrarily selected moment (for example, the synoptic time of the weather chart), or relate to the mobile nature of the salient features of the weather chart (in other words the origin and trajectory of the pressure systems and their directional attributes in relation to the selected region).  

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The advantages of classifying momentary pressure patterns include the ease of utilization of single synoptic charts, and the feasibility of introducing quantitative measurements or guide-lines into the classification. The disadvantage of this method is apparent, as the classification indicates circulational patterns only for an arbitrarily selected moment, while atmospheric patterns are constantly changing. In other words, the instantaneous synoptic feature does not adequately represent the direction or degree of change which the synoptic map is undergoing.

The trajectory method of analysis has the advantage of representing a synoptic continuum which is dominated by the movement of a salient feature or features in relation to a particular region. It has the advantage of representing in terms of generalities the effects of frontal passages and cyclonic passages, although these representations must be in mean terms unless precise and intricate measurements of the intensity, and proximity of passage of the cyclone or front, are introduced. Introduction of more precise measuring techniques, in turn, complicates the classification. A disadvantage of utilizing trajectories of systems is inherent in the need for using more than one synoptic chart, and extending the analysis into the future and the past.

Basis of selection of weather types. -- The method of classification of weather types used in the present investigation posed a number
of problems. First, the classification should convey in meaningful descriptive terms the discrete atmospheric arrangements which occur over and around the area during the winter season, thus expressing the totality of winter weather by means of characteristic circulational symbols. Second, the classification should be definitive of circulational patterns with which snowfall may occur, thus necessitating the need for recognition of several atmospheric situations which may give rise to somewhat similar element-complexes. Third, the necessary subjectivity must be kept at a minimum.

It was decided that a synthesis of classification methods would most effectively fulfill these requirements. Perturbed situations caused by fast moving pressure centers and fronts were felt to be best indicated by plotting the origin and trajectories of these systems and generalizing the effects of vortex and frontal passage. More stable circulational types appeared to be most easily represented by the static location of the dominant highs and lows. It was also felt that the surface weather chart would be most representative of circulational patterns in an area where numerous fronts and cyclones occur, although the link of the surface chart to the upper atmosphere is obvious.

With these criteria in mind, a subjective survey of weather charts was made for each day of the five year period. The commonly occurring atmospheric patterns were identified, and the surface weather associated with these patterns was checked by day to day references to Climatological Data, Michigan.

Discrete surface weather complexes occurred with many of the circulational types. It became apparent, however, that snowfall was
associated with a rather large number of situations, although the dis-
tributional patterns varied widely. Theoretically, these situations
might range from those resulting in heavy snowfall at all stations, to
those causing light snowfall at one or a few stations. The actual
variation fell well within the extremes.

After the synoptic types were identified, quantitative guide-
lines were introduced (see Appendix C) and each day during the five-
year period was classified with the aid of these guidelines and with-
out reference to the weather complex. Ten sub-regions were designated
within the state to aid in the classification where two or more types
might prevail at the same time, and the classification was made in
reference to each of these (see Appendix A). Certain derived values
such as wind direction, frontal passage, and air mass type were also
extracted from the weather chart. Procedure for entry of these values
on IBM punch cards is described in Appendix B.

The Weather Types

Weather days were classified basically as Cyclonic, Anticyclonic,
or Westerly Flow. Cyclonic types occurred with pressures below 1016
mbs. and with cyclonic curvature of isobars over the region. Cyclonic
situations were subdivided into nine subtypes. These were distin-
guished according to the origin and trajectory of the salient pressure
system in relation to the area.

Anticyclonic types occurred with pressures above 1016 mbs. and
straight alignment or anticyclonic curvature of the isobars. The anti-
cyclonic types were divided into five subtypes according to the
location and nature of the dominant anticyclone at the synoptic time of the weather map.

Westerly flow types were associated with post-cold frontal situations, or developed in the rear quadrants of passing cyclones. These types were distinguished from anticyclonic types in that cyclonic isobar curvature occurred at all times over the area. Pressure was variable. Westerly flow types were distinguished according to the location of the major pressure centers at the synoptic time of the weather chart, and four subtypes were identified.

Cyclonic Types

Northwestern Cyclonic (NW), and Northwestern Cyclonic, southern passage (NWs). -- These circulational types occur chiefly with zonal flow at the 500 mb. level, or with expanded amplitude of the eastern North American trough. The surface synoptic features occurring with the Northwestern Cyclonic type include initial appearance of the salient low in western Canada and subsequent trajectory and passage north of the region (Figure 5). This trajectory corresponds to the well defined path taken by "Alberta" cyclones identified by Bowie and Weightman. The weather sequence over the area is dominated by a southerly flow of air. Both warm and cold front passage may occur with this type, and, northward toward the center of the moving vortex, occlusion is common. Warm fronts may be rather indistinct, as marked temperature contrasts usually do not occur in varying quadrants of the cyclone. The warm fronts may become stationary to the north, or over the northern sections.
of the area. Cold front passage commonly occurs following movement of the low to the north and east of the region. The alignment of the surface cold front may form a trough-like arrangement, and the front is frequently connected to another vortex centered on the Canadian plains.

The weather effects with this type are amplified in the higher latitudes closer to the cyclone path. Surface winds are commonly south-east as the low approaches, veering to the southwest or west after passage of the cold front. The cyclones responsible for this weather type frequently occur in families. They are usually rather weakly developed and contain little moisture.

The Northwestern Cyclonic, southern passage type occurs when the salient cyclone passes south of the region (Figure 6). The surface weather sequence is dissimilar to that of the Northwestern Cyclonic type. Frontal passages are lacking, and surface winds are generally from an easterly quadrant, backing to the northwest as the low moves on to the east. In northern areas, where these types are more common, the center of the low is usually close by, and the weather sequence may be accompanied by moderate precipitation, although this type usually does not result in severe weather or heavy precipitation.

With both of these types, a vortex at the 500 mb. level commonly occurs over northeastern Canada. Occasionally, two vortices may be present, one over Labrador, and one over western Hudson Bay.

*Western Cyclonic (W), and Western Cyclonic, southern passage (Ws).* These types usually are accompanied by low zonal index conditions. Strong troughs are generally present over the western states, with ridges over the eastern United States. The ridge apex is displaced
westward toward the Great Lakes. Western Cyclonic types occur when low pressure areas over the central part of the nation follow subsequent trajectories north of the region (Figure 7). These cyclones are frequently well developed, and the weather sequence in the region is characterized by southerly air flow, occasionally consisting of maritime tropical air from the Gulf of Mexico. Mid-winter thaws or mild periods are likely to occur with this circulational pattern, particularly in southern sections. Both warm and cold front passage are common. Shifting of surface winds to a westerly direction occurs after cold front passage, and Arctic incursions may follow. Disturbed weather, and rather high moisture content aloft may accompany this type.

The Western Cyclonic, southern passage type may occur with expanded trough amplitude, or with the trough apex displaced eastward. The cyclonic center responsible for this type moves almost directly eastward, and passes south of the region (Figure 8). Frontal passages at the surface are lacking, and winds from an easterly quadrant predominate, backing to north or northwest. cP or cA air masses occur at the surface with cold temperatures. Considerable precipitation may be associated with this pattern.

Southwest Cyclonic SW, and Southwest Cyclonic, southern passage (SWs). -- These synoptic types occur with low zonal index conditions. Deep troughs are usually present over the west central United States, with ridges over the eastern states. The ridge apex is generally off the east coast, and the trough apex slightly eastward from the front of the Rockies. With these upper air characteristics, lows develop over the western Gulf area and are steered northeastward toward the Great Lakes. The Southwest type occurs when the center of the low passes
north of the region (Figure 9). Frontal passage occurs, and mT air may be advected into the warm sector of the cyclone. Surface winds may initially be northeast or east, usually veering to the south as the warm front passes. Abundant moisture may accompany this type, with thaws and warm temperatures. The Southwestern type, southern passage (Figure 10) occurs when the center of the low passes south of the region. Severe weather may result. However frontal passages are lacking. cP or cA air masses occur at the surface, and wind patterns are easterly or northeasterly, backing to north or northwest. Heavy precipitation frequently occurs with this type, and falling temperatures usually follow movement of the storm center to the east and northeast.

**Gulf Type Cyclonic (G).** -- This type is associated with the movement of a cyclone along the Gulf Coast. Cyclonic curvature associated with the vortex extends northward into the Lakes region, although the center of the low remains far to the south (Figure 11). Considerable moisture may be advected aloft with this type. Upper air circulational patterns usually include deep troughs over the eastern United States. Surface wind direction is most frequently north or northeast. Polar or Arctic air occurs at the surface with this sequence, and frontal passage is lacking.

**Troughs (T).** -- All troughs and indistinct pressure patterns were placed in this category if cyclonic curvature was present and sea level pressures were below 1016 mbs. (Figure 12) These situations were usually associated with high zonal index. Frontal passage may or may not occur with this type, and surface wind directions and characteristics vary considerably.
Hudson Bay Cyclonic (HB). — This type occurs with strong cyclones moving southeastward over the Hudson Bay - Ungava area (Figure 13). Cyclonic curvature extends southwestward into the Lakes area, maintaining a strong westerly flow over the Lakes. Frequently, a cold front extends southwestward from the center of the vortex to the Lakes region. Air flow south of the front may be southwesterly, and north of the front, northwesterly. Upper air circulational patterns usually include ridges over the western states and troughs over the east.

Westerly Flow Types

Westerly Flow, modified (WFm). — Westerly Flow modified situations involve a westerly flow of Arctic air over the area. Strong cyclones generally are present off the east coast, with an anticyclone over the northern or central plains (Figure 14). The center of the low may be as far south as Virginia, or as far north as the Gulf of St. Lawrence, and its location appears to control the gradient wind direction as well as the distance of lake fetch. Heat supplied by the lakes results in the formation of a trough which extends to the rear of the low. Isobar curvature is cyclonic over the area, although pressures are above 1016 mbs. The most common upper air pattern includes a trough over the eastern United States, with a ridge in the west. Frequently, a closed low develops at the 500 mb. level over the Great Lakes.

This type is associated with cold wintry weather and strong west to northwest winds. The coldest weather of the season may occur with this circulational pattern, and below zero readings are common.

Westerly Flow (WF). — This type develops under similar synoptic conditions as WFm. However the flow of air across the Lakes is
unmodified because of warmth of the air mass (Figure 15). Westerly Flow situations are more frequent during early and late winter when Arctic air masses have not attained severe temperatures. They may also occur during midwinter under weak or zonal upper air circulation, when incursions of Arctic air do not occur. Pressures are above 1016 mbs., although cyclonic curvature is at all times present.

Westerly Flow Cyclonic (WFC). -- These types involve post-cold front situations, or westerly flow to the rear of passing cyclones. Pressures remain below 1016 mbs. and cyclonic curvature of isobars is present over the area (Figure 16). This type is preceded by one of the cyclonic types.

Westerly Flow, Cyclonic modified (WFCm). -- These situations occur when strong outbursts of Arctic air occur on the heels of low pressure areas moving through the area (Figure 17). Synoptic requirements are similar to those for WFC, with the exception that the air to the rear of the low is of Arctic origin and actively modified by the lakes. Strong high pressure cells are often present over the central and northern plains. Upper air patterns include troughs over the central United States, and ridges over the west.

Anticyclonic Types

Central Anticyclonic (CA). -- This situation occurs with an anticyclone positioned directly over the Great Lakes area (Figure 18). Clear skies, and light air movement generally are associated with this type. Because of the function of the Lakes as heat sources, this pattern does not develop frequently.

Western Anticyclone (WA). -- Western Anticyclonic types are asso-
ciated with well developed high pressure cells over the northern or central plains area (Figure 19). Westerly air flow predominates over the Lakes area, and anticyclonic isobar curvature associated with the anticyclone extends eastward into the region. Pressures, as with all the anticyclonic types, remain above 1016 mb. This weather type is likely to be preceded by a Westerly Flow type.

**Northern Anticyclone (NA).** — The Northern Anticyclonic type results from positioning of a high pressure cell over Ontario or Quebec, with resultant extension of anticyclonic curvature into the Lakes region (Figure 20). These high pressure cells are the "glancing highs" referred to in the previous chapter. Air flow over the Lakes area is generally from an easterly quadrant. Clear skies and cold temperatures are the most common weather combination.

**Southern Anticyclone (SA).** — This circulational type results from an anticyclone positioned over the southeastern part of the United States (Figure 21). Air flow over the Lakes area is southerly or southwesterly, importing warmer temperatures and generally mild winter weather. The salient high pressure cell may stagnate resulting in a weather sequence of several days duration with this type. Spells of fine weather during the winter frequently are associated with this circulational type.

**Ridge (R).** — All ridges or indistinct pressure patterns involving anticyclonic curvature and pressures above 1016 mbs. are put into this category (Figure 22).

**Synoptic Type Frequencies**

Frequency tabulations of individual weather types were made for each subdivision during the five year period (Table 6). Cyclonic types
occurred most frequently in all subdivisions. The variation in the number of occurrences of Cyclonic types from subregion to subregion was inconsequential. Mean five month frequencies ranged from 72 days (or approximately 46 per cent of the total possible days) in the West Central Lower Peninsula subregion, to 74 days in the Upper Peninsula subregions. The apparent lack of corroboration of the tendency for increasing cyclonic frequency northward over the Lakes area noted by Klein is due to contrasts in specificati on methods (Klein tabulated frequencies of cyclonic crossings, involving smaller areas, while the present study is concerned with cyclonic synoptic types, affecting larger regions). \(^{13}\)

Anticyclonic types occurred on fewer days than Cyclonic types, but were more frequent than Westerly Flow situations. Total frequencies of Anticyclonic types showed little variation within the region. Anticyclones occurred on an average of 45 days during the five month winter season in the southern Lower Peninsula and on 47 days in the Upper Peninsula.

Westerly Flow types averaged 32 occurrences during the winter in southern subregions, and 30 occurrences in the West Upper Peninsula subdivision.

Cyclonic types. -- The frequency of occurrence of Cyclonic subtypes indicated decided contrasts from type to type and subregion to subregion. The Northwestern Cyclonic situation (NW) was the most frequent of the Cyclonic types and also of all individual synoptic

\(^{13}\)W. F. Klein, Principal Tracks and Mean Frequencies of Cyclones and Anticyclones in the Northern Hemisphere, op. cit.
types. This type occurred with near equal frequency throughout the area, averaging 18 to 19 occurrences during the five month period.

**TABLE 6**

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(Rounded to nearest whole day)

Troughs were second in frequency among the Cyclonic types. Trough frequency increased toward the north (trough frequency in the West Upper Peninsula subdivision averaged 17 days during the winter period, while troughs in the East Lower Peninsula subregion occurred on an average of only 14 days).

Southwest Cyclonic, southern passage (SWs) types showed considerable frequency variation throughout the state. They were more common in the south, in subregions closer to the typical paths of Gulf Coast lows, as the circulational characteristics attending these lows usually do not extend a great distance poleward from the vortex center. This type averaged 13 occurrences during the five month period in the East
Lower Peninsula division. In the West Upper Peninsula, the type was less common, with 9 mean occurrences.

The frequency of Western Cyclonic (W) types also decreased toward the north. This type occurs on the equatorward side of low pressure centers developing on the western plains. The mean path of these cyclones is directly through the Lakes region, producing dissimilar weather types in northern and southern areas with the Western Cyclonic, southern passage (Ws) type occurring north of the storm track. Western Cyclonic types occurred on an average of 9 days in the South West Lower Peninsula. They averaged only 5 days occurrence in the Upper Peninsula subdivisions. Ws types occurred 12 times during an average winter in the West Upper Peninsula. In the southern part of the Lower Peninsula, they occurred about 8 times a winter.

Other cyclonic types occurred less frequently. Hudson Bay types (HB) occurred on an average of 5 days in all subdivisions. Southwestern Cyclonic types (SW) were most frequent in the south and east sections of the Lower Peninsula. Frequencies of this type decreased to the north and west, with the West Upper Peninsula subdivision averaging less than one occurrence per year.

The Northwestern Cyclonic, southern passage (NWs) type was very infrequent in southern subdivisions, but increased in frequency toward the north. The West Upper Peninsula subdivision averaged about 6 occurrences of this type during the year. Gulf Cyclonic (G) types were infrequent, occurring once each year on the average in all subdivisions.

\[1^4\] H. K. Saylor and E. B. Fawcett, op. cit. The paths and weather characteristics for 27 spring storms originating in the Colorado area were charted and expressed in mean terms.
Although total occurrences of all Cyclonic types showed little variation within the region, there were decided contrasts in the frequency of individual types, and also in the frequency of occurrence of these types by subregion. Five Cyclonic types, NW, W, Ws, SWs, and T, occurred frequently. The G, HE, NWs, and SW types were less frequent. The frequency of NWs, W, WS, SWs and SW types varied with location within the area, indicating that the mean paths of the salient lows for several Cyclonic patterns were directly across the region.

Westerly Flow types. -- The Westerly Flow modified (WFm) type was by far the most frequent of the Westerly Flow situations. This type was experienced on an average of 15 days during the winter. There was little variability from subregion to subregion in the frequency of this type. Westerly Flow (WF) types occurred on from 4 to 7 days per year. Westerly Flow Cyclonic (WFC) types averaged 7 days occurrence and Westerly Flow Cyclonic modified (WFCm) types occurred 3 days per year.

Anticyclonic types. -- A frequency breakdown of Anticyclonic types was made for subregion South West Lower Peninsula only. Ridges (R) were most frequent with 13 average yearly occurrences. Southern Anticyclonic types (SA) occurred on an average of 12 days. Western Anticyclonic types (WA) averaged 10 days occurrence. Northern Anticyclones (NA) occurred on 8 days, while Central Anticyclones (CA) occurred on only 3 days.

Summary of total weather type frequencies. -- Cyclonic types exceeded all other types in frequency in every subdivision, while the Northwestern Cyclonic type was the most frequent of the individual types.
Other frequently occurring types included Wm, Wa, SA, T, SWS, W, and Ws. CA, WFCm, WF, G, HB, and NWS types occurred infrequently.

**Temporal Contrasts in Synoptic Type Frequencies**

Frequency tabulations of synoptic types for consecutive fifteen day intervals, November through March, were made for two subregions, South East Lower Peninsula (SELP) and West Upper Peninsula (WUP). The effect of latitudinal and longitudinal contrasts within the area on synoptic frequencies was thought to be best indicated by a comparison of these subregions, located respectively near the southeastern and northwestern peripheries.

**Cyclonic and Anticyclonic types.** -- Cyclonic types were more frequent during early winter in the northern subdivision, exceeding those in the southern subdivision until the second bi-week period in January (see Table 7). Peak frequencies occurred during the second bi-week periods of November and December. During late winter, Cyclonic types were more frequent in the South East Lower Peninsula. The decrease in frequency of Cyclonic types in the West Upper Peninsula with the progression of winter corresponds to the southward shift of the jet stream which reaches maximum equatorward displacement in late February. This southward migration of the polar front is also accompanied by intensification and expansion of the Northwest Canada anticyclone. Frequencies of Anticyclonic types in the West Upper Peninsula increased slowly during February, and exhibited a rapid increase in late March.

In the South East Lower Peninsula, frequencies of Cyclonic types remained more stable throughout the year and failed to reflect the mid-winter decline evidenced in the north. Peak frequencies for
TABLE 7

FREQUENCY OF SYNOPTIC TYPES BY 15 DAY CONSECUTIVE INTERVALS

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Cyclonic types occurred during the second bi-week period in December. Anticyclonic types decreased in frequency during November, as they did in the northern area, but no substantial frequency increase was noted until March. Throughout the latter part of winter, after January first, Anticyclonic types were more frequent in the West Upper Peninsula, reflecting greater proximity of this area to the northwest Canada anticyclone, its more continental location, and positioning of the polar front over the southeastern states.

Westerly Flow types. — Frequencies of Westerly Flow types exhibited little contrast between subdivisions. Maximum frequencies occurred during midwinter months when anticyclonic types were infrequent. The frequencies decreased in both subregions after mid-February, primarily because of a drop-off in occurrences of the most common Westerly Flow type, WFm. As lake temperatures reached minimum values, and outbreaks of Arctic air began to lose their intensity, the cyclonic curvature necessary for this type was not so easily produced.

Individual Synoptic types. — The NW type, the most commonly occurring synoptic pattern in both subregions, did not exhibit marked areal contrasts in frequency. The disparity in Alberta cyclone frequencies between northern and southern Lakes areas detected by Bowie and Weightman does not occur when the cyclone is manifested as a weather type. In the West Upper Peninsula, the greatest frequency of this type occurred during the first bi-week period of November. The apparent decrease during the latter part of November is compensated by an increase in frequency of the reciprocal, NWs. In both subregions, however, a marked decrease in frequency of NW types was experienced after the first
bi-week period of January. This decrease corresponds to the southward shift of the polar front.

Troughs, partially because of their diffuse nature and the large areal extent of this type, showed little frequency contrast between subregions. They were most frequent during the second bi-week period in January, and had minimum frequencies in February, and in early November.

SWs types decreased in frequency in the West Upper Peninsula after the second bi-week period in December, and remained infrequent in this subregion until the latter part of February. The period of peak frequency of this type in the South East Lower Peninsula corresponded to the period of minimum frequency in the West Upper Peninsula. During this period a decrease in occurrences of NW and W types and an increase in Westerly Flow types was also observed for the West Upper Peninsula. Apparently, a discernible southward shift of the westerlies took place during the latter part of January, accounting for this tendency.

Westerly Cyclonic types showed little significant variation throughout the five month period. More frequent in the South East Lower Peninsula, this type had peak frequencies during the second bi-week period of November. Ws types were more frequent in the West Upper Peninsula and did not occur during the first half of December in the South East Lower Peninsula. Peak frequencies of this type occurred in both subregions during the latter halves of December and February.

Hudson Bay and Gulf Types showed little frequency variation throughout the season.
WFm types were infrequent during November, when incursions of Arctic air were uncommon. The frequency of this type increased rapidly in early December, and again in late January and early February, when peak frequencies occurred. After mid-February, the frequency of WFm types declined steadily as Arctic air became less frequent. Westerly Flow types were more frequent in both areas during early and late winter, and had minimum frequencies during the mid-winter.

Westerly Flow, Cyclonic types showed smaller variations. The unmodified type was most prevalent during early winter, when high cyclonic frequencies occurred, and had minimum frequencies in mid-winter, when Arctic air masses followed closely on the heels of cyclones moving through the area. The modified type was, accordingly, most frequent during the midwinter period.

**Summary.** -- Distinct variations in the frequencies of several types were observed during the five-month period. Occurrences of Cyclonic types declined in the northern subregion after the second bi-week period of January, with concomitant increase in Anticyclonic types. In both subregions, the frequencies of Anticyclonic types were highest in early November and in late March. NW types were relatively infrequent after mid-January, and WFm types infrequent in November and March. SWs types were most frequent in late winter in the south, although this was the period of minimum frequency in the north.

**Sequence Probabilities**

These synoptic types have, of necessity, been based on arbitrary time units because of the desire to correlate weather information, and the availability of weather data for twenty-four hour periods. Hence
the circulation field, a constantly changing entity controlled by non-periodic functions, has been confined within artificially imposed time boundaries.

Analysis of the probable or likely sequence arrangement of the types, and the temporal persistence of individual types, results in an expansion of this artificial time concept beyond the twenty-four hour unit in the direction of the "Weatherclimatology" of Schuepp\(^{15}\) and the "Grosswetterlage" of Baur.\(^{16}\) These weather situations are of longer durations, and more closely correspond to the natural breakpoints which actually characterize atmospheric circulation.

In an attempt to discern "broad scale" atmospheric combinations over the region, sequence computations were made of individual types for all subdivisions. Over 25,000 arithmetical operations were accomplished in less than ten minutes of computer time. The synoptic type sequences were then expressed in terms of probability of occurrence, using empirical percentages. These probabilities are not random, as synoptic situations are not random, but are based at least partially on pre-existing situations. Simple probability statements may be derived as to the likelihood of a future circulational pattern occurring, given the present pattern. Weather complex prognostication, however, must be based on the assumption that discrete weather complexes occur with discrete circulational patterns, and this assumption remains a subject of investigation.

\(^{15}\)Max Schuepp, "Klassifikationsschema, Beispiele und Probleme der Alpenwetterstatistik," Meteorologie, IV (1957) 291-299. Schuepp makes the distinction between weather, the momentary state, and Weather, or the prevailing atmospheric state for several days duration.

\(^{16}\)Franz Baur, op. cit.
Analysis of results. -- Only an analysis of results is presented here as the machine printout entailed thirteen pages of data. Sub-regions South East Lower Peninsula and West Upper Peninsula, in contrasting quadrants of the area, were again the subject of the analysis. Probabilities were tabulated and ranked in descending order. They are presented in Table 8 for subregion South East Lower Peninsula, and in Table 9 for West Upper Peninsula. Only the higher probability values have been listed.

<table>
<thead>
<tr>
<th>Probability of a two day synoptic sequence initiated by X synoptic type</th>
<th>Probability of two day synoptic sequences</th>
<th>Probability of synoptic type X persisting for a second day</th>
</tr>
</thead>
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TABLE 9
SYNOPTIC SEQUENCES, WUP SUBREGION

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<th>Probability of a two day synoptic sequence initiated by X synoptic type</th>
<th>Probability of two day synoptic sequences</th>
<th>Probability of Synoptic type X persisting for a second day</th>
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Column one of Tables 8 and 9 indicates the probability of a random two-day sequence beginning with X synoptic type, or simply the percentage of occurrence of X synoptic type. These values have been previously discussed.

The probabilities of occurrences of specific two-day weather sequences are indicated in column two of Tables 8 and 9. These probabilities are expressed in terms of the total number of days. In both sub-regions, the highest probabilities involve continuity of similar types. WFM-WFM sequences have the highest probabilities (.0442 in West Upper
Peninsula, .0496 in South East Lower Peninsula) indicating not only the relative frequency of this type, but also its likelihood of persisting for more than one day. The high persistence of this type reflects its construction, involving homogeneous Arctic air flowing eastward over the Lakes toward a strong, slow moving low off the east coast.

Trough-Trough sequences also have high probabilities in both subregions. The persistence of this type from day to day reflects the circulational slowup under which these diffuse or ill-defined types exist. Other high-probability sequences include NW - NW types, and NA - NA types. The persistence of the NW-NW sequence can be explained by the widespread weather response in advance of the storm, and also by the tendency for these types to occur in cycles - i.e. a series of weak depressions will move quickly along the Canadian border resulting in several consecutive days with this synoptic type. The NA types are the "glancing highs" cited by Klein, which move north of the Lakes area and then into northeastern United States. WS-WS sequences have high probabilities in the northern area, while SWs-SWs sequences are frequent in the southern subregion.

The highest probabilities of two day sequences involving non-homogeneous types include T-NW in the West Upper Peninsula, and SWs-WFm in South East Lower Peninsula. Other non-homogeneous sequences of high probability include R-NW, NW-R, and WFm-T in the northern subregion, and SA-NW, NW-W, and R-NW in the south. Only the sequences with higher probabilities were tabulated.

Column three of Tables 8 and 9 indicates the probability that X-synoptic type, occurring on a given day, will persist for a second day.
Very high persistence probabilities were indicated, in both subregions, for two commonly occurring types, NA and WFm. The probability of an NA day being followed by a NA day is .4705 in the north, and .3846 in the south. The probability of a WFm day being followed by another WFm day is .4400 in the northern subregion, and .4625 in the southern subregion. The persistence tendency of both these types has been explained above.

Lowest persistence probability in both subregions was evidenced by the CA type. This type never occurred on two consecutive days. This fact is indicative not only of the low frequency of occurrence of the type, but of the tendency of cyclonic vorticity induced by the Lakes to dissipate anticyclones, and to negate stagnation tendencies. Low-persistence factors were also indicated for Westerly Cyclonic Flow types. These types occurred to the rear of passing cyclones, and were, by construction, temporary and transitional in nature.

Summary. -- Probabilities of occurrence of two-day synoptic sequences have been investigated in an attempt to outline tendencies toward "Grosswetterlage," or large scale weather patterns. As the daily synoptic type is at least partially determined by precedent weather, the sequence probabilities are not random, but reflect the proclivity of given types to develop from pre-existing patterns.

Greatest probabilities of two-day sequences involved homogeneous types. The probability of a random day being preceded by a similar type was in most cases higher than the probability of it being preceded by a non-similar type. Of the more common types, particularly high persistence values were indicated for WFm and NWs in the north and for WFm
and Troughs in the south. In each case, an inclination toward a Grosswetterlage characteristic is indicated.
CHAPTER V

THE CLIMATOLOGY OF WINTER SNOWFALL

The Effect of Lake Proximity When Viewed Within Static Parameters

The mean annual snowfall. -- Some appreciation of the effect of the lakes on the distribution of snowfall in Michigan is forthcoming when snowfall characteristics are viewed within the confines of static climatological methods. The significance of interrelations of temperature, relief, and exposure to winds of lake fetch are well exemplified by maps of annual and monthly mean snowfall. These charts were constructed from data of 153 first order and cooperative stations of the United States Weather Bureau for the period 1931-1960. The fact that most snowfall gages are located near settled areas, which are likely to be in valleys or lower lying sections, means that the relationship between relief and actual snowfall will not always be accurately measured by gage catches. Problems of exposure are accentuated along lake shores, where non-shielded gages are likely to show consistently low catches. With these considerations in mind, the isarithms were drawn on a contour base, and were subjectively interpolated in specific areas where the influence of topography was abnormally strong.

Data for this period were summarized by the United States Weather Bureau and are available at the East Lansing Office. The chart of mean annual snowfall has been slightly modified from one published by the Michigan Weather Service, cooperating with the Weather Bureau.
The chart of mean annual snowfall, Figure 23, indicates that latitudinal controls are only partially evinced and the role of geographic factors, exposure to winds of lake fetch, and highland areas athwart airstreams which have crossed lake surfaces, is strongly reflected.

The smallest annual totals, less than 30 inches, occur in the extreme southeastern counties of the state, over the flat glacial lacustrine plains near the western end of Lake Erie. Maximum amounts occur in the Upper Peninsula along the shore of Lake Superior, where portions of the Keweenaw Peninsula receive more than 180 inches annually. In general, the snowfall increases with latitude. The gradation is far from uniform, however, the geographical factors strongly modifying the general latitudinal trends. A break in this gradation develops over northern sectors of Lake Michigan. Maximum totals of over 100 inches occur in the highland areas to the south and east of Grand Traverse Bay in Lower Michigan, while in the Upper Peninsula, along the north shore of Lake Michigan, the yearly totals range from 50 to 60 inches.

It is apparent that the effect of lake proximity is reflected by a north-south orientation of isarithms in the southern and western

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2 The effect of geographic factors on mean annual snowfall in the Lower Peninsula was represented statistically by a multiple correlation involving three independent variables - altitude, latitude, and lake proximity. The quantitative expression for lake proximity was computed by means of a formula involving vector representation of lake fetch. The multiple correlation coefficient was .77, the partial correlation coefficients for altitude, lake proximity, and latitude were .24, .46, and .66, respectively. T test values for the partial correlations were 2.1, 4.4, and 7.7.
FIGURE 23

MEAN ANNUAL SNOWFALL - inches

FIGURE 24

SNOWBELTS OF THE GREAT LAKES
1. WEST UPPER PENINSULA - KEWEENAW
2. EAST UPPER PENINSULA
3. TRAVERSE BAY HIGHLAND
4. WESTERN LOWER PENINSULA
5. LAKE HURON
6. ONTARIO - LAKE SUPERIOR
7. GEORGIAN BAY
8. LAKE ERIE
9. LAKE ONTARIO
parts of the Lower Peninsula paralleling the Lake Michigan shore line, and by the occurrence of "snowbelts," or zones of relatively heavy snow, on the lee shores of Lakes Michigan and Superior. Similar snowbelts developing on the lee shores of all the Great Lakes are identified by Figure 24. The Michigan snowbelts are characterized by high mean annual totals, and are delineated by extremely steep gradients as evidenced by the close spacing of isarithms around them. The belts are situated within 30 miles of the lake shore, and where rough topography is combined with lake proximity their acuteness is accentuated.

The snowbelts. — The West Upper Peninsula-Keweenaw snowbelt is an attenuated zone of extremely heavy snowfall extending from the Wisconsin border to the tip of the Keweenaw Peninsula. Here the highest mean annual totals in the state occur, and the region has one of the heaviest annual snowfalls east of the Rockies. The location and orientation of this belt are dictated by its proximity to Lake Superior, and by the northeast-southwest alignment of the shore line, normal to northwest winds which have had lengthy fetch over Lake Superior. Westward, near the Wisconsin border, snow amounts decrease as the narrowing western extremities of Lake Superior restrict the length of fetch. Relatively high elevations are attained in this area within short distances from the lake.

The maximum snow totals occur on the elevated plateau of the

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One reason for the selection of Michigan as a sample area was the fact that five of the nine major Great Lakes snowbelts are contained within the state. Lack of recording stations precludes much in the way of a climatological summary for the Ontario belts, and a good deal of research has already been done for the Lake Erie and Lake Ontario belts (see Chapter Two).
Keweenaw Peninsula, which is exposed on three quadrants to lake winds. Houghton Airport, located midway between Calumet and Hancock at an elevation of 1081 feet, averaged 175.9 inches for the 1930-61 period. Undoubtedly, on the higher elevations toward the tip of the peninsula, even greater amounts occur. A State Highway Department gage in operation in recent years at Delaware has shown consistently greater catches than the gage at Houghton Airport.

A second area of maximum snowfall occurs within this snowbelt about 40 miles from the Wisconsin border in the elevated area which extends from the interior toward the shore of Lake Superior and terminates at the abrupt escarpment of the Porcupine Mountains rising 1000 feet above the level of Lake Superior. The only recording station in the area, at Bergland Dam, averaged 166.2 inches annually. It is noteworthy that the greatest snow totals occur inland from the shore in the higher areas, and that a very steep gradient exists between the lake shore and areas 5 to 20 miles inland. Eagle Harbor, located at lake side on the north tip of the Keweenaw Peninsula, averaged only 65 inches annually, whereas, by all indications, Delaware, only five miles away on the spine of the highland which extends to the tip of the peninsula, received three times this total. Granted some loss of catch at Eagle Harbor because of the exposed location of the gage at the Coast Guard Station, the contrast due to topography is remarkable. Similarly, Ontonagon, on the lake shore, recorded 105.8 inches annually, while Bergland Dam, 15 miles inland, received 166.2 inches. The gage on the Michigan Technical University campus at Houghton, at an elevation of 700 feet where the Portage Lake cutoff bisects the Keweenaw Peninsula,
recorded 120 inches annually. Only six miles to the north, Houghton Airport, 500 feet higher, averaged 175.9 inches.

The decline in the mean annual snowfall southward from these maximum areas is extremely rapid, even with an increase in altitude over the Superior Upland of Western Upper Michigan and northern Wisconsin. South and east from the Bergland node toward the interior, average annual totals decrease 70 inches within 25 miles. Along the northwest shore of Lake Michigan, mean averages range from 50 to 60 inches. These amounts are surpassed in sections of the southwestern Lower Peninsula, and in practically the entire northern part of the Lower Peninsula.

A second snowbelt, in the eastern Upper Peninsula, parallels the shore line and is displaced about ten to fifteen miles inland from Lake Superior. This heavy snow area (the Eastern Upper Peninsula snowbelt) is centered in Schoolcraft and Luce counties, where mean totals exceed 150 inches. Westward along the lake shore, amounts decrease in the snow shadow of the Keweenaw Peninsula, and as the shore alignment changes, although a secondary node occurs in the high areas of western Marquette county where the Superior Upland extends northeastward to the shore of the Lake to form the Huron Mountains. The gradient south from this snowbelt is well marked. A decrease of 70 inches can be noted from the center of the belt to the north shore of Lake Michigan, a distance of less than 40 miles.

In the Lower Peninsula, snowbelt areas reflect proximity to Lake Michigan and/or relatively high elevation. The Traverse Bay Highland belt is located in the elevated regions to the south and east of Grand Traverse Bay. Two nodes of maximum snowfall are apparent. One node
corresponds to a triangular shaped area of high elevation (1300 feet) in eastern Antrim and western Otsego counties with annual totals of over 100 inches. Mancelona, near the center of the node, had a mean annual snowfall of 141.8 inches, and Gaylord, also located within the node, 121.8 inches. A second-node occurs in the higher areas to the south and west of Grand Traverse Bay, where Thompsonville received an average of 106.2 inches.

This snowbelt combines the influence of orography and lake proximity, and here again the greatest totals are inland 5 to 20 miles from the lake in hilly areas. Charlevoix, on the lake shore, averaged only 78.5 inches. It is highly probable that the snowfall in this area closely approximates the topographic map. Very steep gradients occur to the south and east of this snowbelt. Between Gaylord and Grayling, a distance of 25 miles, snowfall decreased from an average of 121.8 inches to 83.9 inches. At Atlanta, only 30 miles east of Gaylord, the mean annual snowfall was only 59.7 inches. In both cases, a decrease in elevation and an increase in distance from Lake Michigan are involved.

In southwestern Michigan, north-south alignment of the isarithms indicates the presence of a snowbelt paralleling the Lake Michigan shore, and extending inland about 30 or 40 miles. Within this snowbelt (the Western Lower Peninsula belt) the orographic relation is missing. Maximum amounts of over 70 inches occur along the shore northward from Muskegon. The gradient delineating this snowbelt is not as sharply marked on the mean snowfall chart. However, during years when the lake influence is particularly strong, the gradient can be remarkably abrupt. (During the winter of 1957-1958, Kalamazoo received 108 inches of snow;
Battle Creek, 19 miles to the east, received only 40 inches.) The heaviest amounts in this area are also displaced inland from the immediate lake shore.

A fifth snowbelt of lesser dimensions can be discerned along the extreme eastern thumb area of the Lower Peninsula. This snowbelt is apparently caused by increased moisture content of northeasterly winds which have crossed Lake Huron, and more importantly, by the exposure of the extreme eastern shore to winds of a northerly or northwesterly direction which have had considerable lake fetch.

The effect of lake proximity is thus shown on the mean annual snowfall chart by isarithms paralleling the shore lines of Lake Superior and Michigan, and by the formation of snowbelts within thirty miles of the lakes. These snowbelts are characterized by extremely steep gradients within short horizontal distances. The Michigan snowbelts have been identified and described and have been designated as: (1) the West Upper Peninsula, Keweenaw belt; (2) the East Upper Peninsula belt; (3) the Traverse Bay Highland belt; (4) the Western Lower Peninsula belt; and (5) the Lake Huron belt.

Fluctuations in the temporal significance of Michigan snowbelts - the mean monthly snowfall. -- Charts of monthly mean snowfall were constructed for November through March. Predicated on the assumption that the lake shore snowbelts are directly reflective of the lake snowfall mechanism, the distinctiveness of these belts throughout the winter was investigated.

November snowfall. -- In November, latitudinal contrasts are an important determining factor (Figure 25). However, the presence of

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4Monthly values reduced to standardized time periods.
FIGURE 25
MEAN NOVEMBER SNOWFALL inches

FIGURE 26
MEAN DECEMBER SNOWFALL inches
snowbelts is readily apparent. Large sections of southeastern Lower Michigan receive less than 5 inches of snow, while in the West Upper Peninsula-Keweenaw belt totals exceed 25 inches. The steep gradients to the southeast and south of the Upper Peninsula belts are discernible, as is the gradient south of the Traverse Highland belt. The gradient surrounding the Western Lower Michigan belt is only faintly discernible, as in these lower latitudes much of the November precipitation occurs in the form of rain.

**December snowfall.** — During the month of December the snowbelts are sharply defined, (Figure 26). The West Upper Peninsula-Keweenaw belt receives more than 35 inches. A small area within the Traverse Bay Highland belt receives more than 30 inches, and a triangular area in southwestern Michigan has over 15 inches. Gradients surrounding the snowbelts are steep and most sharply defined during this month. Snow totals decrease by one half within thirty miles of all the major snowbelts. During this month, the heavier totals occurring along the Lake Huron shore are first discernible. Southeastern Lower Michigan and the Bay City Saginaw lowland remain as areas of relatively light snowfall.

**January snowfall.** — The January patterns practically duplicate those of December (Figure 27). The snowbelts continue as well defined entities, surrounded by sharp gradients within short horizontal distances. Stations within the West Upper Peninsula-Keweenaw snowbelt have over 35 inches of snow, while the East Upper Peninsula and Traverse Bay Highland belts receive over 30 inches. The Western Lower Peninsula belt is readily discernible, although the node in the triangular area in the southwest has disappeared. Areas in southeastern Lower Michigan
continue to receive light amounts of snowfall, generally from 5 to 10 inches, while the southern part of the Upper Peninsula is a snow deficient area receiving slightly over 10 inches.

**February snowfall.** -- The February chart contrasts considerably with the January chart (Figure 28). The snowbelts have lost their acuteness, and, although still discernible, are not characterized by the close spacing of isarithms evident on the December and January charts. February is the month of greatest snowfall in non-snowbelt regions of southern and southeastern Michigan, in the Saginaw Bay area, and along the north shore of Lake Michigan in the Upper Peninsula. February totals decline sharply in snowbelt areas, however. Monthly averages on the Keweenaw Peninsula drop to less than 30 inches from January's maximum of 41 inches at Houghton Airport. In the Traverse Bay Highland belt, Mancelona has declined from a mean of 38 inches in January to 26 inches in February. Figure 29 shows the percentage by which January or December mean totals exceed February totals. The pattern closely corresponds to the mean annual snowfall chart. Highest percentages occur in the snowbelt areas (40 to 80 percent) while in the non-snowbelt areas the percentage increase is minimal.

**March snowfall.** -- In March, the snowbelts are rather poorly defined and gradients are less marked than in February (Figure 30). The Western Lower Peninsula belt is no longer in evidence, and the steep gradients south and southeastward from the northern Michigan belts are less sharp. Snowfall is lightest in southeastern Lower Michigan, and heaviest on the Keweenaw Peninsula. A secondary node of maximum snowfall occurs in the Traverse Bay Highland belt.
FIGURE 29
PERCENT INCREASE - JAN. OR DEC. SNOWFALL OVER FEB. SNOWFALL

FIGURE 30
MEAN MARCH SNOWFALL inches
In summary, the distinctiveness of the snowbelts within the monthly distributional patterns shows considerable temporal variation. In snowbelt areas, the month of maximum snowfall occurs during December or January, and snow totals drop off rapidly during February and March. Non-snowbelt areas show much less variation as the season progresses. February totals may exceed those of January. The steep gradients surrounding snowbelt areas are striking during the early winter, and poorly defined during the latter part of the season. The disparity in snowfall amounts between snowbelt and non-snowbelt areas appears strongest in early winter, when lake-air temperature contrasts are at a maximum, and decreases with the progression of winter, as lake-air temperature contrasts lessen.

Contrasts in snowfall intensity between snowbelt and non-snowbelt areas. -- The economic effects of intense snowfalls are of considerable importance. Increased expenditures for snow removing equipment, road chemicals and sands, and county service personnel must be anticipated in areas where a considerable proportion of the annual snowfall occurs in the form of heavy 24-hour snowfalls. In order to permit an estimation of the intensity factor in Michigan and to discern the relation between snowfall intensity, lake proximity and the development of snowbelts, charts were constructed indicating the distributional patterns resulting from daily snowfalls exceeding specified amounts.

Procedure. -- Lack of available data precluded the extension of this investigation to the thirty year period utilized for the construction of the mean annual and monthly charts. Accordingly, data for stations available on punch cards for the five-year synoptic period were used. While the resulting charts should not be taken as indicating
long-term normal or average amounts, they should reflect to a considerable extent the relation between snowfall intensity and contrasting geographic location in the state.

Three precipitation classes were established. All daily snowfall amounts four inches or greater were classed as heavy; amounts from two to four inches were classed as moderate; and amounts less than two inches were classed as light. The IBM 1620 computer was programmed to indicate the number of occurrences, average annual amount, and percentage of total snowfall occurring for each synoptic situation within the three given classes. Isarithm charts were then constructed for each synoptic type, and this analysis will be given in the following section on synoptic snowfall patterns. Computations of totals in each class were also made and plotted for the stations used in the synoptic analysis.

Great caution was employed in attempting to interpret the distributional patterns occurring within the light classification and eventually these efforts were abandoned because of the lack of uniformity in measurement of small daily quantities from station to station. A number of stations recorded all daily quantities less than three-tenths of an inch as "traces," while others attempted to ascertain the exact measurements to the nearest tenth of an inch. As "traces" were not entered on punch card data, no attempt was made to ascertain a "snowiness" factor which might be based upon the occurrence of these small daily totals.

Heavy snowfalls. -- The total number of occurrences of daily heavy snows during the five year period is shown by figure 31. The distributional pattern mirrors that of the mean annual snowfall. Heavy
FIGURE 31
NUMBER OF HEAVY SNOWS

FIGURE 32
MEAN SEASONAL SNOWFALL
FROM HEAVY SNOWS-inches
snows were infrequent and rare over the low-snowfall southeastern sections of the Lower Peninsula, where less than five were recorded. The total number of heavy snows increased northward and toward the shores of the lakes.

A similar geographic pattern was evidenced by the chart of the mean seasonal totals occurring as heavy snowfall, Figure 32. The functional relation between the total heavy snowfall occurring during the period and the total snowfall is indicated by Figure 33. The correlation coefficient for this relation is +.94. Steep gradients delineated the snowbelt areas, particularly near the Traverse Bay Highland Belt, and the West Upper Peninsula-Keweenaw Belt. South and east from the Traverse Bay Highland Belt, the mean seasonal total from heavy snows increased approximately five times within 40 miles, from eight inches at Houghton Lake to 44 inches at Mancelona.

Figure 34 indicates the percentage of the total snowfall received in the form of heavy snowfalls. The functional relation is shown in Figure 33. The correlation coefficient for this relation is +.64. The isopleth pattern is not as distinct as that of Figure 32, although it is apparent that the snowbelt areas receive greater proportions of their snowfall in daily amounts in excess of four inches than do non-snowbelt regions. In the southeastern Lower Peninsula, less than 10 percent of the seasonal total results from heavy snows, while percentages increase to 30 and 35 in the snowbelt areas of the Lower Peninsula, and to over 40 in the snowbelts along the south shore of Lake Superior.

**Moderate snowfalls.** -- Moderate snowfalls (two to four inches) were tabulated, and isarithm charts, not presented here, were
FIGURE 33

PERCENT OCCURRING AS HEAVY SNOW VS. TOTAL SNOW

HEAVY SNOW VS. TOTAL SNOW

MODERATE SNOW VS. TOTAL SNOW

RELATION OF HEAVY AND MODERATE SNOWFALL TO TOTAL SNOWFALL
PERCENT OF TOTAL SNOWFALL OCCURRING AS HEAVY SNOW
constructed. The distribution of mean seasonal snowfall occurring as moderate daily amounts contrasted to the similar chart for heavy snows. In general, low snowfall areas had more snowfall from moderate daily amounts than from heavy daily snows, while snowbelt zones had similar or smaller quantities from moderate snows as compared to heavy snows. The snowbelts were less sharply defined and the gradation was more even. For example, the gradient between Houghton Lake and Mancelona was from only 30 inches to 37 inches for moderate snowfalls. Figure 33 indicates the relation between moderate snowfall totals and the total snowfall during the five year period. The coefficient of correlation for this relation is +.89. The slope of the regression line is less than the regression slope for heavy snows. An attempt to construct isarithm charts of the percentage of the mean seasonal snowfall occurring as moderate snowfalls was abandoned as no readily discernible patterns appeared. The coefficient of correlation for this relation was a non-significant +.20. In general, however, the percentage of the total amount occurring in the form of moderate snowfall decreased slightly as the seasonal snowfall increased.

In summary, great contrasts exist between occurrences of heavy and moderate snowfalls in snowbelt and non-snowbelt areas. Isarithm charts of totals from heavy snows defined the snowbelts sharply, and steep horizontal gradients were observed. The horizontal gradients were less well defined on the charts of moderate snowfall, and the close spacing of isarithms around snowbelts as appeared for heavy snows was not evident. Accordingly, while the number of moderate snowfalls and average seasonal amounts from moderate snows increased in snowbelt areas, they did not increase as rapidly as the corresponding values for
heavy snows, and the percentage of the total amount occurring as moderate snowfalls actually decreased. This strongly suggests that the heavier totals in snowbelt areas result not so much from a greater number of moderate or light snowfalls (or simply more snowy days) but from a higher intensity of snowfall.

Secular tendencies and variability of snowfall in snowbelt and non-snowbelt areas. — Snowfall totals for the winter seasons 1904-1905 through 1960-1961 were contrasted for selected stations in snowbelt and non-snowbelt areas for which homogeneous records were available. These stations were chosen as representative of various geographical areas in the state. Five Lower Peninsula stations -- Alpena, Detroit, Lansing, Bloomingdale, and Muskegon -- were examined for homogeneity and were found to have uninterrupted fifty-seven year records. Bloomingdale and Muskegon are located near Lake Michigan in the heart of the Western Lower Peninsula snowbelt. The remaining Lower Peninsula stations are located well away from the lake, in non-snowbelt areas of the state.

Four Upper Peninsula stations were used. These include Calumet, Sault Sainte Marie, Escanaba and Marquette. Calumet is situated on the Keweenaw Peninsula near the heart of the lake-oriented West Upper Peninsula-Keweenaw snowbelt. Escanaba is located in the low snowfall area of the Upper Peninsula along the north shore of Lake Michigan, far removed from the effect of Lake Superior. Marquette, although situated on the shore of Lake Superior, is protected from winds of

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Seasonal values from 1950-1961 were from the Houghton Airport, near Calumet, and are continuous with the record at Calumet.
westerly and northwesterly lake fetch by the highlands of the Keweenaw Peninsula, and the Huron Mountains immediately to the west. The fourth station, Sault Sainte Marie, is located at the eastern extremity of the Eastern Upper Peninsula snowbelt. The station is affected somewhat by northwesterly winds off the lake, but not as directly as Muskegon, Bloomingdale or Calumet.

Table 10 indicates the means, standard deviations and relative variability of seasonal totals for the fifty-seven year period for each station.

\[ \text{TABLE 10} \]

\text{VARIABILITY OF SEASONAL SNOWFALL}

\text{1904-05 THROUGH 1960-61}

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Relative Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpena</td>
<td>64.6</td>
<td>16.7</td>
<td>20.2</td>
</tr>
<tr>
<td>Detroit</td>
<td>37.0</td>
<td>13.7</td>
<td>28.6</td>
</tr>
<tr>
<td>Escanaba</td>
<td>57.4</td>
<td>17.0</td>
<td>24.8</td>
</tr>
<tr>
<td>Lansing</td>
<td>46.5</td>
<td>14.6</td>
<td>22.5</td>
</tr>
<tr>
<td>Marquette</td>
<td>106.1</td>
<td>29.8</td>
<td>20.6</td>
</tr>
<tr>
<td>Muskegon</td>
<td>61.2</td>
<td>24.8</td>
<td>31.6</td>
</tr>
<tr>
<td>Sault Ste. Marie</td>
<td>86.3</td>
<td>22.7</td>
<td>22.4</td>
</tr>
<tr>
<td>Bloomingdale</td>
<td>58.3</td>
<td>23.1</td>
<td>33.1</td>
</tr>
<tr>
<td>Calumet</td>
<td>148.3</td>
<td>41.7</td>
<td>22.6</td>
</tr>
</tbody>
</table>

The standard deviation was greatest at Calumet, with the highest mean for the period, and least at Detroit with the smallest mean. However, the relative variability was highest at the Lower Peninsula snowbelt stations with values at Muskegon and Bloomingdale of 31.6 and 33.1, respectively.

6 Relative variability computed as \( \nu = \frac{100 \cdot (AV)}{B} \) where \( (AV) = \frac{1}{N} \sum (I_i - \bar{I}) \) (Cf. Conrad, \textit{op. cit.}, p. 54.)
Greater insight into the nature of the large variability at the two Lower Peninsula lake stations may be gained from an examination of ten year moving averages of the stations. Figure 35 indicates the trend of the moving averages for the snowbelt stations as contrasted to the non-snowbelt stations. Marked dissimilarities in the secular trends are discernible. The moving averages for the snowbelt stations show a distinct upward trend. This upward tendency began during the decades including the late 1920's and early 1930's for most stations. The peak in the moving averages for the Upper Peninsula stations was reached in the decades including the late 1940's and early 1950's with a subsequent slight decline. The peaks at Muskegon and Bloomingdale were reached during the last decade of the series. The moving means for non-snowbelt stations, with the exception of Alpena where a slight increase has occurred since the late 1930's, exhibited either stable or decreasing tendencies.

A comparison of the curves for Bloomingdale and Detroit, located at similar latitudes, indicated virtual correspondence until the 1920's when a downward tendency began at Detroit, and an upward trend at Bloomingdale. These disparate tendencies culminated in remarkable contrasts for the latter decades of the series. For the seasonal decade 1950-51 to 1960-61, Detroit had a mean value of 37.9 inches, while Bloomingdale had 84.8 inches. Corresponding values for the 1904-05 to 1914-15 decade were 43.7 inches and 44.6 inches respectively.

A similar comparison for Lansing and Muskegon indicated an identical relationship. The moving averages at Muskegon were slightly higher than those at Lansing until the 1930's after which the means
at Muskegon increased rapidly while those at Detroit decreased. The mean for the last decade of the series at Muskegon was 88 inches; at Lansing, 45 inches. Corresponding values for the first decade were 51.4 inches and 47 inches, respectively. The upward trend of the averages at Bloomingdale preceded the upward trend at Muskegon by about ten years. However, for the last ten decades of the series, the means practically coincided.

The means for the 1950-51 to 1960-61 decade at the non-lake stations were less than the means for the 1904-05 to 1914-15 decade, with the exception of Alpena. The mean at Escanaba for the latter decade was 52.0 inches, while the mean during 1904-05 to 1914-15 was 61.5 inches. Similar values for Marquette were 102.7 inches and 121.6 inches. The downward trend for the southern Michigan non-lake stations (Detroit and Lansing) coincided with the upward trend at the lake stations (Bloomingdale and Muskegon). The troughs in the curves at Marquette and Escanaba in the Upper Peninsula also corresponded with the peaks at Sault Ste. Marie and Calumet.

Table 11 indicates peak and low decades for each station and the absolute range of the moving average. This, in turn, is expressed as a percentage of the mean. The variability of the moving averages was consistently higher at the snowbelt stations, with maximum values at Bloomingdale (80 percent) and Muskegon (77 percent). The absolute range of the moving averages was greatest at Calumet, although this value was only 54 percent of the mean.

In summary, the lake effect and its relation to Michigan snowfall apparently has not functioned with persistent magnitude throughout the years and the contrasts in snowfall characteristics between lake
TABLE 11
VARIABILITY OF MOVING AVERAGES
1904-05 THROUGH 1960-61

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean of Peak Decade</th>
<th>Mean of Minimum Decade</th>
<th>Absolute Range</th>
<th>Percent of Mean of Absolute Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpena</td>
<td>78</td>
<td>57</td>
<td>21</td>
<td>31</td>
</tr>
<tr>
<td>Detroit</td>
<td>47</td>
<td>27</td>
<td>20</td>
<td>54</td>
</tr>
<tr>
<td>Escanaba</td>
<td>67</td>
<td>47</td>
<td>20</td>
<td>35</td>
</tr>
<tr>
<td>Lansing</td>
<td>55</td>
<td>42</td>
<td>13</td>
<td>28</td>
</tr>
<tr>
<td>Marquette</td>
<td>123</td>
<td>83</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>Calumet</td>
<td>190</td>
<td>109</td>
<td>80</td>
<td>54</td>
</tr>
<tr>
<td>Bloomingdale</td>
<td>84</td>
<td>38</td>
<td>46</td>
<td>80</td>
</tr>
<tr>
<td>Muskegon</td>
<td>88</td>
<td>39</td>
<td>47</td>
<td>77</td>
</tr>
<tr>
<td>Sault Ste. Marie</td>
<td>107</td>
<td>61</td>
<td>46</td>
<td>54</td>
</tr>
</tbody>
</table>

oriented snowbelts and non-snowbelt areas have become accentuated in recent decades. Contrasts, at least in annual amounts, appear to have been at a minimum during the initial decades of the century and to have become fully manifested in the Upper Peninsula during the late 1940's and early 1950's, and in southern Michigan during the most recent decade. The high relative variability values for the two Lower Peninsula lake stations appear to be reflected in a secular trend which has, as yet, not peaked.

Investigations into the causation of this apparent secular increase in the magnitude of the lake effect are beyond the scope of this dissertation. The nearly in-phase tendencies and similar lake wind exposures at the four lake stations suggest the occurrence of unidirectional shift in the general circulation. Indications of such a shift for the most recent decade have already been forwarded by
Namias. A common link between snowfall amounts at lake stations, regardless of latitude, may be subnormality of temperature.

Table 12 shows the degree of correlation between January mean temperatures and January snowfall at the nine stations for the period 1930-1961.

**TABLE 12**

**CORRELATION COEFFICIENTS**

**JANUARY SNOWFALL VS JANUARY MEAN TEMPERATURE 1931-61**

<table>
<thead>
<tr>
<th>Station</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alpena</td>
<td>.26</td>
</tr>
<tr>
<td>Detroit</td>
<td>.25</td>
</tr>
<tr>
<td>Escanaba</td>
<td>.21</td>
</tr>
<tr>
<td>Marquette</td>
<td>.23</td>
</tr>
<tr>
<td>Sault Ste. Marie</td>
<td>.02</td>
</tr>
<tr>
<td>Bloomingdale</td>
<td>.75</td>
</tr>
<tr>
<td>Muskegon</td>
<td>.73</td>
</tr>
<tr>
<td>Calumet</td>
<td>.78</td>
</tr>
</tbody>
</table>

The stations for which lake proximity is strongly reflected show uniformly high correlation coefficients, and apparently a strong relation exists between mean temperatures for given periods and snow totals at lake stations regardless of latitude. An exception was Sault Sainte Marie, where the lake influence is moderately felt. This station had the lowest correlation coefficient, although the curve of the moving 57 year snowfall averages appeared in phase with the stations where the lake effect was more strongly felt. All the non-snowbelt stations had very low coefficients.

Subnormal winter temperatures can (although they need not
necessarily) indicate greater frequency of importation of severe Arctic air masses. Thus dynamic interactions between warm lake water and cold Arctic air are heightened with more snowfall occurring in lee shore areas. At the same time, although the subnormal mean temperatures increase the possibility of precipitation in the solid form at non-lake areas, the dominance of Arctic air in these areas may decrease the frequency of cyclonic and frontal action, giving drier than normal winters with little precipitation.

Intercorrelations of the January mean temperatures for the stations indicated that the thermal fluctuations were closely in phase for stations which had either similar longitudes or similar latitudes, but the degree of correlation decreased with variance in both geographic grid determinants. In spite of the correspondence of the curves of the moving averages, intercorrelations of January snowfall amounts showed low values.

Much research is needed before any further conclusions can be drawn. However, for the purposes of this investigation it bears re-emphasizing that the distributional patterns presented for the synoptic types in the following sections should not be taken as indicative of long term or "normal" conditions. From all indications, the period selected for the synoptic analysis was one for which lake-interior contrasts in snowfall were at a maximum for the past fifty years in the Lower Peninsula, and were very strong in the Upper Peninsula.

**The Effect of Lake Proximity When Viewed Within Synoptic Parameters**

**Indications of geographical contrasts.** -- Bar graphs for selected stations within the regional synoptic subdivisions are shown by Figure
36 -- one station for each subdivision with the exception of EUP for which bar graphs for two stations are shown. Four of the selected stations -- Bloomingdale (SWLP), Muskegon (WLP), Gaylord (NWLP) and Houghton FAA Airport (WUP), are located within snowbelts and in close proximity to Lakes Michigan or Superior. Detroit (SELP), Jackson (SLP), Saginaw (SLP), Alma (CLP), Alpena (NELP), and Escanaba (EUP) are located at various latitudes in non-snowbelt locations, well away from the lake. The remaining station, Sault Sainte Marie, is situated on the periphery of the Eastern Upper Peninsula snowbelt. The graphs indicate not only contrasts in mean annual totals between lake and non-lake stations during the five year period of investigation but also the comparative role of the synoptic types in the production of snowfall.

Although consistently heavier snowfall occurred at the higher latitude stations, the greatest disparity in mean seasonal snowfall during the period was between the lake snowbelt stations and the non-snowbelt stations. Seasonal averages at Bloomingdale, the most southerly of the lake stations, easily exceeded mean seasonal totals at Escanaba, the most northerly of the non-snowbelt stations, and also at Sault Sainte Marie. The contrast in mean seasonal snowfall between Jackson and Bloomingdale, at the same latitude, was greater than that between Jackson and Sault Sainte Marie, 300 miles farther north.

The Cyclonic types accounted for the greatest proportion of the snowfall at the non-lake stations where only small amounts were received from Westerly Flow types. Eighty percent of the snowfall was associated with Cyclonic types at Detroit; 81 percent at Alma; and 87 percent at Escanaba. At Bloomingdale and Muskegon, however, near the
FIGURE 36

SEASONAL SNOWFALL FOR SELECTED STATIONS
Lake Michigan shore, the Cyclonic types accounted for only 51 percent and 54 percent of the mean seasonal snowfall, respectively. Although the lake stations received more snowfall from the Cyclonic types, it was the great increase occurring with the Westerly Flow types which accounted for the great disparity between lake and interior stations. The proportion of total snowfall occurring with Westerly Flow types was greatest for the two southwestern Michigan stations (Bloomingdale and Muskegon) where 47 percent and 41 percent of the mean seasonal snowfall occurred with these synoptic types. Although the mean amounts associated with the Westerly Flow types increased at the more northerly snowbelt stations, the proportion of the mean total contributed by these types decreased.

The WFm subtype was by far the most important of the Westerly Flow types, particularly at the two southwestern Michigan stations where WFm accounted for one-third of the snowfall. The impact of this single synoptic type was particularly strong in this area, and for none of the other stations represented by the bar graphs did a single weather type contribute such a high percentage of the snow. With increasing latitude, WFm accounted for smaller percentages, both of the total snowfall, and of the snowfall associated with Westerly Flow types.

The SWs Cyclonic type was the heaviest snow contributor at the non-snowbelt stations, and the most important Cyclonic type at snowbelt stations. The only other weather types which accounted for significant amounts of snow at southern interior stations were Troughs and WS types. At Detroit, almost 60 percent of the mean snowfall was associated with these three types, with the remainder divided between
twelve Cyclonic and Westerly Flow types. The relative significance of these three types decreased at the northern stations, while the NW and NWs types gave increased amounts of snow.

At the southern Lake stations, SWS and WFm were the most important snowfall types. At Muskegon and Bloomingdale, the two accounted for over half of the snowfall. However, in the higher latitude snowbelts, the relative importance of these two types decreased considerably.

Snowfall amounts with the Anticyclonic types were negligible at all stations except Houghton, where 10 percent of the snowfall occurred with these situations.

The effect of geographic location on the probability of snowfall occurring with individual synoptic types. — The bar graphs indicate that marked variations in snowfall amounts from station to station occurred with some synoptic types, while with others variations were minor. The probability of snowfall and the probability of heavy and moderate snowfall occurring on days with given synoptic types were ascertained. The values were then plotted, and charts contrasted for examination and comparison. The probability values obtained should not be placed in a predictor role, but simply used as an aid in the interpretation of the synoptic distributional patterns. Only the charts which showed significant areal variation are presented here.

Maximum snowfall probabilities occurred in snowbelt areas with WFm and WFCm types. At the same time, these types exhibited the greatest areal variation in probability. The snowfall expectancies

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8Values less than three-tenths of an inch were not used in the probability analysis. Empirical percentages used for probability values.
for all the Westerly Flow types varied considerably with location, but only the WFm and WFCm types had high values. The charts for these types are shown here. The probability of snowfall occurring with WFm types was definitely controlled by lake proximity and ranged from less than 10 percent in extreme southeastern Michigan to over 80 percent in extreme southeastern Michigan to over 80 percent in the Upper Peninsula snowbelts, and within two nodes along the Lake Michigan shore in the Lower Peninsula (Figure 37).

The high probabilities for this type in snowbelt areas and the extreme areal variations over the state warranted a closer examination into the character of snowfall occurring with it. The probabilities of heavy and moderate snowfall based on the five year period of investigation are shown by Figures 38 and 39. Large areas in the interior and southeastern sections of the Lower Peninsula and in the southern part of the Upper Peninsula had zero probabilities for heavy snows. Maximum probabilities for heavy snows were in excess of 10 percent in the snowbelt areas near the shores of the lakes. Probabilities of moderate snows, indicated by Figure 39, showed more variation throughout the state. A substantial area in Central Lower Michigan had zero probabilities, while the lee shores of Lakes Michigan and Superior had over 30 percent probabilities. The high probabilities in the snowbelt areas for moderate or heavy snows (on a WFm day in these maximum areas, the chances were almost 50/50 that a snowfall would be over two inches) indicate the high intensity of snowfall associated with these types in lake areas.

The probability pattern for the WFCm synoptic type was similar to that for the WFm, although WFCm occurred much less frequently.
FIGURE 39

WFm
PROBABILITY OF MODERATE SNOW
%

FIGURE 40

PROBABILITY OF SNOWFALL WFCm, %
Consequently, the total snowfall associated with it was considerably less. Maximum probabilities with this type of over 80 percent occurred in the Traverse Bay Highland and in the Upper Peninsula snowbelts (Figure 40).

The probabilities occurring with NW, the most frequent synoptic type, varied primarily with latitude. Values were low in Southern Michigan and increased toward the north. Figure 41 indicates the extreme latitudinal variation of snowfall probability with NW. Values were less than 10 percent over most of southeastern Lower Michigan, increasing to more than 40 percent in northern Lower Michigan and over 50 percent in lake sections of the Upper Peninsula. Very low probabilities for heavy and moderate snows occurred over the state except on the Keweenaw Peninsula. The lower expectancies for moderate and heavy snowfalls indicated that unlike Ws and SWs, the character of snowfall occurring with this type was not intense.

Wide latitudinal variation was also exhibited by the probability patterns of the NWs type. Although the frequency of this type increased toward the north, so also did the snowfall probability. Figure 42 indicates probability values less than 20 percent in southern Lower Michigan, increasing to over 60 percent along the south shore of Lake Superior. The probabilities of heavy snow increased rapidly toward the north, attaining values greater than 10 percent in the Upper Peninsula snowbelts. The higher probabilities of heavy snowfall occurring with this type than with the NW type reflect the greater intensity of snowfall developing on the poleward side of Alberta Lows.

Although occurring relatively infrequently, W and HB cyclonic types had probability ranges which varied widely with location. Values
for the W Cyclonic type increased gradually toward the north, as a greater proportion of the precipitation associated with this situation was received in the form of snow. Probabilities of snowfall with the Hudson Bay type increased toward snowbelt areas, and in the higher latitudes.

Maximum snowfall probabilities in non-lake regions occurred with SWs and Ws Cyclonic types. The probabilities with these types showed little geographic variation and no evidence of the influence of lake proximity. Probabilities ranged between 40 and 60 percent with both types with rather high probabilities for heavy or moderate snows.

In summary, contrasts in latitude and lake proximity had only a small effect on the probability of snowfall occurring with SWs and Ws, the two major snow-producing synoptic types in non-snowbelt areas. The probability values remained essentially stable and high over the entire state.

Probability variation was large for HB, W, NW, and NWs types, and the probability of snowfall occurring with these types appeared to be most directly a function of latitude. Probabilities of a heavy snow remain low in all areas for NW types and increase in the north with NWs types.

The highest probability values, and, at the same time, the greatest geographic variability in probability, were shown by WFm and WFCm types. With these types, the probability values were definitely controlled by lake proximity.

The importance of cyclonic curvature is emphasized by the extremely low probabilities of snow occurring with the Anticyclonic types. Values of 10 percent for these types on the Keweenaw Peninsula may be
attributed to the greater disparity between mean lake and land temperatures in those latitudes, and the abrupt rise in elevation afforded by the topography of the area.

The synoptic distributional patterns. -- The probability patterns associated with the individual synoptic types indicate that marked spatial variations did not occur with all synoptic types, and that the effect of lake proximity on snowfall probability was strongly pertinent with a very limited number of types. Isarithm charts were then constructed for mean seasonal snowfall totals, and for the percentage of the total amount occurring with each synoptic type during the five season period. The distributional patterns, which reflect both probability and frequency values, were examined to discern the effect of lake proximity and latitude on the occurrence of snowfall with each type. Particular attention was given to marked transition zones, their relation to geographic structure, and to the delineation of snowbelts. Charts for synoptic types with which little areal variation occurred are not presented.

Cyclonic types. -- Five of the nine Cyclonic types identified, NW, W, SWs, Ws, and T, occurred frequently. Three of these, SWs, Ws, and T, contributed major amounts of snow, and had relatively uniform probability values over the entire state.

The SWs type occurred less frequently than either the NW or T. However, in southern areas it was the most important snowbringer among Cyclonic types, and for most non-snowbelt areas the most important contributor among all synoptic types. The snowfall distribution associated with this type on February 21, 1962, is shown by Figure 43
FIGURE 43

DISTRIBUTION OF SNOWFALL SWs
FEB. 21, 1962 inches

FIGURE 44

PERCENT OF MEAN SEASONAL SWs
for the Lower Peninsula. The entire area received some snow, although the heaviest totals were concentrated in two narrow bands -- one in southeastern Michigan, and one in the southwestern part of the state. Totals within these two bands were in excess of 6 inches.

These systems brought mean seasonal totals of 10 to 15 inches, with little latitudinal variation, reflecting the geographic consistency of snowfall probability with this type as indicated in the preceding section. There was practically no identification of snowbelts, although there is some evidence of northeast-southwest alignment of the isarithms in the Lower Peninsula. The chart of percentages of total snowfall from this type, Figure 44, was more revealing. Over snowbelt areas in the Upper Peninsula, and in the northwest part of the Lower Peninsula, this type accounted for less than 15 percent of the total snowfall. Its relative significance increased rapidly away from the snowbelts in both peninsulas. SWs accounted for 25 percent of the total snowfall in the extreme southern part of the Upper Peninsula, and for over 35 percent of the total snowfall in the southern Lower Peninsula.

The significance of this synoptic type for the occurrence of heavy snowfalls in southern sections of the state is indicated by Figure 45, showing the percentage of the total number of heavy snowfalls occurring with SWs during the five year period. For large areas in southern and eastern Lower Michigan, this was the synoptic type which accounted for the great majority of the heavy snowfalls. For a substantial area in south-central Lower Michigan, over 90 percent of the heavy snows occurred on days when this atmospheric pattern was in effect. The percentage values decreased rather rapidly westward
FIGURE 45

SWs
PERCENT OF TOTAL NUMBER OF HEAVY SNOWS

FIGURE 46

PERCENT OF MEAN SEASONAL Ws
and northward toward Lakes Michigan and Superior, reaching minimum values of less than 20 percent over the snowbelt areas along the south shore of Lake Superior, and to the east of Grand Traverse Bay in the Lower Peninsula. Mean seasonal totals from heavy snows occurring with SWs were plotted on isarithm charts (not shown) and little variability was indicated from south to north, and from lake to non-lake locations.

The Ws Cyclonic type also contributed significant amounts of snow to all areas of the state. The chart of mean seasonal snowfall indicated only a gradual increase from southern Lower Michigan to the northwestern portion of the Upper Peninsula. This gradation was caused primarily by a northward probability increase, implying that the percentage of precipitation occurring as rain decreased with increasing latitude. Little evidence of lake influence existed with this type, and the isarithm pattern showed few indications of the existence of the lake snowbelts. In terms of percentages of the total amount, shown by Figure 46, this type was the dominant snowgiver over southwestern portions of the Upper Peninsula, where a considerable area it accounted for over 25 percent of the mean seasonal snowfall. In these areas Ws superseded SWs as the chief snow producer.

Troughs were second in frequency among Cyclonic types. Little geographical variation occurred in the mean seasonal snowfall with this type. Amounts increased gradually toward the north, with about 15 to 20 inches occurring over the Keweenaw Peninsula. The effect of lake proximity was only faintly discernible, increasing the mean annual totals slightly toward the shores of Lakes Michigan and Superior.

The NW type was the most frequent of the Cyclonic types. However,
in spite of the frequent occurrence of this type in all regions of the state, it was an insignificant producer in the southern part of the state, and was accompanied by substantial amounts of snow only in northern areas close to the prevailing track of Alberta lows. Figure 47 shows the mean seasonal snowfall occurring with this type. The effects of Lakes Michigan and Superior are somewhat apparent, as the isarithms are aligned in a northeast-southwest direction in the Lower Peninsula and the snowbelt areas in the Upper Peninsula are accentuated. The increase in snowfall from south to north is not uniform. Figure 48 emphasizes the relative importance of NW as a snowfall contributor to northern areas only. On the Keweenaw Peninsula, NW was the leading Cyclonic type in terms of both frequency and snowfall.

Snowbelts are loosely identified with NW, although there is no evidence of steep gradients near these areas. Snowfall probabilities indicated that the disparity in mean seasonal totals with this type, between northern and southern regions of the state, was due to the increased probability of snowfall in the north, and not to a higher frequency of the synoptic type. The inconsequential snowfall totals with this type over southern sections of the state were associated with the low moisture content of the Alberta cyclone, and its prevailing path far to the north over interior Canada removed from large scale moisture sources. The slight relation of lake proximity to snowfall amounts is due probably to the impact of lake fetch and orography on precipitation occurring with and immediately behind cold fronts accompanying the type.

Major amounts of snow occurred with NWs types only in northern sections of the state. Both the frequency of NWs and the probability
of snow with this type increased to the north. Little effect of lake proximity could be discerned with the distributional patterns associated with this type. Of the remaining Cyclonic types, occurrences were either infrequent, or snowfall amounts inconsequential. Only the HB Cyclonic type showed evidence of the lake influence, and the distributional patterns rather sharply identified the more northerly snowbelts. However, this type occurred rather infrequently, and the snow totals accompanying it were not large.

The mean seasonal snowfall resulting from combined Cyclonic situations is shown by Figure 49. Some effect of lake proximity can be discerned although the sharp gradients evident on the mean annual and monthly charts are not present. Maximum amounts of over 100 inches occurred on the Keweenaw Peninsula, and minimum amounts, less than 20 inches, fell over the flat areas in the southeastern portion of the Lower Peninsula. Isarithms were enclosed around the Traverse Bay Highland snowbelt, and around the high areas of the Upper Peninsula.

Figure 50, indicating the percentage of total snowfall occurring from Cyclonic types, exhibited a contrasting pattern and the gradations were less uniform. In southwestern Michigan, an area extending about 35 miles inland from the lake received less than 50 percent of its snowfall from Cyclonic situations. Eastward, the percentages increased rapidly, especially within a 30 mile belt between Kalamazoo and Battle Creek, where a very sharp gradient occurred. In the low snowfall areas of both peninsulas, the Cyclonic types accounted for from 80 to 90 percent of the snow.

In summary, Cyclonic types were responsible for the majority of the snowfall in all but the immediate lake regions, although
FIGURE 49

MEAN SEASONAL-CYCLONIC TYPES
inches

FIGURE 50

PERCENT OF MEAN SEASONAL CYCLONIC TYPES
percentages were much higher in non-snowbelt areas. The T, Ws, and SWs types gave relatively uniform amounts over the entire state, and the isarithm patterns occurring with these types failed to indicate the existence of lake snowbelts. Fluctuations in latitude caused marked contrasts in the snowfall amounts occurring with NW and NWs types and this factor accounted for a large part of the disparity in snowfall between northern and southern non-snowbelt areas. The lake-oriented snowbelts are discernible with distributional patterns associated with several Cyclonic types, but not to a marked extent with any one type. They are most marked with HB, although this type occurred infrequently, and total accumulations were small. The relation of lake proximity and snowfall with these several Cyclonic types was reflected by a southwest-northeast alignment of isarithms in the Lower Peninsula on the chart for combined Cyclonic types. Closed isarithms occurred surrounding the areas of high elevation near Grand Traverse Bay, and on the Keweenaw Peninsula. In the Northeast Upper Peninsula and Western Lower Michigan belts, where the orographic factor is lacking, snowfall increase with Cyclonic types was minimal.

Westerly Flow types. — The lack of sharp demarcation of the lake snowbelts with the distributional patterns accompanying individual Cyclonic types points toward a close relation between lake proximity and snow amounts occurring with Westerly Flow types. Of the four Westerly Flow types, two, WFM and WFCm, showed high snowfall probabilities in snowbelt areas. The WFM type occurred most frequently. This type developed within a homogeneous westerly flow of Arctic air, with the salient cyclonic disturbance located off the east coast of North America. Figure 51 indicates the snowfall distribution over Michigan for a
FIGURE 51

DISTRIBUTION OF SNOWFALL WFM
FEB. 8-10, 1958 inches

FIGURE 52

MEAN SEASONAL SNOWFALL - WFM inches
three-day period when this type prevailed. The entire southeastern half of the Lower Peninsula and the southern half of the Upper Peninsula received only traces, while western portions of the Lower Peninsula, and, in particular, a zone inland about 15 to 20 miles from the lake in southwestern Michigan received up to a foot. Heavy snow also occurred over the high areas of northwestern Michigan, and in the snowbelts of the Upper Peninsula. Maximum amounts were within a sharply defined node in the East Upper Peninsula snowbelt. The snowbelts were marked by very steep gradients, particularly in eastern Upper Michigan and in southwestern Lower Michigan. The limited area along the Lake Huron shore, which received heavy snowfall, is also conspicuous. The close relation between the heavy snow areas and prevailing northwest winds during the period was quite evident.

The mean seasonal distributional pattern associated with WFm for the five year period showed strong indications of the lake-effect (Figure 52). In the Lower Peninsula, isarithms paralleled Lake Michigan, and extremely sharp gradients occurred thirty or forty miles from the lake. Isarithms were closely spaced near snowbelt areas, and particularly near the snowbelt areas along the south shore of Lake Superior. Maximum annual snowfall amounts of over 30 inches occurred in both Upper Peninsula snowbelts, and in Lower Michigan along the shore from Benton Harbor north to Ludington. The highlands to the east of Grand Traverse Bay received over 25 inches of snow seasonally from

9 Computations of vorticity induced by heat exchange from the Lakes were made for this period by Petterssen and Calabrese, op. cit. A precipitation chart accompanied this article, although the values were given in melted precipitation. Actual snowfall amounts were abstracted from cooperative observer forms for Figure 51.
this type. Minimum areas were in east central Lower Michigan and southern Upper Michigan where means of less than 5 inches of snow occurred. The Huron Mountain area, in the snow shadow of the Keweenaw Peninsula, received small amounts.

Figure 53 shows the percentage of total snowfall resulting from WFm. In the low snow areas of the Lower and Upper Peninsulas, WFm was relatively unimportant as a snowfall producer, contributing only about 5 to 10 percent of the total. The percentages increased toward the lake shore, and markedly within areas less than 50 miles from the lakes. In snowbelt areas, this type, which accounted for insignificant snow totals in non-snowbelt regions, became the single most important atmospheric situation for the production of snowfall. Along the lee shore of Lake Michigan, in the Lower Peninsula, it accounted for over 35 percent of the annual snowfall.

Not one station over a very large area in the interior and eastern sections of the Lower Peninsula received a heavy snowfall from WFm, while occurrences of heavy snowfalls increased rapidly near the lakes (Figure 54). The steep gradients, once again, were confined to a 40 mile wide belt, paralleling the lake shore. The increase in intensity of the snowfall occurring with this type near the lake shores is also shown by Figure 55, indicating the percentage of total WFm snowfall resulting from heavy snowfalls. Zero values occurred at interior points. Percentages increased rapidly near the lakes to over 40 percent along the Lake Michigan shore and on the Keweenaw Peninsula, and to over 50 percent in the East Upper Peninsula snowbelt. The sharpest gradients occurred southeast of the Traverse Bay Highland Belt, and south of the East Upper Peninsula belt.
FIGURE 53

PERCENT OF MEAN SEASONAL WFm

FIGURE 54

NUMBER OF HEAVY SNOWS - WFm
FIGURE 55
PERCENT OF TOTAL FROM HEAVY SNOW - WFm

FIGURE 56
WFm PERCENT OF TOTAL NUMBER OF HEAVY SNOWS
Figure 56 indicates the percentage of the total number of heavy snowfalls which resulted from the WFm situations. The values increased to over 40 percent along Lake Michigan shores, and to over 30 percent in other snowbelt areas. This pattern indicates that while a heavy snowfall never occurred during the five-season period with WFm in non-snowbelt areas, nevertheless the type was the single heaviest contributor of heavy snows in the heart of the snowbelt regions.

The dominance of WFm and the Cyclonic type, SWs, in the propagation of heavy snowfalls in the southern part of the state is shown by Figure 57. South of a line from Ludington to Saginaw, the majority of the heavy snowfalls was caused by these two synoptic types. With increasing latitude, the significance of the two for heavy snows decreased considerably, and heavy snowfalls resulted from a greater variety of synoptic types.

High snowfall probabilities also occurred in lake areas with the WFCm type. However, the type occurred so infrequently that it accounted for more than 5 percent of the total snowfall in only the Traverse Bay Highland belt, and in the snowbelts of the Upper Peninsula. The WFC type, although having lower probabilities than WFCm, occurred more frequently and in the Upper Peninsula snowbelts it contributed slightly over 10 percent of the snowfall. Neither of the two Westerly Flow types with cyclonic pressures evidenced the marked control of lake proximity over the distributional patterns as did the WFm type, although there was some hint of the snowbelt effect. The distributional charts for these types are not shown.

The WF type had very low snowfall probabilities and contributed minor amounts of snow in all areas.
FIGURE 57

PERCENT OF TOTAL NUMBER OF HEAVY SNOWS - WFm and SWs

FIGURE 58

MEAN SEASONAL WESTERLY FLOW TYPES inches
The mean seasonal snowfall occurring with the combined Westerly Flow types is indicated by Figure 58, and the pattern bears very close correspondence to the chart of mean annual snowfall. The arrangement of isarithms is closely controlled by lake shore alignment, and the snowbelts are marked by steep surrounding gradients. Gradients of almost 30 inches within 30 miles occur near the interior margin of the Western Lower Peninsula belt, and near the Traverse Highland belt. Gradients southward from the Upper Peninsula belts are even sharper. Maximum seasonal totals in excess of 40 inches occurred in the snowbelts, while non-snowbelt areas received less than 10 inches.

Figure 59, showing the percentages of the seasonal totals from the combined Flow types, showed a similar pattern, although the gradients were less steep. The Flow types accounted for maximum percentages of snowfall near the shore of Lake Michigan in the southwestern section (over 45 percent of the total), and northward along the shore to the Leelanau Peninsula. This belt extended inland about 20 miles from the lake, although in southwestern Michigan it extended inland about 40 miles. Another node occurred in the Mancelona-Gaylord area. The steep gradients depicted by the chart of mean seasonal amounts were not so prominent, as the total amount of snow increased rapidly toward lake areas.

In summary, the effect of lake proximity showed marked control over the mean distributional patterns associated with the Westerly Flow types. The majority of the snowfall occurred with the WFM type, which involved arctic air masses and occurred frequently in all areas. The increase in snowfall with this type appears as a major cause of the existence of sharply defined snowbelts on the lee shores of the lakes.
FIGURE 59

PERCENT OF MEAN SEASONAL WESTERLY FLOW TYPES
CHAPTER VI

SUMMARY AND CONCLUSIONS

Introduction. -- The rather uniform northward increase in mean annual snowfall over the eastern United States is interrupted where orographic and lake effects are discernible, and complex patterns appear in these areas. The persistent snowfalls occurring on the lee shores of the Great Lakes reflect the interaction of geographical factors with mesoscale atmospheric processes. Although a number of studies have described the nature and extent of individual lake-effect snowstorms, no studies have attempted to discover the climatological impact of these phenomena over large areas.

The state of Michigan was selected as a sample area for which a quantitative appraisal of the climatological nature of the lake effect was conducted. The area contains five of the nine major Great Lakes snowbelts, and a dense station network from which climatic analysis may be made. The controls of winter precipitation were outlined, and a synoptic climatology formulated in order to observe the effect of lake proximity on the distribution of snowfall occurring with individual atmospheric situations.

Controls of winter precipitation. -- Both atmospheric and geographic controls are determinative of the distribution of snowfall. Atmospheric controls include the perturbations of the general circulation, both at the surface and at the upper levels. Fluctuations in
the mean location and intensity of the mid-tropospheric trough over
the eastern United States have been cited. These fluctuations are
manifested by changes in the frequencies and preferential tracks of
surface cyclones and anticyclones, and by changes in air-mass tra-
jectories in relation to the area.

The surface features are directly related to winter precipita-
tion and were expressed more succinctly by means of a synoptic classi-
fication. The increase in amplitude of the mid-tropospheric trough,
the speedup of air flow at the 500 millibar level, and the southward
migration of the polar front are reflected by a high frequency of Cy-
clonic synoptic types during the winter months, and by minimum fre-
quencies of Anti-cyclonic types. The dominance of westerly air flow
in this latitudinal zone at all levels of the atmosphere resulted in
a large number of days during which Westerly Flow types were in effect
at the surface. Anticyclonic types increased in frequency in March,
with weakening of the mid-tropospheric trough and decline of the
upper level circulational intensity. A noticeable decrease in the
frequency of Northwestern Cyclonic types in the Upper Peninsula oc-
curred in late winter, corresponding to the maximum southward displace-
ment of the jet axis.

**Grosswetterlage** tendencies were best indicated for the WFm
synoptic type among homogeneous types, and for the SWs-WFm sequence
among non-homogenous types. In each case, maximum probabilities for
two day weather sequences were indicated.

Geographic controls involve the marine effect of the lakes and
topographic contrasts within the area. The marine controls function
both at the macro and meso-levels. Macro-level controls include
attraction of low pressure centers during the winter, creation of a
region of cyclogenesis over the lakes, and development of cyclonic
vorticity and lowering of sea level pressure in overpassing Arctic
air. Meso-level controls involve heat and moisture transference from
the lakes, and changes in the motion field caused by frictional
effects. The development of cyclonic curvature and the lowering of
sea level pressure as a result of the marine influence of the lakes
were observable on the synoptic chart and were most noticeable with
a single Westerly Flow type, WFm. The enhanced precipitation proba-
bilities accompanying these marine influences were not evinced on the
synoptic chart, but were deductively ascertained by an examination
of accompanying precipitation patterns.

Topographic controls were most noticeable where highland areas
present substantial rises to winds of lake origin, and the effect on
precipitation patterns were also ascertained.

Meso-scale lake and topographic modifications as measured by
static parameters. -- An examination of the chart of mean annual snow-
fall for Michigan indicated that the controls exerted by lake proximity
are evidenced by the development of a number of snowbelts paralleling
the shore lines of Lakes Michigan and Superior. These snowbelts are
accentuated where orographic influences are present, although they may
occur where elevated topography is lacking.

The snowbelts extend inland from 30 to 40 miles and are less well
marked or non-existent where westerly or northwesterly fetch over lake
waters is restricted for example, in the extreme northern portions of
the Lower Peninsula. Snowbelts may also be discerned on the Lake Huron
side of the state, where the Presque Isle and Harbor Beach areas jut
out into the lake sufficiently to allow these regions to be affected by lake winds from a northwesterly quadrant.

The occurrence of these lake-oriented snowbelts results in a tendency toward north-south isarithm arrangement in the Lower Peninsula, in accordance with the geographical alignment of Lake Michigan, and in opposition to the latitude gradient.

In the Upper Peninsula, the isarithm arrangement corresponds to the east-west alignment of Lake Superior. A hiatus in the progression of snowfall increase from southeast to northwest within the state occurs along the north shore of Lake Michigan in Upper Michigan. Mean annual snowfall in the Upper Peninsula in this area is less than the annual snowfall for several stations in southwestern Lower Michigan.

The snowbelts are surrounded by extremely steep gradients toward interior sections of the state. In some cases, the mean annual snowfall decreases as much as 65 inches within 30 miles with increasing distance from the lake. Lake areas have many more snowy days and also a higher intensity of snowfall than interior sections.

The snowbelts lose their acuteness as the season progresses. They are well defined and exhibit steep gradients during the late fall and early winter. By late winter, the gradients have diminished, and the isarithm orientation is more highly reflective of latitude. By March, the effect of lake proximity is barely discernible, and latitude is the dominant control.

A comparison of ten year moving averages over a fifty-seven year period for selected snowbelt and interior stations with uninterrupted records suggested that the disparity in annual snowfall amounts between lake and interior areas has shown a secular increase trend. This
is accounted for by a marked increase at lake stations and a slight decrease at non-lake stations. The increase trend at lake stations appears to have been initiated in the late 1920's and early 1930's, to have peaked for Upper Peninsula stations in the late 1940's and early 1950's, and to have shown a phenomenally rapid increase in the southern Lower Peninsula during the decade of the 1950's. These trends indicate that the strong influence of lake proximity shown by the mean annual snowfall chart for 1931-60 has not operated with persistent magnitude throughout the years. The fact that the secular increases at the lake stations occurred nearly in phase with the decreases at non-lake stations, suggests that similar causation factors may be responsible. Logic points toward fluctuation of atmospheric parameters, as changes in geographic factors are likely to have been minor.

Although the contrast in mean annual snowfall between snowbelt and interior areas is marked, investigations into the regimes of mean monthly melted precipitation in Michigan by Brunnschweiler showed only minor indications of the impact of lake effect snows in snowbelt areas.¹ This may be explained by the low moisture ratio of lake effect snowfall, estimated as low as 40 to 1 by Wiggins.² The rapid settling rate of the snowcover in lake shore areas also attests to the low moisture ratio.

The lake effect measured in relation to synoptic weather types.-- An examination of the effect of lake proximity on the production of snowfall with recurrent atmospheric types was made for a five season

¹Brunnschweiler, op. cit.

period, 1957-58 through 1961-62, during which time the lake effect action was frequent and marked. The distributional charts and probability charts for the synoptic types suggest that although the effect of lake proximity can be discerned with several types, the most noticeable effect occurred with the distributional patterns accompanying WFm types. This synoptic situation involved intense cyclones off the east coast of the United States or over the Maritime Provinces, with a strong homogeneous flow of Arctic air over the lakes. Although surface pressure values were high in the lakes region, the frictional and heat exchange processes induced by the surface of the lakes resulted in the formation of a trough which extended hundreds of miles to the rear of the low. With this situation, clear, cold, anticyclonic weather occurred on the windward side of the lakes, while frequent snowsqualls and flurries developed in lee shore areas. Frequency analysis of this synoptic type showed that it occurred quite often during the winter, developing on about ten percent of the days.

The highest probabilities for snowfall and for heavy snows of any of the synoptic types occurred in snowbelt regions with the WFm type; however, very low probabilities were indicated for low snow areas toward the interior of the state. WFm evidenced the greatest geographic variation of probability of any of the types, with the probability pattern strictly determined by lake proximity.

Examination of isarithm charts for this type revealed the snowbelts delineated by sharp gradients. Isarithms were aligned parallel to Lake Michigan, and large contrasts occurred between the snow amounts in snowbelt and interior sections. Maximum amounts were displaced inland in accordance with theoretic considerations outlined by
The steep gradients were not associated with any salient topographic feature, but appeared to be simply a response to decreasing lake proximity.

The mean seasonal snowfall was increased by this type over 30 inches in lake shore areas of the Lower Peninsula, over 30 inches on the Keweenaw Peninsula, and over 35 inches in the snowbelt of the northeastern Upper Peninsula. This synoptic type accounted for over 35 percent of the total snowfall along the lake in Lower Michigan, over 25 percent in the eastern Upper Peninsula snowbelt, and over 20 percent on the Keweenaw Peninsula.

The sharp gradients occurred about 30 to 40 miles from the lakes, and little snowfall of consequence resulted from this synoptic situation at stations located more than 40 miles from the shore. No heavy snowfalls were recorded at interior stations, although they occurred frequently in snowbelt areas.

At least during the investigative period, the effect of rough topography in the Traverse Bay Highland snowbelt and on the Keweenaw Peninsula did not appreciably increase snowfall amounts occurring with the type, although there was a considerable increase associated with the Cyclonic types in elevated areas. Little relation could be discerned between latitude differences and snowfall amounts occurring with WFm.

When the greater disparity of mean land-lake temperatures in the Upper

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Petterssen and Calabrese. The inland displacement of maximum precipitation amounts is not reflected by the isarithms in southern and western Lower Michigan as there are few gages located directly on the lake shore, as is true in the Upper Peninsula. The gages at lake stations such as Muskegon, Holland, and Ludington are located several miles inland and receive considerably greater catches than immediate shore areas.
Peninsula is considered, this fact appears to corroborate the suggestion that the peak of lake activity in the Upper Peninsula was reached a decade ago. The more oblique fetch in the Upper Peninsula may have reduced the amounts occurring with the type, however, and the east-west alignment of the shore areas was responsible for a break in snowfall amounts occurring with WFm in the Huron Mountain region east of the Keweenaw Peninsula. These regions were in a snow-shadow and not directly affected by lake winds of westerly or northwesterly fetch.

Frequency counts of the WFm type by fifteen day intervals revealed a rather rapid late season decline. This strongly suggests that the loss of acuity by the snowbelts during the late winter is due to a decline in the frequency of the major snowbringing synoptic type. Some fundamental questions remain. Was the frequency dropoff due to a late winter circulational shift with fewer strong cyclones traveling or stagnating along the east coast, hence, circulational arrangements unpropitious for strong Arctic air invasions? Or did the weakening of water-atmospheric temperature contrasts in late winter prohibit the formation of cyclonic isobar curvature on which the classification of the type is based? With the former case, the lessening of the snowbelt tendency in late winter becomes, after all, simply a response to changing seasonal atmospheric circulation. In the latter situation, it remains a direct function of decreasing geographic influence on atmospheric phenomena. The increase of anticyclonic types in late winter and the fact that the jet axis remains at its most southerly position well into March suggest that the lessening of air water contrasts must certainly be involved, although it is also probable that the decrease of intensity of the mid-tropospheric circulation is a contributing factor.
The Grosswetterlagen tendencies exhibited by WFm, as evidenced by high probability of persistence, points toward the occurrence of "spells" of snowy weather in the lake snowbelts. A cursory examination of daily snowfall records for lake stations indicated that much of the snowfall occurred during series of consecutive days, punctuated by intervals during which little or no snow occurred. The highest probability for two day weather sequences of non-homogeneous weather types was for SWs-WFm, the two leading snowfall producers in southern snowbelt areas, further substantiating the tendency toward a "snow Grosswetterlagen" in snowbelt zones.

Evaluation of methodology. -- The merits of synoptic climatologies have been fully discussed in earlier sections. In this investigation, synoptic climatology has been used as a tool and as an aid in discerning the impact of a mesoscale geographic complex with characteristic atmospheric arrangements. It has been directed toward exposition of a climatic phenomenon linked inextricably to atmospheric and terrestrial factors, yet divorced from wholly independent relationships with each. The relation between meteorology and geography has been hopefully carried a step closer by this symbiotic approach.

The formulation of a synoptic classification based on a synthesis of classification methods appears particularly applicable in mid-latitude areas which have a high frequency of cyclonic activity and are characterized by rapid air mass interchange. The Great Lakes area is such a region. The marked contrasts in weather between the poleward and equatorward sides of moving surface cyclones must be depicted by any classification concerned with a middle latitude continental area, particularly during the winter season when the latitudinal thermal
gradient is sharpened. The present classification has the advantage of retaining a desired degree of objectivity, representing discrete weather complexes, and yet expressing the vagaries of the synoptic chart in terms meaningful to the geographer.

Implications for future research. — The opportunities for future research into the effect of the Great Lakes on meteorological phenomena are many and varied. The lack of a dense net of sounding stations on the surrounding shores of the lakes has hampered more precise measurements of the dynamic interactions between the lake surface and the atmosphere. New insights into these processes are being made available through the meteorological studies conducted under the auspices of the Great Lakes Research Division of the University of Michigan.

Further research is needed into the nature of individual lake effect snows, their relation to prevailing gradient winds, their frequency, duration, and areal extent. Radar surveillance, snow surveys in critical areas, and the establishment of a micro-network of snow gages are needed in order to understand more precisely the areal and temporal characteristics of developing snowfall cells. The present investigation has emphasized the role of the atmosphere, and the atmospheric situations with which lake-effect snowfalls develop. Further research is also needed into the effect of changing lake characteristics—current fluctuation, extent of ice cover, changing volume and surface area—and their relation to the snowfall of surrounding areas. Investigations into the effect of abnormalities of the general circulation and associated lake effect responses are also indicated. Attempts to correlate the position and intensity of the meridional trough to lake effect activity may show satisfying results.
Little has been said of the economic implications of the heavier snowfalls in lake regions. They are of considerable importance, being both salutary, and at the same time, taxing of local and state budgets. The persistent snows and snowcover of the lake snowbelts have contributed to the financial success of the winter sports industry in the state, and to the great rush of associated tourist activity in recent years into snowbelt areas during the winter. On the other hand, road maintenance costs are increased, transportation is hampered, schools close, and commercial establishments lose customers when paralyzing snows blanket the area. The implications of the weather factory role of the Great Lakes on the economic functions of nearby areas are those for which many generalities are forthcoming, but few specifics. The geographer is the one most suited for an exposition of the specifics.

Conclusion. — A general conclusion to be drawn from this study is that the link to the seasonal intensity of lake-effect snowfalls must be sought within the general circulation itself. Indications are strong that the relationship between geographic factors and snowfall in the Great Lakes area functions with catalysts of specific atmospheric arrangements. In the absence of these atmospheric common denominators, the lake effect is minimal. Predicated on this assumption, evidence suggests that frequent occurrences of the atmospheric catalysts were not forthcoming during the early years of this century. The existence of secular shifts and changes of the general circulation which have given maximum impact to the lake effect in recent years remain as yet unsubstantiated, and pose major gaps in the inventory of climatological knowledge of the Great Lakes area.

The inherent difficulty of attempting to discern between purely
lake induced snowfall and cyclonic snowfall, if such a dichotomy exists, is obvious. The distributional patterns examined in relation to the commonly occurring atmospheric types suggest, however, that during years when lake activity is strong, snowfall amounts are nearly doubled in lake regions. A large proportion of this increase occurs in conjunction with a single synoptic type with no cyclones in the area, and almost inconsequential snowfall amounts being received in interior regions.

There can be little doubt that the Great Lakes impose strong controls over the winter climate of surrounding areas. Lake-effect snowfalls are probably the most overt revelation of these controls. It is hoped that a greater understanding of the climatological significance of these phenomena has been imparted by this investigation.
APPENDIX A

STATIONS USED AS DATA SOURCES FOR SYNOPTIC ANALYSIS

A. First Order U. S. Weather Bureau Stations.

Data Source - Climatological Data for Michigan, November 1957 - March 1962

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<th>Station</th>
<th>IBM Code Number</th>
<th>Observation Time</th>
</tr>
</thead>
<tbody>
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<td>756</td>
<td>Mid.</td>
</tr>
<tr>
<td>Detroit WB City</td>
<td>845</td>
<td>Mid.</td>
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<td>Detroit WBAP Wayne Cty.</td>
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B. U.S. Weather Bureau Cooperative Stations

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| West Central Lower --- 1        |                 |                 |
| Grand Haven Fire Dep.           | 101             | 6p             |
| Montague                        | 104             | 5p             |
| Hart                            | 107             | 5p             |
| *Ludington 4 SE                 | 108             | 5p             |

*Snowfall data published in Climatological Data, Michigan. Otherwise snowfall data abstracted from Cooperative Observer Form 612-14.
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FIGURE 60

- USWB Stations
- Highway Dept. Snow Stations
APPENDIX B

IBM PUNCH CARD FORMAT

Eighteen columns of the IBM punch card #5081 were used for entries in coded form indicating the station, date, snowfall total, synoptic situation, surface wind, frontal passage, isobar curvature, air mass, and temperature classification. One card was punched for each station for each day on which measurable snow occurred. The station number, the date, and the total snowfall for the date were first entered in columns one through eleven. Later a synoptic analysis was made for each day during the five year period for each of the ten regional subdivisions. This information was then punched in coded form in columns twelve through eighteen. As a substantial number of stations had similar synoptic conditions for the same day, the 514 IBM Reproducing Punch was employed for this operation, with a considerable saving of time.

Data Arrangement

Columns 1 - 3 Region and Station Number
Column 1 -- Region -- 0 through 9
Column 2 and 3 station number

Columns 4 - 7 Date
Column 4 -- year 1957-58 season -- (1)
1961-62 season -- (5)
Column 5 -- month November -- (1)
March -- (5)
Column 6 -- day 01 -- 31
Column 7 -- day

Columns 8 - 11 Snowfall Amount -- three digits and decimal

Columns 12 - 13 Synoptic Situation
Column 12 -- Cyclonic, Flow Pattern, or Anticyclonic
Cyclonic 0
Flow Pattern 1
Anticyclonic 2

Column 13 -- Subdivisions of above
Cyclonic
NW ------ 1
NWS------ 2
W ------ 3
Ws ------ 4
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<td>NE -----</td>
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<td>SW -----</td>
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<td>warm -----</td>
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<td>occluded</td>
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<td>cold and warm</td>
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<td>straight</td>
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<td>20-32</td>
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<td>10-20</td>
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<td>less than 10</td>
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035  SW Lower Michigan, Kalamazoo
2302  January 2, 1959
05.3  5.3 inches of snow
06   SWs cyclonic
  2   NE wind
  0   no frontal passage
  1   cyclonic isobar curvature
  1   cP air mass
  3   maximum temperature between 20 and 32 degrees
APPENDIX C

CLASSIFICATION OF SYNOPTIC TYPES

In order to introduce a greater degree of objectivity into the classification process, a plastic overlay grid was constructed using a polar stereographic projection at the scale of the daily weather chart. The grid extended from 25 to 60 degrees north latitude, and from 60 degrees to 105 degrees west longitude. The grid was then placed over each weather chart, and the classification made according to specific grid guide marks.

Cyclonic Types

Days were classed as cyclonic if pressures over the area were below 1016 mbs., isobar curvature cyclonic, salient low approaching area or within the region on the 1:00 A.M. chart.

NW First appearance on grid north of 50 degrees north latitude, trajectory north of, or directly over area, trajectory south of 55 degrees north latitude.

NWs First appearance on grid north of 50 degrees north latitude, trajectory south of area, frontal passage lacking.

W First appearance on grid south of 50 degrees north latitude, north of 37 degrees north latitude, trajectory of center to the north of area.

Ws Same as W, but trajectory south of area, frontal passage lacking.

SW First appearance on grid south of 37 degrees north latitude, trajectory to the north of area, frontal passage.

SWs First appearance on grid south of 37 degrees north latitude, trajectory north of 37 degrees north latitude, but south of region at longitude of region, lack of frontal passage.

G First appearance on grid south of latitude 37 degrees north, subsequent trajectory south of latitude 37 degrees, north at longitude of region, extension of cyclonic curvature over the region.
T  Indistinct pressure pattern, cyclonic curvature, and pressures below 1016 mbs.

HB  Low pressure over Hudson-Bay Ungava, cyclonic curvature over area, pressure below 1016 mbs.

**Westerly Flow Types**

WFm  Westerly flow, Arctic air mass, cyclonic curvature over area, pressure above 1016 mbs. Center of salient low east of longitude 75 degrees west on 1:00 A.M. chart.

WF  Same as WFm, Arctic air mass not involved.

WFC  Westerly flow following cyclone or frontal passage, cyclonic curvature of isobars, pressure below 1016 mbs., salient low or front located west of longitude 75 degrees west on 1:00 A.M. chart.

WFCm  Same as WFC with Arctic air mass.

**Anticyclonic types**

Anticyclonic types were designated according to the location of the letter H on the chart, either west, north, south, or over the region. Pressure either above 1016 mbs. on both 1:00 A.M. and 1:00 P.M. charts, or rising and above on 1:00 P.M. chart. Anticyclonic curvature prevails.

**Half Days**

If the type change is Cyclonic to Anticyclonic, or Cyclonic to Westerly Flow, the day is classified as Cyclonic. If the change is from Anticyclonic to Cyclonic or from Westerly Flow to Cyclonic, the day is classed as Cyclonic. If the change is from Cyclonic to Cyclonic, the 1:00 A.M. specification is used.
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Church, Phil. The Annual Temperature Cycle of Lake Michigan, University of Chicago Miscellaneous Reports in Meteorology, Nos. 4 and 18 (1943).


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U. S. Weather Bureau, Columbus, Ohio. Personal interview with Mr. Howard Kenney, Meteorologist in Charge, May, 1962.