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ABSTRACT

A CLIMATOGRAPHY OF MICHIGAN

by

Thomas Eugene Niedringhaus

Climatography comprises quantitative and qualitative description of the climate for a given area. It involves analysis of genetic factors, individual climatic elements, the relationships which exist between controls and elements, and a synthesis of the foregoing investigations into a classification of climatic types. It is the purpose of this study to develop a climatography for the state of Michigan.

The genetic factors are the major atmospheric and locational-terrestrial variables that control Michigan's climate. The atmospheric factors that are analyzed include the general circulation, water vapor flux, the quasi-stationary action centers, migratory cyclones and anticyclones, air masses and fronts, and synoptic weather types. The general climatic patterns of the study area are shown to be strongly influenced by upper air flow (zonal or meridional), the steering of air masses by the Bermuda and Canadian Highs, the prevalence of migratory cyclones and anticyclones, and the movements of the polar front.

The second part of the study is concerned with the spatial and temporal behavior of climatic elements. Thermal elements, precipitation elements, other moisture indices, and winds are described and their areal distributions analyzed. The parameters that are established include means, extremes, variabilities, and frequencies. The effects

of the Great Lakes are discussed, and they are shown to be locally significant modifiers of several climatic elements.

The relationships between selected climatic elements and atmospheric controls are examined in part three. Frequency studies of genetic factors are also included in this section. Climatic elements are combined with the atmospheric factors with which they are temporally associated, and the results are subjected to statistical analysis in order to establish elemental parameters for the controls and to make inferences concerning the uniqueness of the genetic factors. Significant conclusions derived from these analyses are: (1) continental polar (cP) air masses occur more frequently throughout the year than any other type; however, continental arctic (cA) is important during winter and maritime tropical (mT) in all other seasons; (2) the Northern High to the South of the Great Lakes (nHs) is the synoptic weather type normally associated with very low temperatures, while the Northern and Eastern Highs (n&eH) system and the Alberta Low to the North of the Great Lakes (aLn) produce warmer than average conditions; and (3) the synoptic types yielding the largest amounts of precipitation are the Montana Low through the Lakes (mLl), the Southern Low through the Lakes (sLl), and n&eH.

In part four the relationships between selected climatic elements and locational-terrestrial factors are investigated by means of regression and correlation analysis. Correlation coefficients show that the strongest relationship exists between temperature and the locational-terrestrial factors, the weakest between precipitation and the latter, with snowfall being intermediate. Partial correlation coefficients reveal that latitude has the highest degree of relationship to spatial

variations of the climatic elements, and elevation and distance from a Great Lake are also significantly associated with elemental differences. The mapping of residuals from regression indicates that the unexplained variance in climatic elements is regionally distributed, with, in general, the Upper Peninsula being divided into eastern and western segments and the Lower Peninsula being divided into northern and southern sections.

The study is concluded by synthesizing the results of the foregoing analyses into a system of climatic regions. The classification consists of four orders of magnitude, namely: (1) the climatic (or planetary) zone; (2) the macroclimatic region; (3) the mesoclimatic province; and (4) the mesoclimatic subprovince. Michigan is shown to be within the circumpolar westerly planetary zone, to be a part of the humid microthermal (D-type in the Koeppen system) macroclimatic region of North America, and to comprise three mesoclimatic provinces. The mesoclimatic provinces are: (1) the Southern Lower Peninsula Transitional Province; (2) the Northern Lower Peninsula-Eastern Upper Peninsula Lacustrine Province; and (3) the Western Upper Peninsula Highland Province. The provinces are divided into subprovinces, and the principal climatic characteristics of each are described.

A CLIMATOGRAPHY OF MICHIGAN

By

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TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS..... ii

LIST OF TABLES..... vii

LIST OF ILLUSTRATIONS..... viii

LIST OF APPENDIXES..... x

INTRODUCTION..... 1

Statement of Problem 1
Availability of Data 1
The Study Area 2

Chapter
I. GENETIC FACTORS AFFECTING THE CLIMATE OF MICHIGAN..... 5

Locational and Terrestrial Factors 5
Latitude 5
Relative Location 6
Lacustrine Controls 7
Topography 10
The Atmospheric Factors 12
The General Circulation 12
Water Vapor Flux into Michigan 16
Quasi-Stationary Action Centers 17
Migratory Cyclones and Anticyclones 20
Air Masses and Fronts 23
Synoptic Weather Types 26
Conclusion 29

II. THE SPATIAL AND TEMPORAL BEHAVIOR OF CLIMATIC ELEMENTS IN MICHIGAN..... 30

The Thermal Elements 30
Mean Annual Temperatures 30
Mean Temperatures of the Mid-Season Months 33
January 33
April 35
July 35
October 36
Mean Annual Maximum and Minimum Temperatures 36
Temperature Extremes 38

TABLE OF CONTENTS (CONT.)

Chapter		Page
	Frequencies of Days Above, Below, or Between Certain Threshold Temperatures	39
	Temperature Variability	43
	The Spatial and Temporal Behavior of Precipitation	44
	Mean Annual Precipitation	45
	Mean Monthly and Mean Seasonal Precipitation	47
	Winter	47
	Spring	47
	Summer	51
	Fall	53
	Mean Frequency of Days with Precipitation Equal to or Greater than .10 Inch	55
	Precipitation Variability	55
	The Temporal Precipitation Regime	59
	The Distribution of Mean Annual Snowfall	64
	Solid Precipitation other than Snow	67
	Hail	67
	Freezing Rain	69
	Moisture Elements other than Precipitation	70
	Humidity	70
	Cloudiness	70
	Fog	74
	Winds and Tornadoes	75
	Surface Winds	75
	Tornadoes (High Velocity Wind Systems)	79
	Effects of the Great Lakes on Climatic Elements	81
III.	THE RELATIONSHIPS BETWEEN SELECTED CLIMATIC ELEMENTS AND ATMOSPHERIC CONTROLS.....	88
	Frequencies of Migratory Cyclones and Anticyclones	88
	Relationships between Air Masses and Climatic Elements	91
	Air Mass Frequencies	92
	Temperature Characteristics of Air Masses	96
	Precipitation Characteristics of Air Masses	100
	Frequency of Frontal Activity	106
	Relationships between Synoptic Weather Types and Climatic Elements	108
	Synoptic Weather-Type Frequencies	109
	Temperature Characteristics of Synoptic Weather Types	114
	Precipitation Characteristics of Synoptic Weather Types	122
	Analysis of Combined Cyclonic and Anticyclonic Weather Types	126
	Association of Air Masses, Synoptic Weather Types, and Climatic Elements	129

TABLE OF CONTENTS (CONT.)

Chapter		Page
IV.	THE RELATIONSHIPS BETWEEN SELECTED CLIMATIC ELEMENTS AND TERRESTRIAL CONTROLS	138
	Relationships between Mean Monthly Temperature and Selected Terrestrial Variables	141
	Relationships between Mean Monthly Precipitation and Selected Terrestrial Variables	144
	Relationships between Mean Monthly Snowfall and Selected Terrestrial Variables	147
	Summary and Conclusions	151
	Analysis of Residuals from Regression	153
	Residuals from Regression for Mean Monthly Precipitation	154
	Winter	154
	Spring	158
	Summer	159
	Fall	160
	Conclusions	162
	Residuals from Regression for Mean Monthly Snowfall	166
	Residuals from Regression for Mean Monthly Temperature	170
	Conclusions	174
V.	THE CLIMATIC REGIONALIZATION OF MICHIGAN	176
	The Climatic Zone	176
	The Macroclimatic Region	178
	Mesoclimatic Provinces and Subprovinces	184
	Description of Mesoclimatic Provinces and Subprovinces	187
	The Southern Lower Peninsula Transitional Province	187
	The Genetic Pattern	187
	The Elemental Pattern	188
	Southern Lake Michigan Lowland Subprovince	189
	Southern Lower Peninsula Interior Subprovince	190
	Thumb Upland Subprovince	191
	Erie-St. Clair Lowland Subprovince	191
	Saginaw Lowland Subprovince	192
	The Northern Lower Peninsula-Eastern Upper Peninsula Lacustrine Province	193
	The Genetic Pattern	193
	The Elemental Pattern	195
	Northern Lake Michigan Lowland Subprovince	196
	Central Lower Peninsula Interior-Transition Subprovince	197
	Northern Lake Huron Subprovince	197
	Southern Lake Huron Subprovince	198
	Northern Upland Subprovince	199

TABLE OF CONTENTS (CONT.)

Chapter		Page
	Western Northern-Upland Subprovince	200
	Eastern Upper Peninsula Subprovince	200
	Munising-Grand Marais Subprovince	201
	East-Central Upper Peninsula Interior Subprovince	202
	The Western Upper Peninsula Highland Province	202
	The Genetic Pattern	203
	The Elemental Pattern	204
	Ishpeming-Escanaba Transition Subprovince	205
	Keweenaw Bay-Western Lake Superior Lowland Subprovince	206
	Western Northern-Highland Subprovince	207
	Huron Mountains Subprovince	208
	Western Upper Peninsula Interior Subprovince	208
BIBLIOGRAPHY.....		211

LIST OF TABLES

Table		Page
1.	Source Regions, Trajectories, and Characteristics of Air Masses Affecting Michigan	24
2.	Mean Number of Days with Dense Fog	75
3.	Prevailing Wind Directions According to Air Mass Type	78
4.	Seasonal Effects of Lake and Land on the Climate of Michigan	83
5.	Low and High Pressure Systems Passing Through Michigan	89
6.	Frequency and Percentage of Occurrences of Air Mass Types	93
7.	Means, Variances, and Standard Deviations for Temperatures of Air Mass Types	97
8.	Precipitation Frequencies for Air Mass Types	101
9.	Total and Average Precipitation for Air Mass Types	103
10.	Frequency of Frontal Passages in Michigan	107
11.	Frequencies of Synoptic Weather Types at Five Selected Stations	110
12.	Temperature Means, Variances, and Standard Deviations as Related to Synoptic Weather Types	115
13.	Total and Average Precipitation for Synoptic Weather Types	123
14.	Synoptic Weather Types, Associated Air Masses, and Values of Selected Climatic Elements for Detroit	130
15.	Correlation Coefficients between Mean Monthly Temperature and Selected Terrestrial Variables	142
16.	Correlation Coefficients between Mean Monthly Precipitation and Selected Terrestrial Variables	145
17.	Correlation Coefficients between Mean Monthly Snowfall and Selected Terrestrial Variables	148
18.	Orders of Magnitude in Climatic Classification	177

LIST OF ILLUSTRATIONS

Figure		Page
1.	Weather Station Index	3
2.	Elevation and Station Network	9
3.	Upper-Atmospheric Circulation	14
4.	Centers of Action, Air Masses, and Frontal Zones	19
5.	Principal Tracks of Pressure Centers	21
6.	Synoptic Weather Types for Michigan	27
7.	Mean Annual Temperatures	32
8.	Mean Temperatures of the Mid-Season Months	34
9.	Mean Annual Maximum, Mean Annual Minimum, Absolute Maximum, and Absolute Minimum Temperatures	37
10.	Mean Frequencies of Days Above or Below Threshold Temperatures	40
11.	Mean Length of Period between Last 32° F. Temperature in Spring and First in Fall	42
12.	Mean Annual Precipitation	46
13.	Mean December, January, February, and Total Winter Precipitation	48
14.	Mean March, April, May, and Total Spring Precipitation	50
15.	Mean June, July, August, and Total Summer Precipitation	52
16.	Mean September, October, November, and Total Fall Precipitation	54
17.	Mean Number of Days with Precipitation Equal to or Greater than .10 Inch	56
18.	Coefficient of Variation for Mean Annual Precipitation	58

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.....
.....
...
..
.....
.....
...

LIST OF ILLUSTRATIONS (CONT.)

Figure		Page
19.	Precipitation Regimes	61
20.	Mean Annual Snowfall	65
21.	Prevailing Wind Directions and Tornado Tracks	76
22.	Seasonal Modifications of the Great Lakes on the Climate of Michigan	82
23.	Residuals from Regression: The Regression of Mean Monthly Precipitation on Distance from a Great Lake, Latitude, and Elevation (December, January, February, March, April, and May)	155
24.	Residuals from Regression: The Regression of Mean Monthly Precipitation on Distance from a Great Lake, Latitude, and Elevation (June, July, August, September, October, and November	156
25.	Residuals from Regression: The Regression of Mean Monthly Snowfall on Distance from a Great Lake, Latitude, and Elevation (November, December, January, February, March, and April)	167
26.	Residuals from Regression: The Regression of Mean Monthly Temperature on Distance from a Great Lake, Latitude, and Elevation (December, January, February, March, April, and May)	171
27.	Residuals from Regression: The Regression of Mean Monthly Temperature on Distance from a Great Lake, Latitude, and Elevation (June, July, August, September, October, and November)	172
28.	Climatic Regions of Eastern America	181
29.	Climatic Provinces and Subprovinces of Michigan	182

LIST OF APPENDIXES

Appendix		Page
A.	Lists of Stations Used in Temperature, Precipitation, and Regression Analyses	218
B.	Tables Summarizing Difference of Means and Chi-Square Tests of Chapter III	224
C.	Explanation of Regression and Correlation Analyses of Chapter IV	229

INTRODUCTION

Statement of Problem

Climatography comprises quantitative and qualitative description of the climate for a given area. It involves systematic and correlative analyses of individual climatic elements and investigations of their relationships to locational-terrestrial and atmospheric factors.

In contrast to many other states, a climatography of Michigan has not yet been written. It is the purpose of this study to fill this gap by evaluating the available climatic record of the state as follows:

1. descriptive analysis of genetic factors with special emphasis on meteorological element complexes (general atmospheric circulation, pressure systems, air masses and fronts, and synoptic weather types), and discussion of climatically relevant locational-terrestrial factors;
2. descriptive and inferential analyses of individual climatic elements (temperature, hydrometeors, and winds);
3. correlation analyses, with climatic elements and genetic factors as parameters; and
4. classification of climatic types.

Availability of Data

The data used in this study are from official records of the

United States Weather Bureau. The network of stations is shown in Figure 1.[1] In general, the network is composed of sites having continuous observations for the period 1931-1960. Different combinations of stations appear in some sections of the paper because of the nature of the analysis or the absence of suitable data. In the air mass and weather type analyses, the network is limited to the five stations appearing on the Daily Weather Map because these genetic phenomena are meteorologically similar over short distances. The correlation analyses are based on stations for which weather records on punched cards are available (see Appendix C).

In addition to an observation period of sufficient length, two other prerequisites had to be met by each station: (1) the records must be homogeneous, i.e., a sample from a single population (this may normally be assumed if the station has not been moved to a new location and the instrument exposures have not been fundamentally changed);[2] and (2) the selected stations must be as evenly distributed over the study area as possible.

The Study Area

The area selected for this study is the territory comprising the state of Michigan. Michigan is located in the east-central section

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[1]See Appendix A for lists of stations used in temperature, precipitation, and regression and correlation analyses.

[2]For a summary of information on substation locations, elevations, exposures, instrumentations, records, and observers from the year each station was established and through 1955, see U.S., Dept. of Commerce, Weather Bureau, Substation History: Michigan, Washington, D.C., 1956.

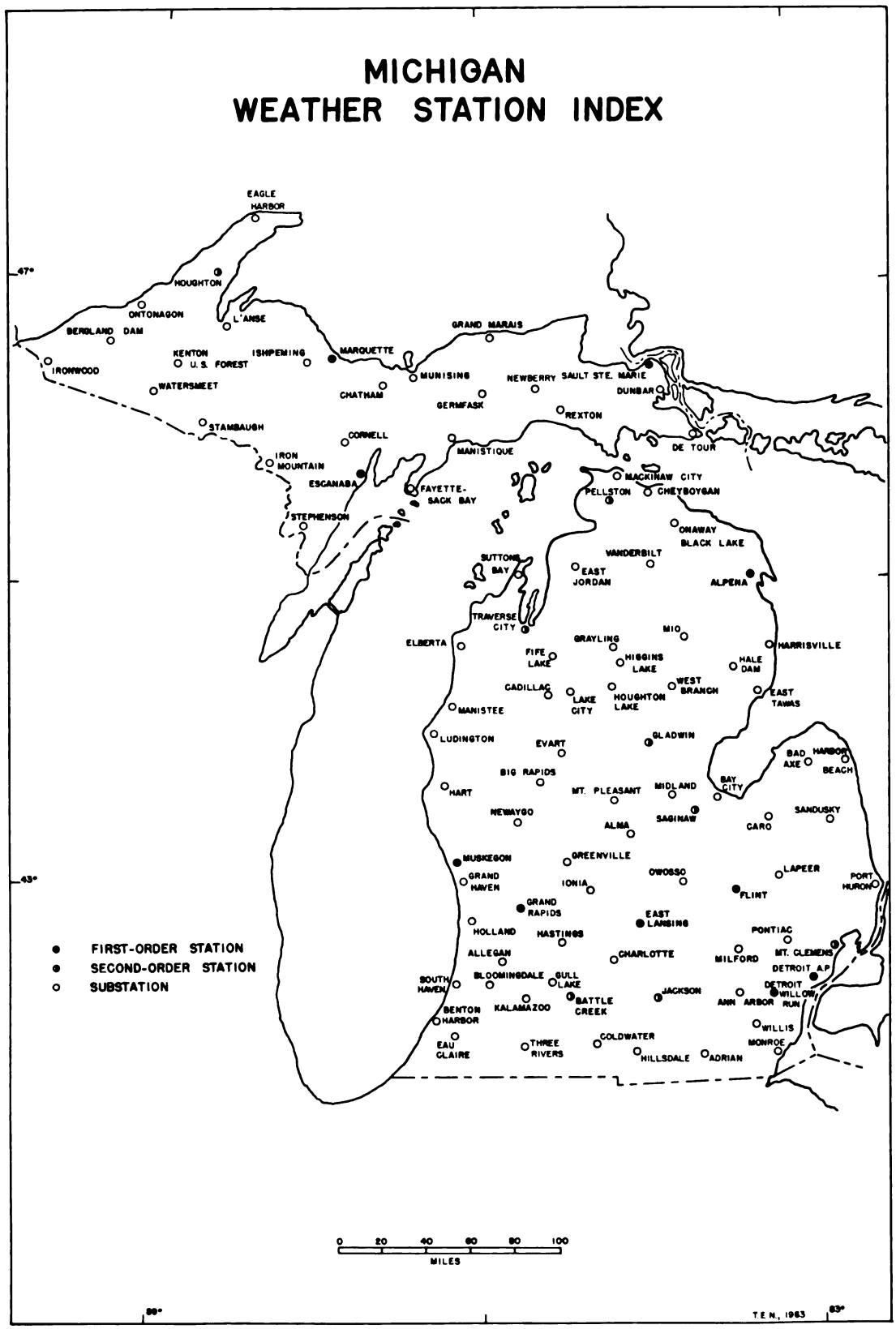

MICHIGAN
WEATHER STATION INDEX
EAGLE HARBOR
HOUGHTON
ONTONAGON
L'ANSE
BERGLAND DAM
KENTON
ISHPEMING
MARQUETTE
GRAND MARAIS
U.S. FOREST
IRONWOOD
WATERSMEET
MUNISING
NEWBERRY
SAULT STE. MARIE
DUNBAR
CHATHAM
GERMFASK
REXTON
STAMBAUGH
CORNELL
MANISTIQUE
DE TOUR
IRON MOUNTAIN
ESCANABA
MACKINAW CITY
FAYETTE-SACK BAY
PELLSTON
CHEBOYGAN
STEPHENSON
ONAWAY
BLACK LAKE
SUTTONS BAY
WANDERBILT
EAST JORDAN
ALPENA
TRAVERSE CITY
MIO
ELBERTA
GRAYLING
HARRISVILLE
FIFE LAKE
HIGGINS LAKE
HALE DAM
CADILLAC
WEST BRANCH
LAKE CITY
HOUGHTON LAKE
EAST TAWAS
MANISTEE
LUDINGTON
EVART
GLADWIN
BAD AXE
HARBOR BEACH
BIG RAPIDS
HART
MT. PLEASANT
MIDLAND
BAY CITY
NEWAYGO
SAGINAW
SANDUSKY
ALMA
CARO
MUSKEGON
GREENVILLE
OWOSSO
LAPEER
GRAND HAVEN
IONIA
PORT HURON
FLINT
GRAND RAPIDS
EAST LANSING
HOLLAND
HASTINGS
PONTIAC
ALLEGAN
CHARLOTTE
MILFORD
MT. CLEMENS
DETROIT A.P.
BLOOMINGDALE
GULL LAKE
SOUTH HAVEN
JACKSON
DETROIT WILLOW RUN
ANN ARBOR
KALAMAZOO
BATTLE CREEK
BENTON HARBOR
WILLIS
COLDWATER
EAU CLAIRE
THREE RIVERS
MONROE
HILLSDALE
ADRIAN
FIRST-ORDER STATION
SECOND-ORDER STATION
SUBSTATION
0 20 40 60 80 100
MILES
47°
43°
89°
83°
T.E.N., 1963

Figure 1

of North America (see inset map on Figure 2). The general situation of the study area may be called mid-latitude-continental.

Physiographically, the state is divided into two main peninsulas which are enclosed by four of the Great Lakes of North America. The isthmuses of both peninsulas are oriented toward the south. The northern peninsula is referred to in this text as the Upper Peninsula and the southern is called the Lower Peninsula.[1] The entire Lower Peninsula and the eastern half of the Upper Peninsula are parts of the Central Lowland physiographic province which, topographically, is an extensive area of plains. The western Upper Peninsula is a part of the Laurentian Upland, a more elevated area having somewhat greater local relief than the Central Lowland portion of the state.[2] A more detailed examination of the relationship between locational-terrestrial factors and the climate of the study area is provided in Chapter I.

The selection of the study area was made on the basis of three principal criteria: (1) the lack of previous, detailed investigations; (2) the unusual climatic characteristics of a mid-latitude, continental area enclosed by large, inland water bodies; and (3) the availability and suitability of data.

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[1]These terms, although incorrect in a strictly geographic nomenclature, are so entrenched in common language that their use in a scientific context seems justified.

[2]See Wallace W. Atwood, Physiographic Provinces of North America, (Boston: Ginn and Co., 1940) Pp. 185-228.

CHAPTER I

GENETIC FACTORS AFFECTING THE CLIMATE OF MICHIGAN

The genetic factors that affect the climate of Michigan may be divided into two major groups for analytical purposes. These are: (1) the locational and terrestrial factors; and (2) the atmospheric factors.

Locational and Terrestrial Factors

Latitude

Michigan has a latitudinal extent of nearly 6° with its southern and northern boundaries lying at 41° 45' N. and 47° 30' N, respectively. Its mid-latitude position is responsible for the large annual variations in zenithal sun angle and length of daylight period. Along the 45th parallel, for example, the noon altitude of the sun is 68½° at the time of the Northern Hemisphere summer solstice, and 21½° at the time of the winter solstice. Length of daylight period along the same parallel changes from 15 hours and 37 minutes at the summer solstice to 8 hours and 46 minutes at the winter solstice.[1] Latitudinal extent also causes small, but significant, regional differences in sun angle and length of day. For instance, at the summer solstice, length of

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[1]Glenn T. Trewartha, An Introduction to Climate, (New York: McGraw-Hill, 1954) Pp. 8-9.

day at the state's southern extremity is 15 hours and 15 minutes while in the extreme north it is 45 minutes longer. A constant sun angle variation of approximately 6^{o} exists between the north and south extremities. Thus, the amount of insolation received at the edge of the atmosphere above the study area differs greatly between summer and winter, and to a slight degree during any given season between north and south.

The mid-latitude position of the state is reflected in the high degree of weather changeability. Lying in the zone of prevailing westerlies, the study area is subjected to constantly changing circulation patterns, while the migration of the polar front brings the area alternately under the influence of polar and tropical air masses.

Relative Location

Continental location is a major control of Michigan's climate. No ocean lies within 500 miles of the study area, and westward and southward the distances are much greater. To the west, 2,000 miles separate the state from the Pacific Ocean. To the east, the Atlantic Ocean is only about 500 miles away, but it lies leeward of the state with respect to prevailing winds. The Gulf of Mexico is about 1,000 miles due south of the study area; if circulation is meridional (i.e., south-to-north) tropical air masses from this source region can easily reach the Great Lakes area. The nearest large water body to the north is nearly 500 miles distant; although extensive, Hudson Bay is nearly surrounded by land, is frozen during the winter, and, unlike the Gulf of Mexico, does not represent an air mass source region. Thus, it exerts only a negligible influence on the climate of the

study area.

The Western Cordillera of North America reinforces continentality by protecting areas on its lee (eastern) side from Pacific maritime influences. Between the study area and the Atlantic Ocean, the Appalachian Highlands stand as a lower, but not insignificant, barrier to the occasional westward movements of maritime air masses. No similar barriers block the movement of air masses into the study area from either the north or the south. The depression of the Mississippi River valley allows air originating over the Gulf of Mexico to penetrate deep into the interior of the continent without modification by orographic effects. To the north, air masses from the arctic area of Canada move toward the state with little retardation or modification by mountain barriers.

Lacustrine Controls

The two main peninsulas that compose the territory of the study area have their bases toward the south, and these are rather wide in relation to the total areas of the peninsulas, with both bases measuring about 170 miles. The extent of water surface separating the main peninsulas from other land areas rarely exceeds 200 miles, and throughout most of the state is considerably less. Yet, the water bodies surrounding these peninsulas, namely, Lake Superior, Lake Michigan, Lake Huron, and Lake Erie (and much less importantly, Lake St. Clair) significantly modify the climate of the adjacent areas.

Only a relatively small part of the land area of Michigan is more than 75 miles from one of the Great Lakes, and over half of its area is within 50 miles. Because of the 3,235 miles of shoreline,

an appreciable part of the study area lies within a few miles of Lake water. However, the climatic modification that each Lake exerts on the adjacent land depends not only on distance between land and water, but also on the Lake's size, shape, depth, and position relative to prevailing winds (see Figure 2). The influence of the Lakes on land is not direct; it is transmitted through the meteorological modifications of air masses that pass over the water bodies before reaching the study area.

Lake Superior is the largest, most northerly, and deepest of the Great Lakes. Its long axis is east-west (350 miles), but it has considerable north-south extent also (160 miles). The Lake's shape is complicated by the Keweenaw Peninsula which juts out almost to its center. With a water surface of approximately 30,000 square miles, Lake Superior is over half the size of the entire land area of Michigan.

Lake Michigan, which occupies the windward position with respect to the Lower Peninsula, has a north-south axis, and its shape is more elongated than that of Lake Superior. The west-east dimensions of the Lake vary from about 50 miles in the south to 100 miles in the north. Air masses traveling meridionally may traverse 300 miles of water before reaching land. The shoreline is relatively straight, particularly in the south. In the north, the Door Peninsula of Wisconsin and the Leelanau Peninsula of Michigan cause irregularities in shape.

Lake Huron, like Lake Michigan, has a north-south axis (220 miles), but is not as elongated. It has a greater east-west extent

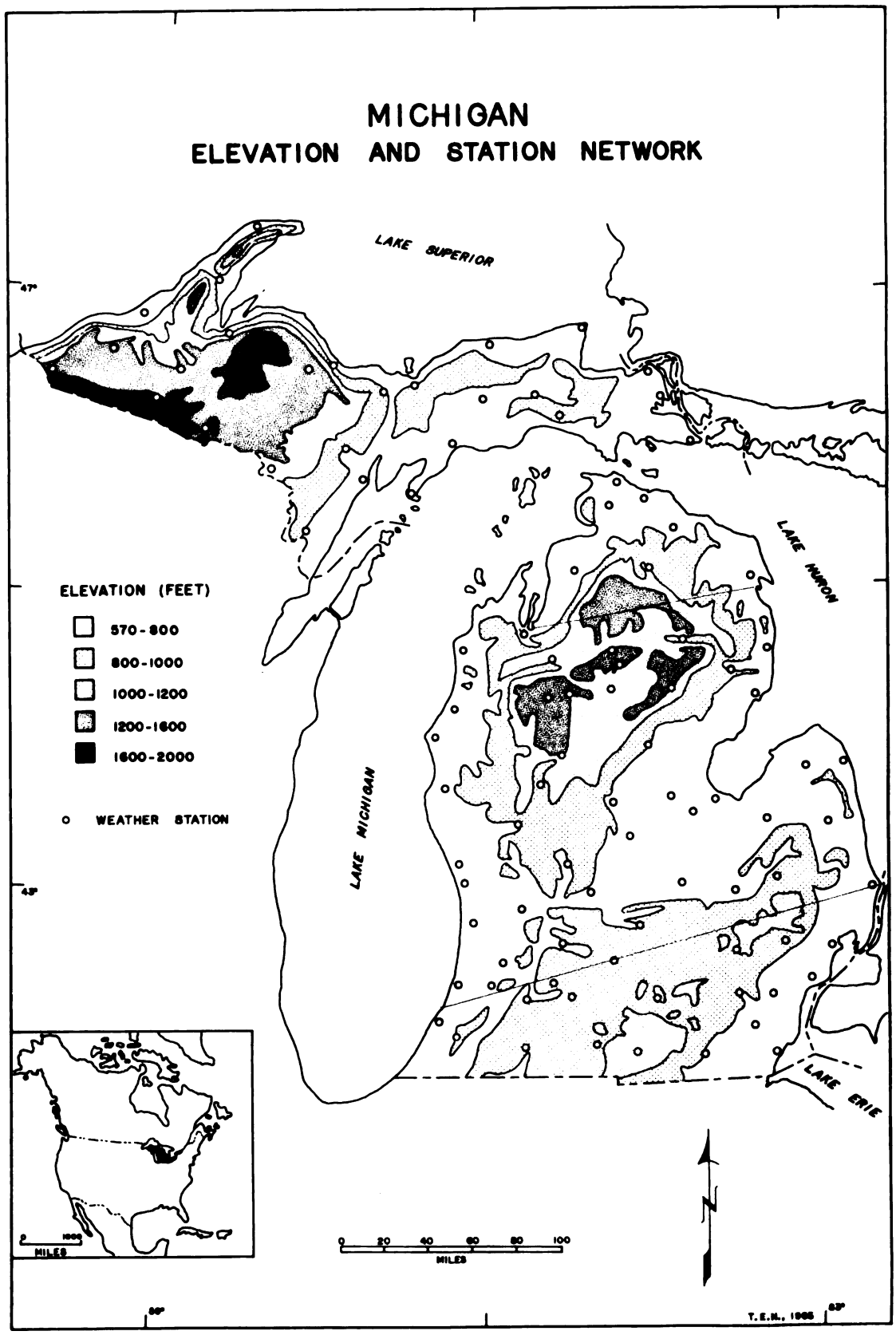

MICHIGAN
ELEVATION AND STATION NETWORK
LAKE SUPERIOR
LAKE HURON
LAKE MICHIGAN
LAKE ERIE
47°
43°
ELEVATION (FEET)
570-800
800-1000
1000-1200
1200-1600
1600-2000
WEATHER STATION
0 20 40 60 80 100
MILES
N
T.E.M., 1966

Figure 2

(180 miles) and a more irregular shape than does its western counterpart. Lake Huron's shape is complicated by the ~~Skaugen~~ SAUGEEN (BRUCE) Peninsula and Manitoulin Island in Ontario, and by the indentation of Saginaw Bay to the southwest.

Lake Erie, like Lake Superior, has an east-west axis; however, it is only one-third the size and considerably shallower than the northern Lake. Both Lakes Erie and Huron lie to the east of the study area, or leeward with respect to prevailing winds, while Lakes Superior and Michigan have positions on the windward side.

Topography

Topographic elements of direct climatic significance are elevation, local relief, and orientation of landforms. With regard to absolute elevation, the state may be divided into lowlands, uplands, and highlands.[1] These are shown in Figure 2. The lowlands generally border the Great Lakes and have elevations from 570 to about 900 feet. The principal lowland regions are: (1) the Erie-St. Clair Lowland in the southeastern Lower Peninsula; (2) the Saginaw Lowland surrounding Saginaw Bay in the east-central Lower Peninsula; (3) the Michigan Lowland along the eastern shore of Lake Michigan; (4) the Eastern Lowland of the eastern half of the Upper Peninsula; and (5) the Keweenaw Lowland fringing the Keweenaw Peninsula in the western Upper Peninsula.

There are two upland areas in the state, both in the Lower Peninsula. The uplands are found at altitudes between 900-1300 feet,

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[1]Bert Hudgins, Michigan: Geographic Backgrounds in the Development of the Commonwealth, (Ann Arbor, Mich.: Edwards Bros., 1958), P. 17.

with one being located in the north-central portion of the peninsula and the other in the southeastern section, to the northwest of the Erie-St. Clair Lowland. The former is referred to as the Northern Upland (or the High Plains), and the latter is called the Thumb Upland, because it forms the physiographic backbone for the thumb of the mitten-like shape of the Lower Peninsula.[1]

The western half of the Upper Peninsula is dominated by topography that has elevations between 1200 and 2000 feet. This area, referred to as the Northern Highlands, is the only truly mountainous section of the state. In particular, the Huron Mountains, the Porcupine Mountains, the Gogebic Range, and the Copper Range stand higher than the surrounding terrain, and are the most significant orographic barriers within the study area.

Local relief is moderate; at no place within the study area does it exceed 1500 feet, and much lower values are typical. The greatest elevation differences are found in the Northern Highlands in the vicinity of the Porcupine Mountains (along Lake Superior in the extreme west of the Upper Peninsula), the Copper Range (extending southwest-northeast along the Keweenaw Peninsula), and the Huron Mountains (a group of hills between L'Anse and Ishpeming). Here, local relief exceeds 1400 feet in some places, but, over most of the area, is less than 1000 feet.

Local relief within the remainder of the state is of less magnitude than that of the Northern Highlands. The principal features of above average local relief in the eastern Upper Peninsula and the Lower Peninsula are belts of hills which constitute very

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[1] Ibid.

irregular, hummocky topography. In most parts of the above areas, however, the hills do not rise more than 200 feet above the surrounding terrain. Important exceptions are (1) on the rim of the Northern Uplands where relief exceeds 500 feet in a few places, and (2) in parts of the Thumb Upland. Many of these belts of hills are oriented meridionally, and consequently transverse to the prevailing winds.

Most of the remainder of the Central Lowlands portion of the state consists of flat or gently undulating plains with no appreciable local relief. However, two additional climatically relevant relief features do occur in some parts of the study area. At many places along Lake Superior the eastern Upper Peninsula has high, cliff-like shores, for example, in the Pictured Rocks area northeast of Munising. In the Lower Peninsula extensive sand dune formations are found along the eastern and southern shores of Lake Michigan, with maximum local relief over 300 feet. Sand dunes with appreciable local relief do not occur on the shores of Lakes Superior, Huron or Erie.

The Atmospheric Factors

The General Circulation

The general circulation is the complex pattern of atmospheric motions that results from the unequal heating of tropical and polar areas and from the earth's rotation.[1] The atmosphere over the study area is dominated by a component of the general circulation referred to as the circumpolar westerlies, which may be defined as a tropospheric wind belt, shifting latitudinally from season to season, but always

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[1]Sverre Petterssen, Introduction to Meteorology, (New York: McGraw-Hill, 1941) Pp. 98-110.

characterized by a west-to-east (quasi-geostrophic) flow of air in a circumpolar orbit.[1] Figure 3 illustrates the two basic types of circumpolar westerly circulation which govern the upper air flow over Michigan throughout the year. By means of height contours, wind directions, and temperatures at the 500 millibar level, a zonal flow pattern is contrasted with a meridional flow pattern.

The zonal flow map is representative of a winter situation. The winds over the Great Lakes at the 500 millibar level (corresponding to about 18,000 feet in altitude) are oriented almost straight west-to-east, with a consequent westerly flow of air. Colder air at this elevation lies well to the north of the study area, whereas warmer air is found slightly to the south. When this type of circulation prevails, surface temperatures in Michigan are usually near, or slightly above average.

The synoptic pattern chosen to indicate meridional flow shows a movement of air from the north to the south. The study area lies near the center of a pronounced trough in the circumpolar westerlies which is causing very cold air to flow over the state with meridional orientation rather than latitudinal. Relatively warm air now lies far to the east, west, and south. Surface temperatures in Michigan are normally well below average during the persistence of the upper trough.

The location of upper waves, their season of occurrence, and their mean and extreme periods of persistence, greatly influence the weather and climate of the study area. Zonal flow (high index) may

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[1]Kenneth F. Hare, "The Westerlies," Geog. Review, Vol. 50, No. 3, July 1960, Pp. 345-367.

UPPER-ATMOSPHERE CIRCULATION
ZONAL FLOW PATTERN
MERIDIONAL FLOW PATTERN
COLD
WARM
COLD
WARM
500 MB. CONTOURS IN FEET ABOVE SEA LEVEL
WIND DIRECTION AT 500 MB. LEVEL
TEMPERATURES -35° C., OR LOWER, AT 500 MB. LEVEL
TEMPERATURES -15° C., OR HIGHER, AT 500 MB. LEVEL
T.C.N. 1953
SOURCE: U. S. WEATHER BUREAU, DAILY WEATHER MAP, JANUARY 8, 1958
SOURCE: U.S. WEATHER BUREAU, DAILY WEATHER MAP, JANUARY 8, 1958

Figure 3

change into meridional flow (low index), and vice versa, thus causing non-periodic temperature changes. A change from zonal to meridional and again to zonal flow may be referred to as an index cycle.[1] Namias[2] has stated that the quasi-permanent troughs and ridges of the circumpolar westerlies are anchored in different longitudinal positions in different years, and thus in some years the flow patterns become more highly organized into confluence (high index) bands than in others. In this manner the reservoir of cold polar air in the north is stored or depleted over different time intervals. The intensity of the cycle is thought to depend on net outgoing radiation and length of storage time in the area of the cold air reservoir. Therefore, variations in the character of index cycles from year to year are very likely. This differentiation in the intensity of cycles is one of the chief factors for the high degree of weather variability in Michigan.

Another important factor which must be considered in the dynamic climatology of the state is the jet stream. On most flow maps drawn for the 500 millibar level, or higher, bands of high wind velocity can be recognized over the interior of North America throughout the year. It has been shown that the movement of surface weather systems, such as cyclonic centers along the polar front, is governed by the "steering" of jet streams, and that the distribution of precipitation

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[1]For a discussion of high and low indexes and the index cycle see Jerome Namias, "The Index Cycle and its Role in the General Circulation," Journal of Meteorology, Vol. 7, No. 2, April 1950, Pp. 130-139.

[2]Ibid.

bears close relationship to the location and intensity of the jets.[1] In winter the zone of strongest jets is located well to the south of the state (25-30° N.), but they are often found over the Great Lakes in the transitional seasons, and reach their northernmost position over southern Canada in summer. While weakened due to the absence of strong temperature contrasts in the upper atmosphere during summer, jet stream activity is conspicuous during spring and fall, as evidenced by the high frequency of cyclonic and frontal systems passing through the state in these periods (see Chapter III for frequency analyses).

In the preceding section of this chapter it was noted that there are no major topographic barriers to the north or south of Michigan which might seriously impede the free movement of air from these directions into the study area. This fact takes on added significance with the knowledge that meridional transfers of air, induced by upper waves and the meanderings of the jet streams, occur with regularity within the framework of the circumpolar westerly circulation.

Water Vapor Flux into Michigan

The general circulation is responsible for the movement of water vapor into the study area. The transfer of moisture from the oceans onto the North American continent is accomplished mainly by two well-defined streams: (1) a strong southerly flow from the Gulf of Mexico; and (2) a comparatively weak westerly movement from the Pacific Ocean.

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[1]For discussions of the jet stream see Jerome Namias and Philip Clapp, "Confluence Theory of the High Tropospheric Jet Stream." Journal of Meteorology, Vol. 6, No. 5, October 1949, Pp. 330-336; and Lloyd G. Starret, "The Relationship of Precipitation Patterns in North America to Certain Types of Jet Streams at the 300 Millibar Level," Journal of Meteorology, Vol. 6, No. 5, October 1949, Pp. 347-352.

These streams of water vapor converge in central North America to form an intense region of outflow extending from North Carolina to the southern coast of Labrador. Of the two major streams, the southerly flow from the Gulf of Mexico makes by far the greatest contribution to water-vapor flux into the study area.[1]

The net water-vapor transfer from the oceans to the atmosphere over Michigan varies greatly from winter to summer. In winter the average flux ranges from 1600 grams per cubic mile per second in the southeast to a minimum of 600 grams in the northwest. In summer the moisture transfer is more uniform over the area, varying from about 1500 grams per cubic mile per second in the southwest to nearly 2000 grams in the northeastern Upper Peninsula. The southern Lower Peninsula thus has the highest flux during winter and the Upper Peninsula has the highest vapor transfer during summer. For the entire year, however, the southeastern section has the strongest mean flux (1500 grams) and the northwest has the weakest (1000 grams).[2] This is reflected in the somewhat greater mean convectional and warm-sector precipitation received in the southern part of the state (see Chapter II).

Quasi-Stationary Action Centers

The quasi-stationary pressure cells which govern the circulation over the state may be grouped into two general types: (1) the oceanic or planetary cells consisting of subpolar lows (Aleutian and Icelandic);

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[1]George S. Benton and Mariano A. Estoque, "Water Vapor Transfer over the North American Continent," Journal of Meteorology, Vol. II, No. 6, Dec. 1954, Pp. 462-477.

[2]Ibid.

and (2) the continental or thermal cells which normally have high pressure in winter (Canadian and Basin Highs) and low pressure in summer (Arizona Low). Of these systems (see Figure 4) only the Canadian High and the Bermuda High have both direct and frequent influence over the weather of the study area.

Figure 4 clearly indicates the dominance of the Bermuda High over the eastern United States during summer, with its anticyclonic flow of warm, moist tropical air around its western flank into the study area. However, the equatorward migration of the Bermuda system during winter significantly decreases its ability to steer air masses as far north as Michigan.

In winter the Canadian High often covers the major portion of the northern interior of the continent. The center of the anticyclonic system may lie as far south as the Great Lakes area but even if it is located far to the north, its dominance may extend from the arctic to the mid-latitudes, especially if a low index (meridional) circulation is established. It is the principal action center controlling the movement of cold, dry air masses into the study area. The Basin High, occurring during winter over the intermontane area of the western United States, is only indirectly related to Michigan weather as a blocking anticyclone, preventing the entrance of Pacific cyclones to the interior of North America.

During fall, winter, and spring, when polar and tropical air masses have substantial temperature differences, air forced southward by the Canadian High may encounter air forced northward by the Bermuda High with the resultant development of a wave disturbance. The subsequent propagation of migratory cyclones, and frontal systems

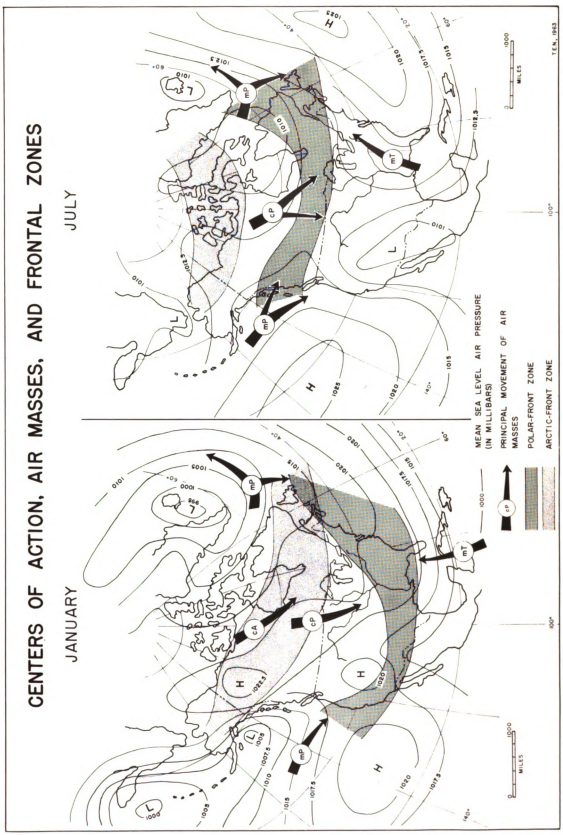

CENTERS OF ACTION, AIR MASSES, AND FRONTAL ZONES
JANUARY
JULY
MEAN SEA LEVEL AIR PRESSURE (IN MILLIBARS)
PRINCIPAL MOVEMENT OF AIR MASSES
POLAR-FRONT ZONE
ARCTIC-FRONT ZONE
MILES
TEN. 1943

Figure 4

is one of the chief factors responsible for the non-periodic temperature changes, precipitation patterns, and other weather phenomena characteristic of the study area.

In summer wave disturbances are less frequent because of the lack of great temperature differences between polar and tropical air masses. At this time the Canadian High retreats far to the north of Michigan, and the interior of the continent develops a tendency toward low pressure. This permits unstable, maritime air masses to penetrate deep into the continent with the Bermuda High performing the major steering function.

Migratory Cyclones and Anticyclones

Closely associated with the centers of action and the air mass-frontal complexes (see preceding and following sections, respectively) are the migratory cyclones and anticyclones. These transitory, moving systems of air represent the dynamic element in the surface circulation pattern, and are thus responsible for the steering of air masses and fronts into specific locations.

Figure 5 illustrates the principal tracks and relative numbers per month (for January, April, July, and October) of pressure centers crossing the study area.[1] In January most cyclones pass through the southeastern quadrant of the state (cf. p. 25 for winter position of polar front). A minor route, not shown on the map but located to the north of Lake Superior, is associated with the mean location of

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[1]Data for this study were derived from U.S., Dept. of Commerce Weather Bureau, Principal Tracks and Mean Frequencies of Cyclones and Anticyclones in the Northern Hemisphere, Research Paper No. 40, Washington D.C., 1957.

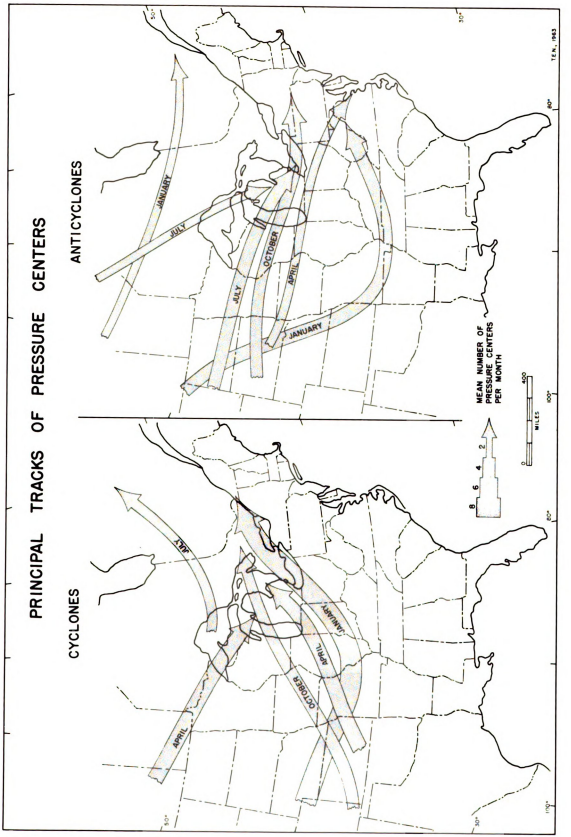

PRINCIPAL TRACKS OF PRESSURE CENTERS
CYCLONES
ANTICYCLONES
JULY
APRIL
JANUARY
OCTOBER
MEAN NUMBER OF PRESSURE CENTERS PER MONTH
8 6 4 2
0 400
MILES
Feb. 1943

Figure 5

the arctic front.

In April migrating cyclones traverse Michigan on well-defined southeast- and northeast-trending tracks. By July the zone of maximum cyclonic frequency has shifted north of the study area. The October pattern resembles the April situation except that the fall month has only one major track bisecting the state.

There are two major paths of anticyclones during January although neither passes through the study area, one being to the north and northeast, the other to the west and southwest. The former track represents zonal flow while the latter indicates meridional motion. The extensive areas covered by the typical migratory high pressure systems often incorporate the state at least in their peripheral circulation.

In April anticyclones tend to travel closer to Michigan, as indicated by the major track through the extreme southern part of the state. By July anticyclones frequently move across the center of the Great Lakes region. A latitudinally oriented track is influenced by upper-atmospheric zonal flow while a northwest-to-southeast route corresponds to meridional flow. In October the dominance of zonal migration is indicated by the typically west-to-east trajectories of most anticyclones, with a major track oriented through the center of the study area.

Figure 5 clearly shows that moving anticyclones tend to avoid the study area in January with the opposite being true in July. Although this is basically the result of the mean position of the

polar and arctic fronts, Lautenhiser[1] has suggested that the Great Lakes have to be considered as causative factors. He has stated that the Lakes are responsible for a rise in atmospheric pressure during late spring and summer when they are colder than the air temperatures over adjacent land; conversely, they tend to lower the pressure in late fall and winter when they are warmer than the surrounding land. Therefore, Highs that reach the study area are strengthened in summer and weakened in winter. Similarly, Lows tend to deepen in winter and to disintegrate or be deflected from the Lakes during summer.[2]

Air Masses and Fronts

The principal air masses affecting Michigan's climate are illustrated in Figure 4 and described in Table 1.[3] Continental polar (cP) and maritime tropical (mT) are the dominating air masses, with continental arctic (cA) air being significantly represented in winter, and maritime polar (mP) air, although having its source regions far from the study area, occasionally invading the region.

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[1]R. E. Lautenhiser, "Great Lakes Weather," Weatherwise, Vol. 6, No. 1, Feb. 1953, Pp. 3-6.

[2]Frequency and elemental analyses of Highs and Lows, air masses and fronts, and synoptic weather types are presented in Chapter III.

[3]Table 1 and the subsequent discussion are based largely on the following sources: D. H. Brunnschweiler, "The Geographic Distribution of Air Masses in North America," Vierteljahrsschrift der Naturforschenden Gesellschaft, Zurich, 1952, Pp. 42-49; H. C. Willett, "Characteristic Properties of North American Air Masses," in J. Namias, et. al., An Introduction to Air Mass and Isentropic Analysis, (Milton, Mass.: The American Meteorological Society, Oct. 1940), Pp. 73-74; Albert K. Showalter, "Further Studies of American Air Mass Properties," Monthly Weather Review, Vol. 67, No. 7, July 1939, Pp. 204-218; and, A. Austin Miller, "Air Mass Climatology," Geography, Vol. 38, No. 180, Part 2, April 1953, Pp. 53-67.

TABLE 1

SOURCE REGIONS, TRAJECTORIES, AND CHARACTERISTICS OF AIR MASSES AFFECTING MICHIGAN

Winter

Type	Source Region	Frequent Trajectory	Characteristics
cA continental Arctic	Arctic Ice Cap and Northern Canada	Into southern Canada and northern United States	Extremely cold, dry, stable
cP continental Polar	Central Canada, Northern Great Plains, Great Basin	Southward along Mississippi R. Valley into S. Great Plains	Cold, dry, stable
mP maritime Polar	A) Northern Pacific B) Northwest Atlantic	A) Along Pacific Coast, interior of Pacific Northwest B) Southwestward through St. Lawrence Valley	A) Cool, moist, unstable B) Cool to cold, moist, unstable
mT maritime Tropical	Gulf of Mexico and Caribbean Sea	Northward through Mississippi Valley and N.E. United States	Warm, moist, unstable, but becoming more stable over land because of surface chilling, lowering of lapse rate
NcP modified continental Polar	Same as continental Polar	Into southeastern U.S., returning to northeastern U.S. along western flank of anticyclone	Warmer, more moist, and more unstable than unmodified cP

Summer

cP continental Polar	North-central Canada	Southward through Great Lakes region, and into western Great Plains	Relatively cool and stable in source region, but becomes warmer and less stable as it moves equatorward
mP maritime Polar	Northermost Pacific and Arctic Basin	Along North Pacific, British Columbia, and into northeastern Canada	Coldest summer air mass, highly unstable, moist
mT maritime Tropical	Same as in winter	Mississippi Valley and southeastern Canada	Very warm, very moist, and unstable

Two major frontal zones influence the study area: (1) the polar front, separating tropical from polar air masses; and (2) the arctic front, separating polar from arctic air masses. Mean locations of the polar and arctic frontal zones are shown in Figure 4. The polar front is normally situated in the southern part of North America during January, while the arctic front lies only a short distance north of the study area. As a consequence the state is dominated by northern-continental air masses during winter, with cP usually occurring at times of zonal flow and cA with well-developed meridional flow. The position of the polar front prevents frequent movements of mT air masses into the Great Lakes region.

Figure 4 shows the junction of the arctic and polar fronts in the vicinity of Newfoundland during winter. Their proximity is of great significance to Michigan's climate because the numerous cyclonic storms originating along these fronts will either pass through the study area or at least involve it in their circulation systems.

By July the arctic front is far to the north of the study area, while the polar front has a mean position similar to that of the arctic front in January. As far as air masses are concerned the result is alternate domination by mT and cP air, the former filling warm sectors, the latter penetrating the area behind cold fronts of individual cyclonic storms. The same air masses may also arrive under anticyclonic regime, with the Bermuda High and the Canadian High serving as circulation vehicles.

Figure 4 indicates only the mean summer and winter positions of the frontal zones. In the transitional months the polar front is often situated directly over Michigan as a result of its latitudinal

movement. Although the location of the front may vary considerably from year to year for any given month, September and October in the fall and May and June in the late spring are the normal periods in which frontal activity is strongest in the study area.

Synoptic Weather Types

A synoptic weather type may be defined as an isobaric configuration which controls the weather of a large area through the combined effectiveness of its associated meteorological complexes, viz. pressure fields, air masses, and fronts.[1] It is areally and temporally definable. Once the synoptic type is recognized on the weather map, its trajectory can be followed and the behavior of individual weather elements at a particular station can be conceived as the consequence of the persistence of relatively homogeneous atmospheric conditions. (The recurrence of particular synoptic types at certain times of the year is called a singularity.)

A classification of synoptic weather types which play a role in the climate of Michigan is presented in Figure 6.[2] It is based on the following criteria: (1) the gross surface circulation pattern; (2) the place of origin of cyclonic or anticyclonic systems, expressed relative to the Great Lakes region; and (3) the subsequent trajectory

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[1]See, e.g., Wesley Calef, et. al., Winter Weather Type Frequencies in the Northern Great Plains, Technical Report of the Quartermaster Research and Engineering Command, U.S. Army, Regional Environments Research Branch, Natick, Mass., August 1957; California Inst. of Technology, Meteorology Dept., Synoptic Weather Types of North America, Pasadena, Calif., Dec. 1943; and R. D. Elliott, "The Weather Types of North America." Weatherwise, Vol. II, 1949, Pp. 40-43, 64-67, 110-113, 136-138.

[2]This classification is derived from Larry A. Hodgins, Genetic Climatology of the Great Lakes Region, Master's Thesis, Michigan State University, East Lansing, Mich., 1960.

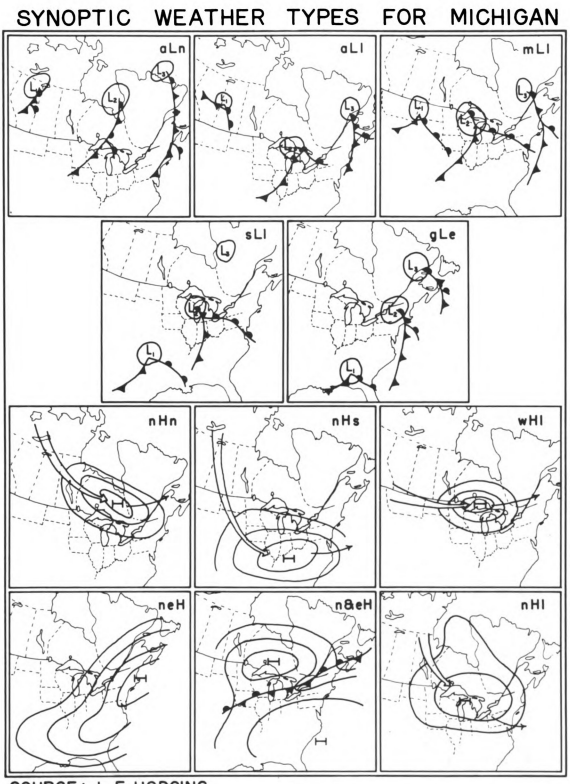

SYNOPTIC WEATHER TYPES FOR MICHIGAN
aLn
aLl
mLl
sLl
gLe
nHn
nHs
wHl
neH
n&eH
nHl
SOURCE: L.E.HODGINS

Figure 6

of the system with respect to the Great Lakes.

In Figure 6 and subsequent analyses (see Chapter III) each synoptic type is represented by a combination of letters as follows: (1) the first letter designates the area where the system originated with respect to the Great Lakes, by cardinal direction or the first letter of a place name; (2) the second letter is either "L" indicating cyclonic circulation or "H" indicating anticyclonic circulation; and (3) the third letter, if present, denotes the trajectory of the system's track in relation to the Great Lakes, by cardinal direction.

Five cyclonic and six anticyclonic types were found to have climatic effects on the study area. These are:

CYCLONIC:

1) aLn[1] - (Alberta Low to the North)

2) aLl - (Alberta Low through the Lakes)

3) mLl - (Montana Low through the Lakes)

4) sLl - (Southern Low through the Lakes)

5) gLe - (Gulf of Mexico Low to the East)

ANTICYCLONIC:

1) nHn - (Northern High to the North)

2) nHs - (Northern High to the South)

3) wHl - (Western High through the Lakes with a subtype wHs, Western High to the South)

4) neH - (New England High, remaining in a stationary position)

5) n&eH - (Northern and Eastern Highs, separated by a stationary front over the Lakes)

6) nHl - (Northern High through the Lakes)

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[1]aLn refers to a Low originating in, or near, Alberta, Canada with a subsequent path of movement to the north of the Great Lakes. Designations L_1, L_2, and L_3 denote the successive daily positions of the system's center.

With the exceptions of the neH and n&eH types, all of the above are based on migratory pressure systems. The New England High is synonymous with a northward displacement of the Bermuda High. The Northern and Eastern High also includes the Bermuda system as well as a continental anticyclone and, in addition, incorporates cyclonic circulation because the stationary front is a low pressure saddle between the two Highs.

Conclusion

In the preceding paragraphs the major terrestrial and atmospheric controls of the climate of Michigan were introduced. It is the purpose of the ensuing chapters to subject the elemental climatic record to statistical analysis and to establish the relationship of the primary climatic elements to atmospheric controls on one hand, to locational-terrestrial influences on the other.

CHAPTER II

THE SPATIAL AND TEMPORAL BEHAVIOR OF CLIMATIC ELEMENTS IN MICHIGAN

The purpose of this chapter is to subject the elemental climatic record of the study area to spatial and temporal investigations, including analyses of mean values, extremes, variabilities, and relative frequencies of occurrence. The base period for the climatic data used in this study is 1931-1960.

The Thermal Elements

In order to analyze the temperature parameters in Michigan's climate, a network of 95 stations was established, giving an average density of one station per 630 square miles. Each station is located approximately 25 miles from its nearest neighbor, although this varies somewhat in the different sections of the state. The stations of the northern peninsula are more widely spaced than those of the southern peninsula. The reliability of the isotherms and temperature frequencies shown on the following series of maps is limited to the extent of the available station network.

Mean Annual Temperatures

Mean annual temperatures ("normals") for the period 1931-1960

are shown in Figure 7.[1] Most of the area of the state has mean temperatures between 40° F. and 50° F. The exceptions are the relatively small areas in the extreme southwest and southeast which are warmer than 50° F., and the northwestern and northeastern sections which average less than 40° F.

The general trend of isotherms is zonal; however, there are significant deviations from this pattern. In the areas of higher elevation (i.e., Northern Highlands, Northern Uplands, and Thumb Uplands) the isotherms form cells, as indicated most clearly by the Northern Uplands where mean temperatures decrease from 45° F. at the periphery to 42° F. at the center. Other aberrations are notable near the Great Lakes, such as in the northwestern Lower Peninsula where the isotherms are deflected into a meridional orientation so that they are parallel to Lake Michigan. Higher temperatures are found near the Lakes, lower temperatures inland.

Two anomalies in the zonal pattern that are not directly associated with high elevations or proximity to a Great Lake are: (1) the poleward bending of the 48° F. isotherm into the Saginaw Lowland, a relatively warm area of the state with respect to its latitude; and (2) the equatorward bending of the 40° F. isotherm in the northeastern Upper Peninsula, a relatively cold area for its latitude.

The steepest latitudinal temperature gradient in the study area occurs between Saginaw-Bay City and Tawas City along the northwest

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[1]Data from U.S., Dept. of Commerce, Weather Bureau, Decennial Census of United States Climate--Monthly Normals of Temperature, Precipitation, and Heating Degree Days: Michigan, Washington, D.C., 1962; and Climatological Data: Michigan, Washington, D.C., 1931-1960.

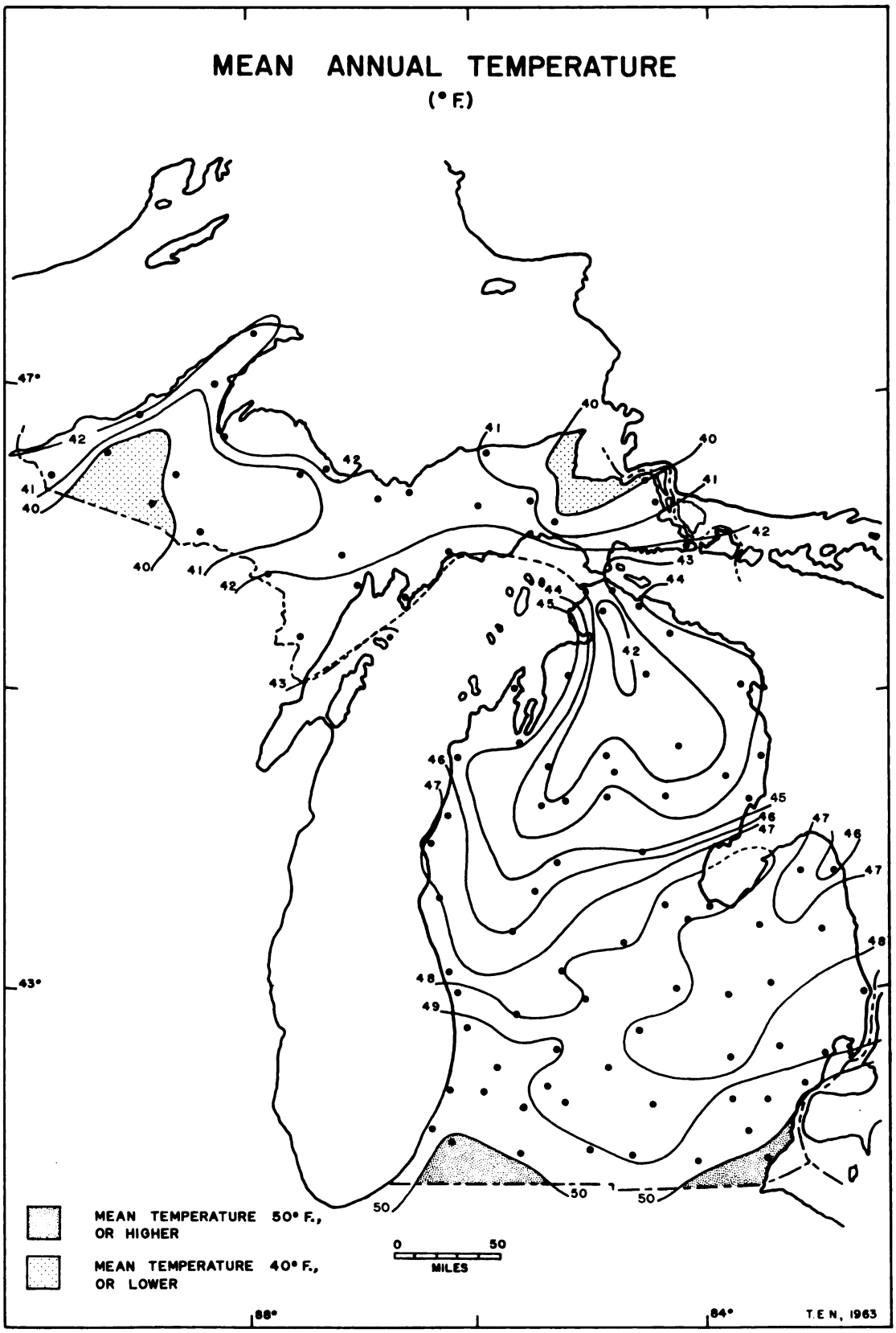

MEAN ANNUAL TEMPERATURE
(° F.)
47°
43°
88°
84°
MEAN TEMPERATURE 50° F., OR HIGHER
MEAN TEMPERATURE 40° F., OR LOWER
0 50
MILES
T.E.N., 1963

Figure 7

shore of Saginaw Bay. Mean temperature decreases from over 48° F. to less than 45° F. within a distance of 50 miles. Although the steep gradient continues westward toward the center of the Lower Peninsula, it is less obvious in the vicinity of Lake Michigan. The crowding of isotherms in this belt represents a marked thermal boundary in the state.

Mean Temperatures of the Mid-Season Months

Figure 8 shows mean temperatures for the mid-season months of January, April, July, and October. Water isotherms of surface temperatures of the Great Lakes are also shown on these maps in order to illustrate thermal differences between land and water during the various seasons.[1]

January.- Mean air temperatures in mid-winter vary from over 28° F. in the southwest to 12° F. in the northwest. The maximum regional temperature contrast is 16 F.°, or about 6 F.° more than for mean annual temperature. The greater regional differentiation for January is indicated by the closer spacing of isotherms. It is notable that water temperatures in the Great Lakes are from 5 to 15 F.° warmer than corresponding air temperatures over the land surfaces adjacent to the shorelines.

In all parts of the state, higher temperatures occur near the Great Lakes. For example, the 25° F. isotherm parallels the Lake Michigan shoreline for nearly half the latitudinal extent of the Lower Peninsula. The cells which were observed on the mean annual map likewise appear on the January map, although shapes and gradients differ. In particular, the cellular patterns of the Northern Highlands and Northern Uplands are indicative of very steep temperature gradients.

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[1]Lake temperatures taken from U.S., Dept. of Commerce, Weather Bureau, Climatology and Weather Services of the St. Lawrence Seaway and Great Lakes, Technical Paper No. 35, 1959.

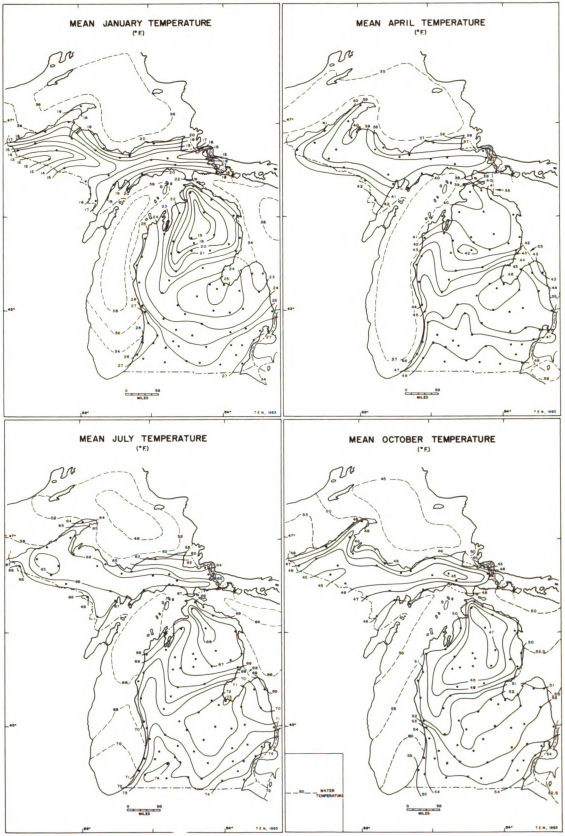

MEAN JANUARY TEMPERATURE
(°F)
MEAN APRIL TEMPERATURE
(°F)
MEAN JULY TEMPERATURE
(°F)
MEAN OCTOBER TEMPERATURE
(°F)
WATER TEMPERATURE

Figure 8

The Saginaw Lowland still stands out as a warm area and the northeastern Upper Peninsula appears again as a cold area.

April.- The range of mean air temperatures for the mid-spring month is from 48° F. in the extreme southern-interior to 36° F. in the northeast Upper Peninsula, for a statewide differential of 12 F.°[1] In contrast to January, water temperatures are now from 1 F.° to 9 F.° colder than corresponding air temperatures over the land surface adjacent to shorelines.

Thermal patterns differ fundamentally from those of mid-winter, as indicated by the marked poleward bending of isotherms in the Lower Peninsula and the occurrence of higher temperatures inland rather than along the Lakes in both peninsulas. The cellular patterns, which were conspicuous in January, are now very nearly absent.

July.- Mean temperatures during the middle of summer vary from over 74° F. in the southeastern and southwestern Lower Peninsula to less than 63° F. in the northeastern Upper Peninsula, for an areal range of about 12 F.° Water temperatures are from 1 to 16 F.° colder than air temperatures over the adjacent land surfaces.

The July temperature pattern is similar to that of April, indicating that the same controls are dominant in both months. Poleward bending of isotherms in the Lower Peninsula is a feature of both months, and, although warm and cold cells, corresponding to low and high elevations respectively, are better marked in July than in April, they are not as well defined as in January.

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[1]Absolute temperatures are stated as °F., differences as F.°

October.- The range of mean temperatures in the mid-fall month is from 55° F. in the southwestern Lower Peninsula to 45° F. in three separate areas of the Upper Peninsula, or a difference of about 10 F.° for the entire state. Water temperatures vary from 2 F.° colder to 5 F.° warmer than air temperatures of neighboring shoreline stations.

The regional pattern resembles that of January very closely, except that the isotherm gradients are somewhat steeper in the winter month. Temperature differences between October and April are noteworthy, with the mid-fall month being considerably warmer than the mid-spring month throughout the study area.

It is evident from Figures 7 and 8 that the mean annual temperature pattern of the state resembles the January and October maps more closely than those of April and July, particularly in the equatorward-bending of isotherms in the Lower Peninsula and the location and orientation of warm and cold cells. The greater persistence of winter temperature conditions and the greater thermal contrasts over the region during this season may be cited as primary factors for the similarity between winter and annual temperatures.

Mean Annual Maximum and Minimum Temperatures

Mean annual maximum and minimum temperatures are shown in Figure 9. The highest mean maximum is 61° F. and the lowest is 47° F., for a regional difference of 14 F.° Mean minima range from 43° F. to 28° F. for a maximum regional contrast of 15 F.°, indicating that these parameters are similar in their differences over the study area.

In terms of patterns, however, mean minimum and mean maximum temperatures present a marked contrast. Mean maxima resemble the April and July averages, while mean minima correspond to October and

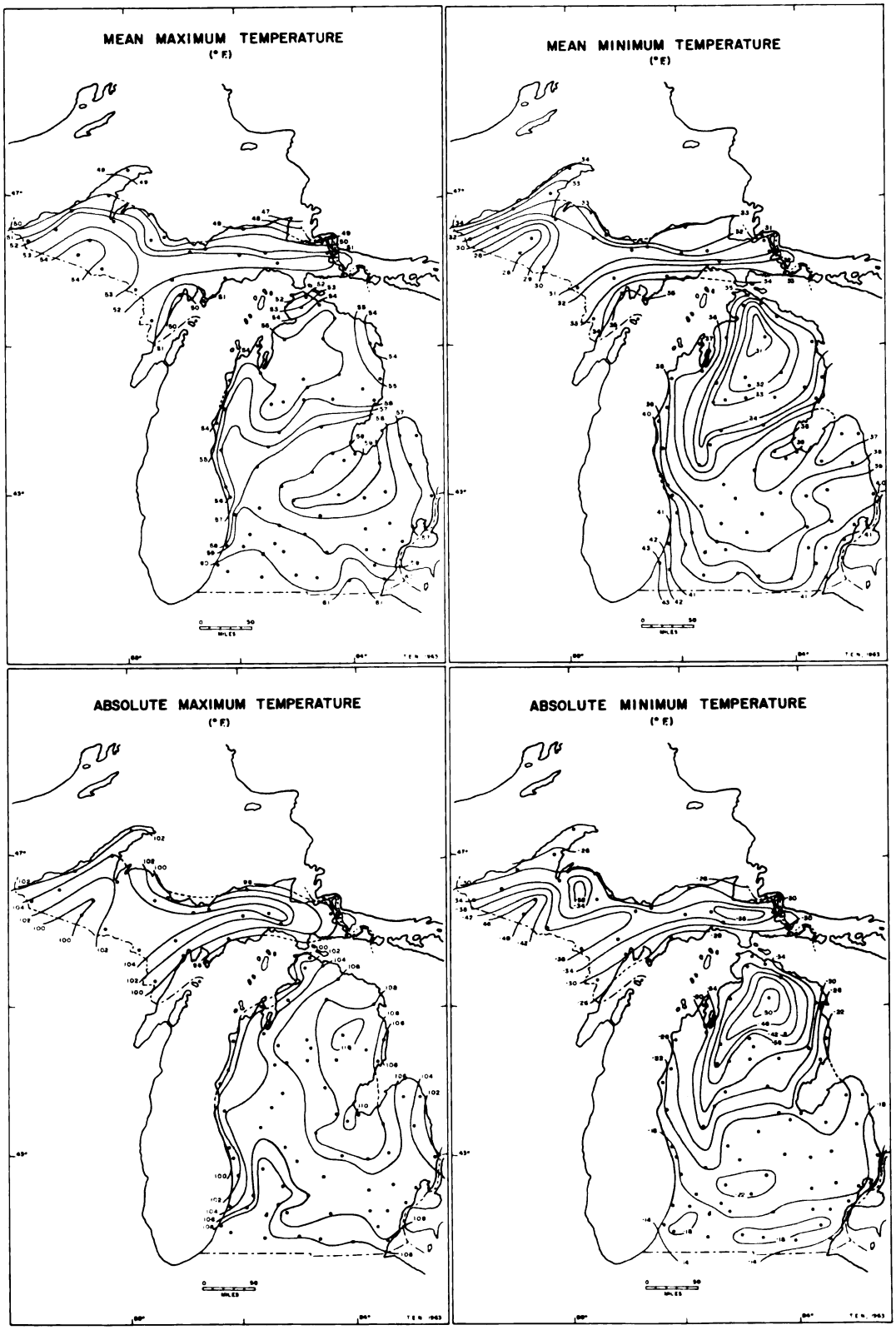

MEAN MAXIMUM TEMPERATURE
(°F)
MEAN MINIMUM TEMPERATURE
(°F)
ABSOLUTE MAXIMUM TEMPERATURE
(°F)
ABSOLUTE MINIMUM TEMPERATURE
(°F)

Figure 9

January averages. Mean maximum temperatures are thus highest in the interior and mean minimum temperatures are highest near the Great Lakes. To illustrate, Muskegon, on Lake Michigan, has a mean maximum of about 56° F. while Greenville, 50 miles eastward at the same latitude, has a maximum averaging 2 F.° higher. For mean minima the corresponding temperatures are 40° F. at Muskegon and 38° F. at Greenville.

Temperature Extremes

Temperature extremes for Michigan are given in Figure 9. Absolute maximum temperatures (the highest official temperature recorded at each station) range from 110° F. at Mio and Saginaw to less than 98° F. along the shores of the eastern Upper Peninsula. Absolute minima vary from -14° F. in the extreme southwest and southeast to -51° F. in the center of the Northern Upland (Vanderbilt). It is interesting to note that absolute minima in the Upper Peninsula are higher than those in the Northern Upland. The statewide difference in absolute minimum temperatures is much greater than that for absolute maxima (approximately 37 F.° for minima and 12 F.° for maxima).[1]

The pattern of absolute maxima is similar to that of mean maxima. The isotherms are bent parallel to the Great Lakes, and higher temperatures are observed in the interiors of both peninsulas. Isotherms of absolute minima resemble those of mean minima. They are parallel to the Lakes or form cells, but with the higher values near the water bodies.

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[1]This difference is not readily apparent from observation of the respective maps, because the isotherm interval for maxima is 2 F.° while that for minima is 4 F.°, in order to prevent crowding of lines on the latter map.

Frequencies of Days Above, Below, or Between Certain Threshold Temperatures

The following analysis concerns frequencies of days above, below, or between certain threshold temperatures. The significant thresholds used in this study are 0° F., 32° F., and 90° F. Four thermal frequency maps appear in Figure 10: (1) mean number of days with a minimum temperature of 0° F., or below; (2) mean number of days with a maximum temperature of 32° F., or below; (3) mean number of days with a minimum temperature of 32° F., or below; and (4) mean number of days with a maximum temperature of 90° F., or above.[1]

Large regional differences in frequencies occur for all of the above threshold parameters. For "polar days" the values range from 2 days along the Lake Michigan shoreline to over 42 days in the Northern Highlands. There are only 40 "ice days" in the south but more than 100 in the Northern Highlands. One-hundred and thirty "frost days" in the south contrast with 195 in the western Upper Peninsula, giving the largest regional difference in this series, 65 days. "Tropical days" vary from less than 2 along the Lake shores of the Upper Peninsula to 26 in the southern interior of the Lower Peninsula. The persistence of temperatures over 90° F. shows less regional variability than that of the other temperature conditions, but the statewide difference of 24 days is still appreciable.

In all of the threshold analyses it is notable that frequencies increase toward the interior of the study area. Areas adjacent to

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[1] A popular, but descriptively useful terminology for these threshold-frequencies is, respectively: (1) "polar days"; (2) "ice days"; (3) "frost days"; and (4) "tropical days".

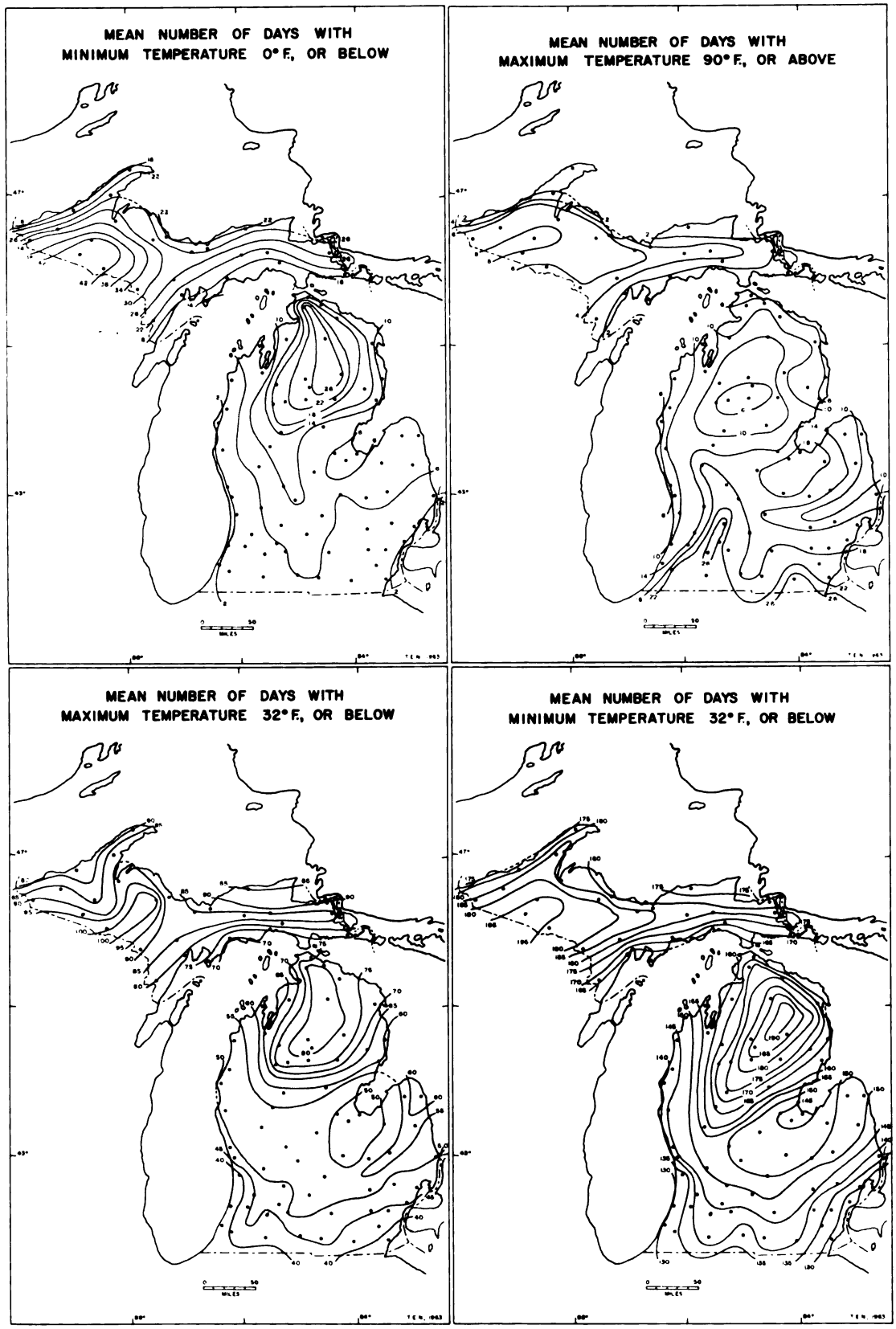

MEAN NUMBER OF DAYS WITH
MINIMUM TEMPERATURE 0° F, OR BELOW
MEAN NUMBER OF DAYS WITH
MAXIMUM TEMPERATURE 90° F, OR ABOVE
MEAN NUMBER OF DAYS WITH
MAXIMUM TEMPERATURE 32° F, OR BELOW
MEAN NUMBER OF DAYS WITH
MINIMUM TEMPERATURE 32° F, OR BELOW

Figure 10

the Great Lakes have fewer days with extreme temperatures, while stations located inland experience a greater number of days with above or below average temperatures. The former areas may be considered as belonging to a lacustrine type of temperature regime, the latter areas a continental type.

Figure 11 shows the length of the frost-free season, here defined as the mean number of days between the last 32° F. temperature in spring and the first in fall. This period varies from over 170 days in the southeast and southwest to less than 70 days in the center of the Northern Highlands. It must be emphasized that in an area of the limited size, latitudinal extent, and elevational differences characterizing Michigan, this large contrast (100 days, or the equivalent of more than three calendar months) is of outstanding climatic significance.

The isoline pattern for frequency of frost-free days very closely resembles those of the 0° F. and 32° F. thresholds shown in Figure 10. In the Lower Peninsula most isolines are deflected equatorward over the interior, indicating shorter frost-free periods with increasing distances from the Great Lakes. Gradients are slightly steeper than average near the Lakes, but are steepest in the areas of higher elevation. The Northern Upland cell, for example, is well-defined with its values ranging from about 130 days on its periphery to less than 80 days at the center.

In the Upper Peninsula, isolines either parallel the shores or conform to the outlines of the Northern Highlands. The length of the frost-free season varies little along the shores of Lake Michigan and Lake Superior (140 days, except in the extreme west where it

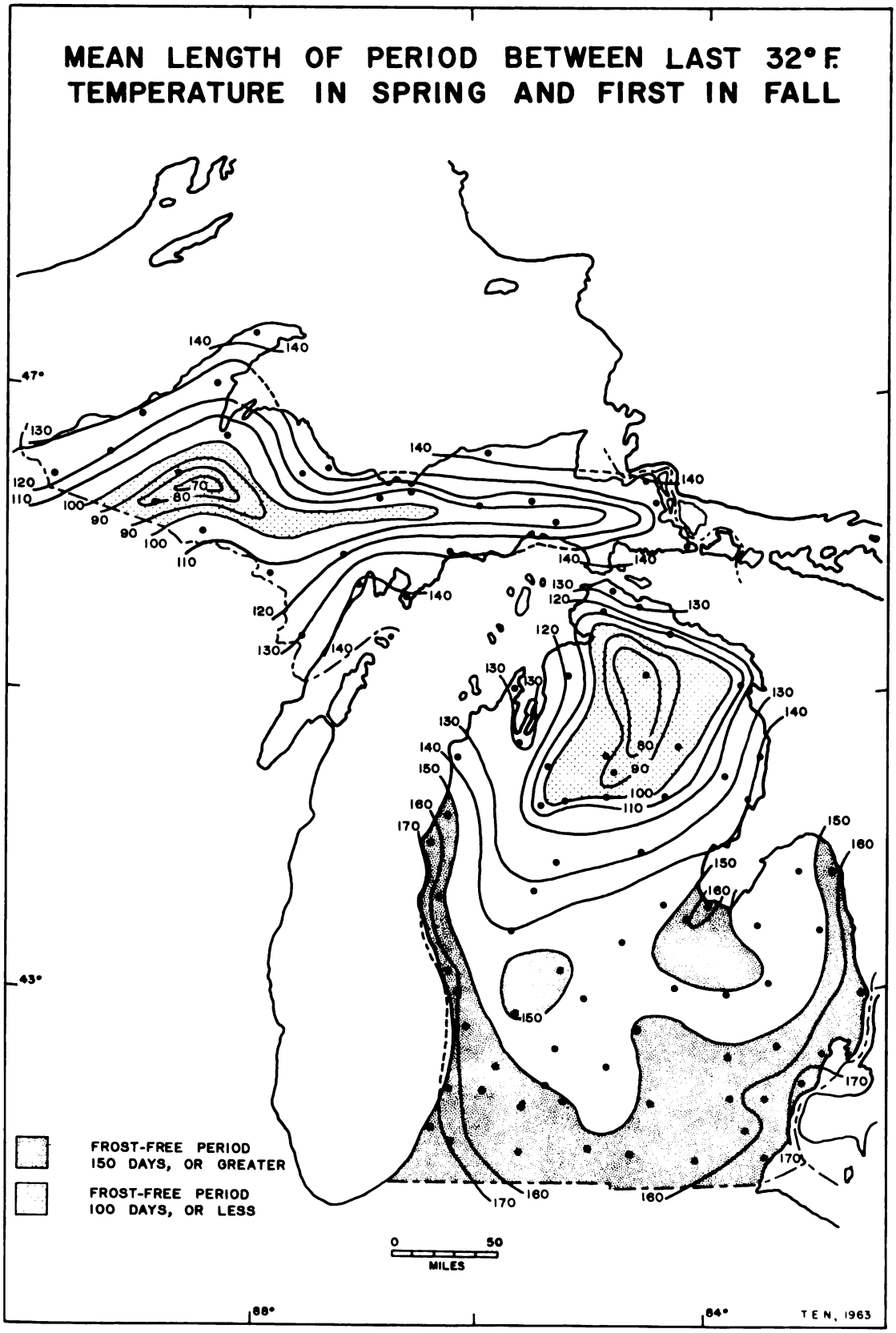

MEAN LENGTH OF PERIOD BETWEEN LAST 32° F. TEMPERATURE IN SPRING AND FIRST IN FALL
47°
43°
88°
84°
FROST-FREE PERIOD 150 DAYS, OR GREATER
FROST-FREE PERIOD 100 DAYS, OR LESS
0 50
MILES
T E N, 1963

Figure 11

decreases to 130 days). However, frequencies decrease very rapidly with increasing distance from the shores.

The importance of Lake proximity is illustrated by comparison of Fayette-Sack Bay (Upper Peninsula) and Ionia (Lower Peninsula). Both stations have average frost-free seasons of 140 days. Ionia is located 180 miles to the south of Fayette-Sack Bay, but, while the latter is situated on Lake Michigan, Ionia lies 60 miles inland from the shores of the same Lake.

Temperature Variability

For the determination of temperature variability, a sample of 25 stations was selected. Variances, standard deviations, and coefficients of variation were computed for mean annual temperature and mean monthly temperatures of the 4 mid-season months (January, April, July, and October).[1] The coefficients of variation for mean annual temperature are very low, averaging about 3 per cent for the 25 station sample. Upper Peninsula annual temperatures are slightly more variable than those of the Lower Peninsula, but the differences do not exceed 2 per cent. This indicates little variation in mean annual temperature from year to year at any particular station as well as a small intraregional variability.

In January the coefficients of variation are from 5 to 9 times greater than they are for the annual temperatures. Temperature variability is greatest in the northern part of the state during winter, with Ironwood and Stambaugh, for example, having coefficients of over 30 per cent. The lowest thermal variation (about 15 per cent)

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[1]The coefficient of variation is calculated by dividing the standard deviation by the mean and multiplying the quotient by 100.

occurs in the south along the Lake Michigan shore at Benton Harbor, Ludington, and Manistee. Somewhat higher variability is found in the interior, with the highest coefficients in the Lower Peninsula occurring in the Northern Uplands at Mio and Cadillac (23 and 25 per cent, respectively).

The high variability characteristic of winter disappears during the summer. Coefficients of variation for July are approximately the same as for mean annual temperatures, and at several stations are even lower. The highest variabilities during July are in the Northern Highlands and Northern Uplands, and the lowest are in the southeastern Lower Peninsula. In spring and fall, thermal variances are intermediate between the high variabilities of winter and the low variabilities of summer. In general, spring is more variable than fall; April has a coefficient range from 7 to 11 per cent, while October has a range from 5 to 8 per cent.

The Spatial and Temporal Behavior of Precipitation

The purpose of this section is to indicate the spatial and temporal patterns of precipitation. The investigation is based on a network of 110 stations for which appropriate data are available. This represents a density of one station per 525 square miles, or an average distance of 23 miles between stations. Precipitation is more variable at any given station than is temperature and also varies more over short distance. Unlike temperature, precipitation is a non-continuous variable.[1] However, the use of a 30-year period

[1]Every station (or place) has a measurable temperature on every day of the year. However, precipitation does not occur at any station every day of the year, and is, thus, non-continuous.

(1931-1960) tends to smoothen regional and temporal differences.

Mean Annual Precipitation

Precipitation falls to the surface of Michigan in several forms, including drizzle, rain, snow, granular snow, sleet, glaze (or freezing rain), and hail. In this discussion all of these forms are considered under the general heading of precipitation.

Figure 12 indicates the distribution of mean annual precipitation. Values range from 36 inches in the southwestern Lower Peninsula and Gogebic Range of the Upper Peninsula to 26 inches on the eastern side of the Northern Upland, a regional difference of approximately 10 inches.

The western sections of the peninsulas are the wettest parts of the study area, particularly where the two isthmuses connect with land to the south. This results in a meridional orientation of the general pattern of precipitation. However, the pattern is complicated considerably by the large number of cells appearing in both peninsulas.

Precipitation gradients are moderate in some parts of the state but very steep in others. Steep gradients occur primarily in the Northern Highland, the Chatham-Munising area of the northern Upper Peninsula, the Northern Upland, the southwestern Lower Peninsula, and along the shores of Lake Michigan. The steepest gradients are found in the central Northern Upland where precipitation decreases from 32 inches to 26 inches within a distance of 25 miles. In general, the interiors of the peninsulas have moderate gradients and average amounts of precipitation, while the eastern Lower Peninsula also has moderate gradients but is drier than the interior.

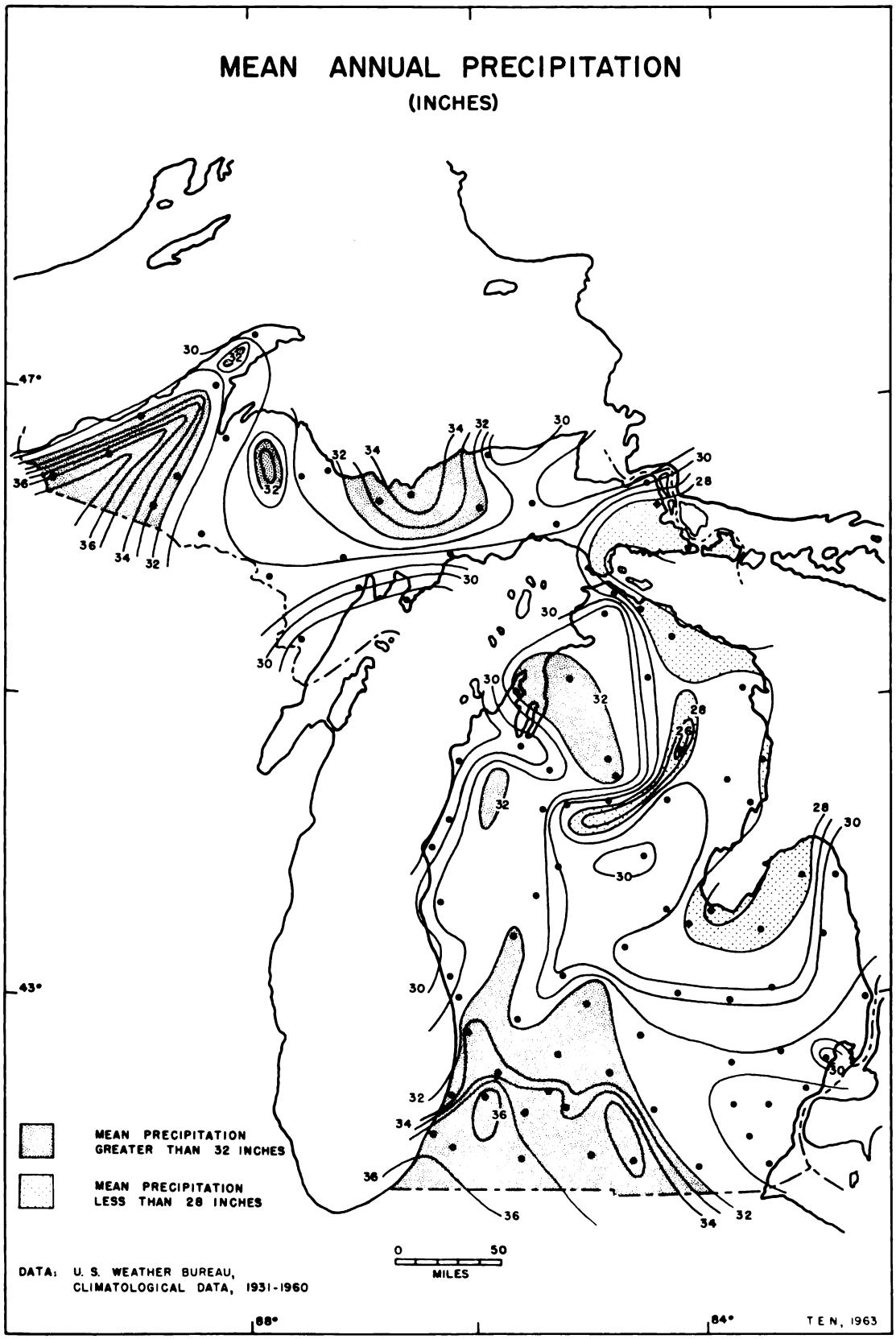

MEAN ANNUAL PRECIPITATION
(INCHES)
47°
43°
88°
84°
MEAN PRECIPITATION
GREATER THAN 32 INCHES
MEAN PRECIPITATION
LESS THAN 28 INCHES
0 50
MILES
DATA: U. S. WEATHER BUREAU,
CLIMATOLOGICAL DATA, 1931-1960
T E N, 1963

Figure 12

Mean Monthly and Mean Seasonal Precipitation

Winter.- Mean precipitation for each of the three winter months (December, January, and February), and for the three months combined, is shown in Figure 13.[1] Mean precipitation at nearly all Michigan stations is lower during winter than in any of the other seasons. Only a few stations on the Keweenaw Peninsula exceed 3 inches precipitation for at least 2 of the winter months. Other areas of above average winter precipitation are the southwestern Lower Peninsula (Allegan-Benton Harbor-Eau Claire triangle), the east-west corridor between Milford and Detroit, the small area along the Lake Michigan shore of the northwestern Lower Peninsula, and the northeastern Upper Peninsula.

The areas of low precipitation are principally in the interior of the state, although the area around Saginaw Bay and the Upper Peninsula shore along Lake Michigan are also rather dry. Areas of above and below average precipitation are shown by contrasting stipple patterns on the composite winter precipitation map. On the monthly maps the means for December and January are generally higher than those for February.[2]

Spring.- The spring months (March, April, and May) are marked by a progressive increase in precipitation over the entire study area, excepting the aforementioned Keweenaw Peninsula. The increase begins in March in the extreme southern part of the state, and advances

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[1]Data represent water equivalent of snow; i.e. one inch of precipitation equals 10 inches of snow.

[2]December and January, with 31 days each, are 3 days longer than February in 3 of every 4 years and 2 days longer in the fourth year. If this difference in number of days is taken into account, the mean precipitation at most stations in February would not differ significantly from December and January.

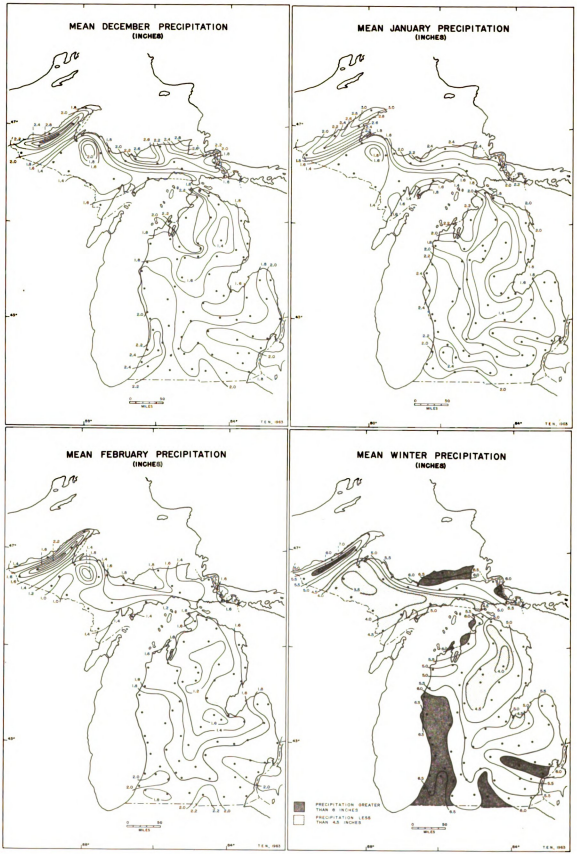

MEAN DECEMBER PRECIPITATION
(INCHES)
MEAN JANUARY PRECIPITATION
(INCHES)
MEAN FEBRUARY PRECIPITATION
(INCHES)
MEAN WINTER PRECIPITATION
(INCHES)
PRECIPITATION GREATER THAN 8 INCHES
PRECIPITATION LESS THAN 4.5 INCHES

Figure 13

northward during April and May. In March, no part of Michigan averages 3 inches of precipitation. In April, however, the southern quarter of the Lower Peninsula has at least this amount, and during May the 3 inch isohyet moves far enough poleward to enclose all of the study area except the extreme north and northeast. In the latter month 4 inches are recorded for the first time in the calendar year, but only in the extreme southwestern Lower Peninsula. The distribution of spring precipitation may be observed in Figure 14.

During March and April the Upper Peninsula has less precipitation than the southern Lower Peninsula, and resembles the northern Lower Peninsula in this respect. For example, the 3 inch isohyet, which encompasses a sizable area in the Lower Peninsula during April, does not appear in the Upper Peninsula at this time. By May, however, a wedge of heavier precipitation extends into the area from the land bridge to the south. Most of the Upper Peninsula has at least 3 inches of precipitation during the last month of spring.

The zonal distribution of spring precipitation in the Lower Peninsula contrasts with the meridional orientation of annual precipitation. In the Upper Peninsula the relationship between mean spring precipitation and latitude is less obvious with the general decrease being from southwest to northeast. The largest totals for spring precipitation in the Upper Peninsula are above 8.5 inches and occur in the southwest. In the Lower Peninsula over 10 inches are recorded in the extreme south-central section. The area of least precipitation lies astride the Straits of Mackinac and in the southeastern Upper Peninsula where less than 6 inches are recorded.

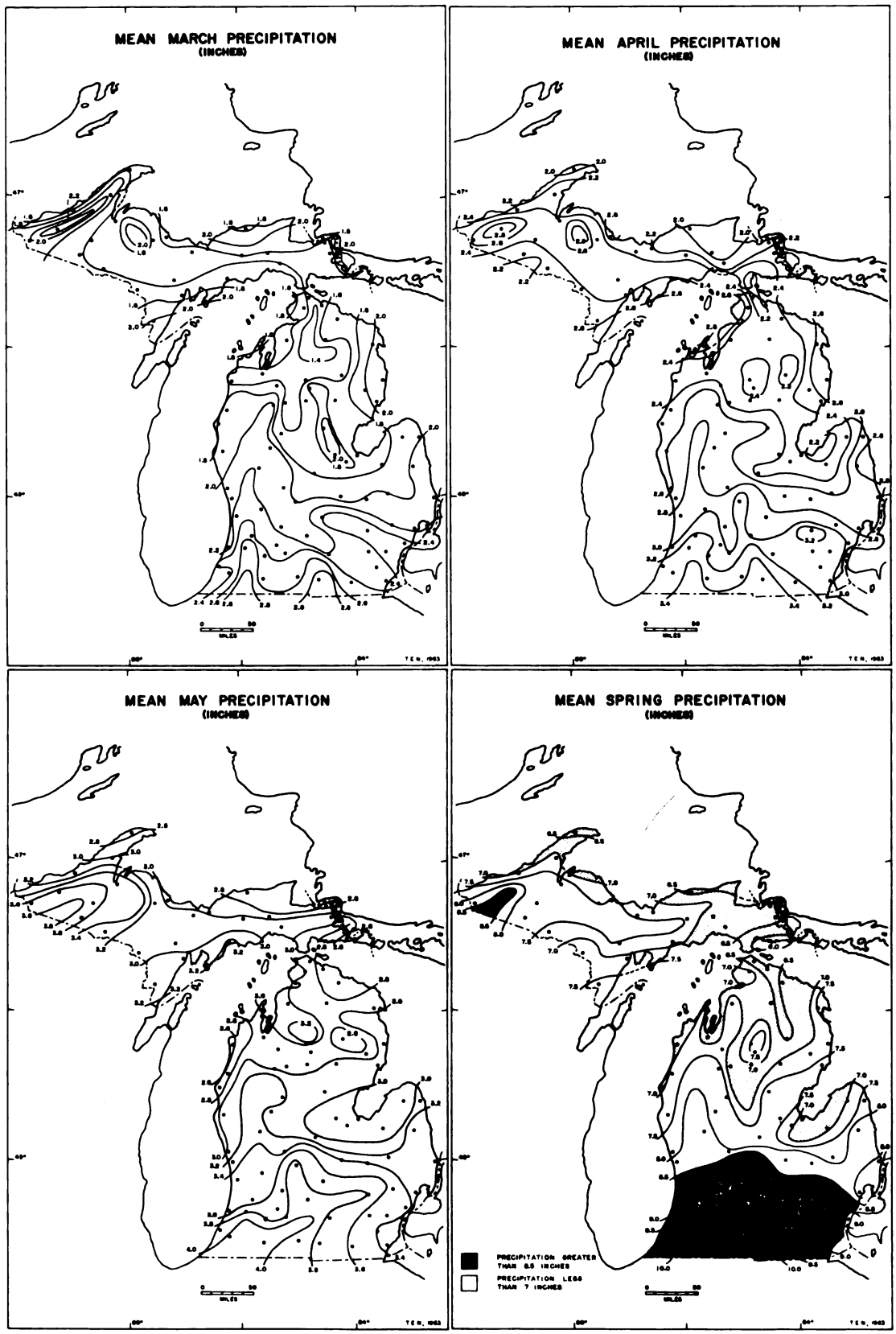

MEAN MARCH PRECIPITATION
(INCHES)
MEAN APRIL PRECIPITATION
(INCHES)
MEAN MAY PRECIPITATION
(INCHES)
MEAN SPRING PRECIPITATION
(INCHES)
PRECIPITATION GREATER THAN 0.5 INCHES
PRECIPITATION LESS THAN 7 INCHES

Figure 14

Summer.- For all parts of the study area summer is the season of maximum precipitation, as may be observed in Figure 15. June is the wettest of the summer months, as exemplified by the large area with at least 4 inches of precipitation. The areas with the greatest precipitation at this time are the southwestern Lower Peninsula and the southwestern Upper Peninsula. The latter area (particularly in the center of the Northern Highlands) is the rainiest part of the study area in June, and is the only section that has a mean of over 5 inches for any month of the year.

During July, mean precipitation decreases throughout most of the state. The important exceptions are (1) a narrow corridor from Marquette southward to Escanaba and Stephenson in the Upper Peninsula, (2) the Grayling area of the Northern Upland, and (3) the Port Huron-Sandusky section of the Lake Huron shore. In each of these areas June and July precipitation are approximately equal. However, for the great majority of stations a decrease in precipitation between June and July is conspicuous. In August, mean precipitation increases again over most of the study area, but not to the high levels attained in June.

The map of mean summer precipitation accentuates the areas of above and below average precipitation. Clearly, the southwestern Lower Peninsula and the western Upper Peninsula are the two principal areas of above average precipitation. Two small cells, one in the vicinity of Grayling in the Northern Upland, the other surrounding Newberry in the eastern Upper Peninsula, are also above average. The two principal areas of below average precipitation are (1) the periphery of the northern Lower Peninsula, including the Saginaw Lowland, and


MEAN JUNE PRECIPITATION
(INCHES)
MEAN JULY PRECIPITATION
(INCHES)
MEAN AUGUST PRECIPITATION
(INCHES)
MEAN SUMMER PRECIPITATION
(INCHES)
PRECIPITATION GREATER THAN 10 INCHES
PRECIPITATION LESS THAN 8.0 INCHES

Figure 15

(2) the littoral of the eastern Upper Peninsula.

Fall.- Mean precipitation for the three fall months (September, October, and November) is illustrated in Figure 16. The most significant fact concerning the fall pattern is the change in location of the zones of heaviest precipitation. The northwestern Lower Peninsula (centered around East Jordan) and the northeastern Upper Peninsula, with over 9.5 inches of precipitation, are the wettest parts of the state during fall, in sharp contrast to spring and summer when they have average or below average precipitation. September contributes most to the high autumn rainfall in these zones, with many stations recording means of over 3.5 inches and some over 4 inches. No other part of the study area exceeds 4 inches during September or any of the other fall months.

In October precipitation averages decrease and regional differences are lessened. In November, however, the same sections that are rainiest in September are again significantly above the statewide average. November marks the beginning of the return to the winter pattern with precipitation decreasing over most of the state (notable exceptions are the northwestern Lower Peninsula, the northeastern Upper Peninsula, and the Keweenaw Peninsula).

Minimum fall precipitation occurs in the eastern half of the Lower Peninsula, the interior of the western Upper Peninsula, and along the Keweenaw Peninsula-Lake Superior shoreline in the vicinity of Ontonagon. The latter area and the Lake St. Clair-Lake Erie shoreline, at the northwestern and southeastern extremities of the state, respectively, are the only sections with less than 7 inches

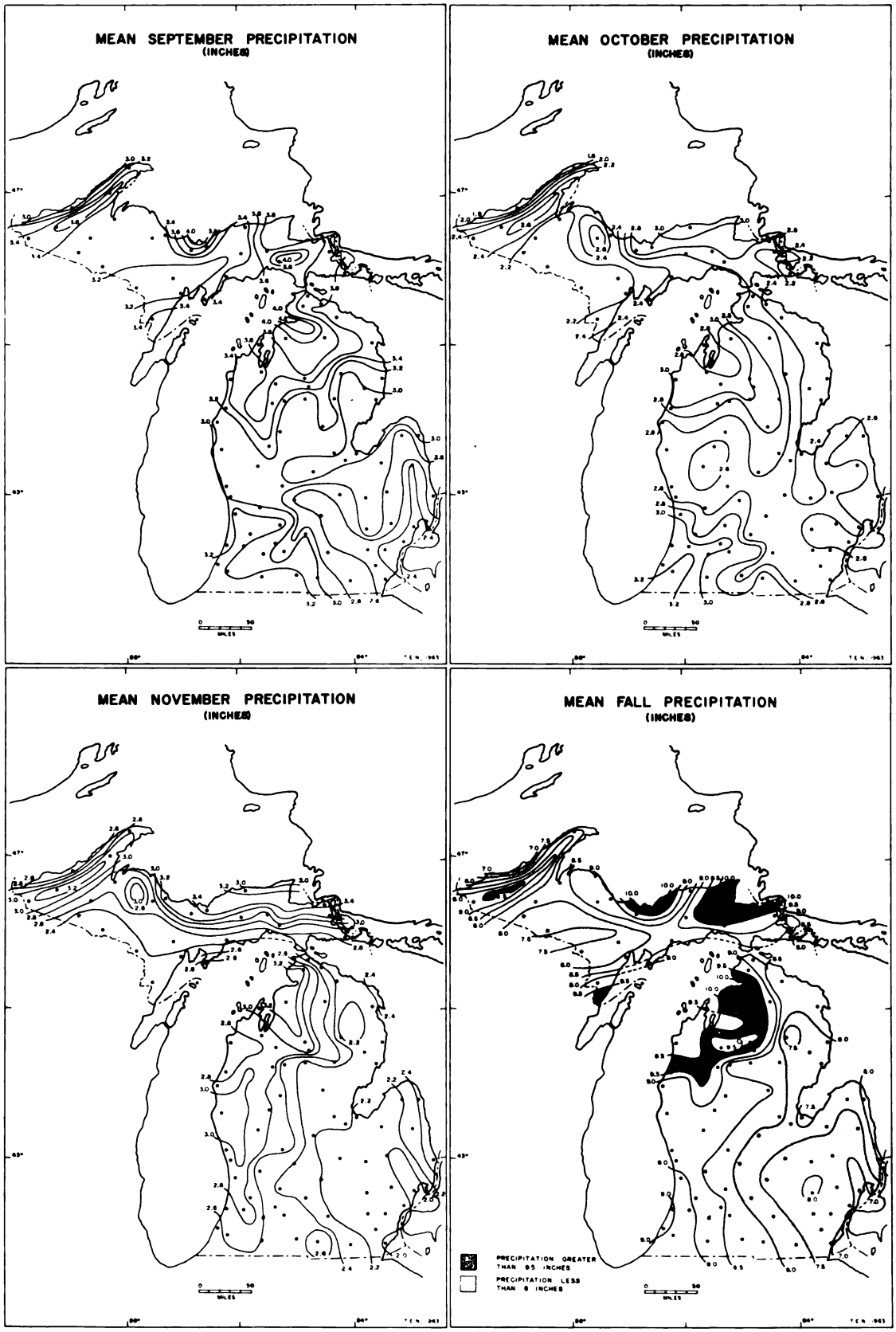

MEAN SEPTEMBER PRECIPITATION
(INCHES)
MEAN OCTOBER PRECIPITATION
(INCHES)
MEAN NOVEMBER PRECIPITATION
(INCHES)
MEAN FALL PRECIPITATION
(INCHES)
PRECIPITATION GREATER THAN 9.5 INCHES
PRECIPITATION LESS THAN 6 INCHES

Figure 16

of precipitation during fall.

Mean Frequency of Days with Precipitation Equal to or Greater than .10 Inch

In addition to annual and monthly totals, frequency values of precipitation are valuable climatographic parameters. The threshold value selected for this analysis is .10 inch of precipitation per day (an arbitrary division between relatively light and moderate daily precipitation). The resultant pattern, shown in Figure 17, denotes a regional variation in values from 85 in the western Upper Peninsula to less than 65 in the vicinity of the Saginaw Lowland.

In the Lower Peninsula the highest frequencies occur as cells in the western section but at least 20 miles from Lake Michigan. Values rarely exceed 80 days in the Lower Peninsula. The lowest frequencies are in the Saginaw Lowland, with an extension southeastward toward Detroit, although values increase slightly in this direction. Eastward from the 65-day isoline, values increase until they reach 75 along the shore of Lake Huron.

In the Upper Peninsula the isolines trend parallel to the shorelines of the adjacent Lakes with higher values generally occurring near the water bodies. The only exception is the Keweenaw Peninsula where the higher frequencies are found in the elevated parts of the Porcupine Mountains and the Copper Range. It is concluded that the combination of close proximity to a Great Lake and high elevation produces the maximum frequency of days with at least .10 inch of precipitation.

Precipitation Variability

Variability of annual precipitation in Michigan is shown in

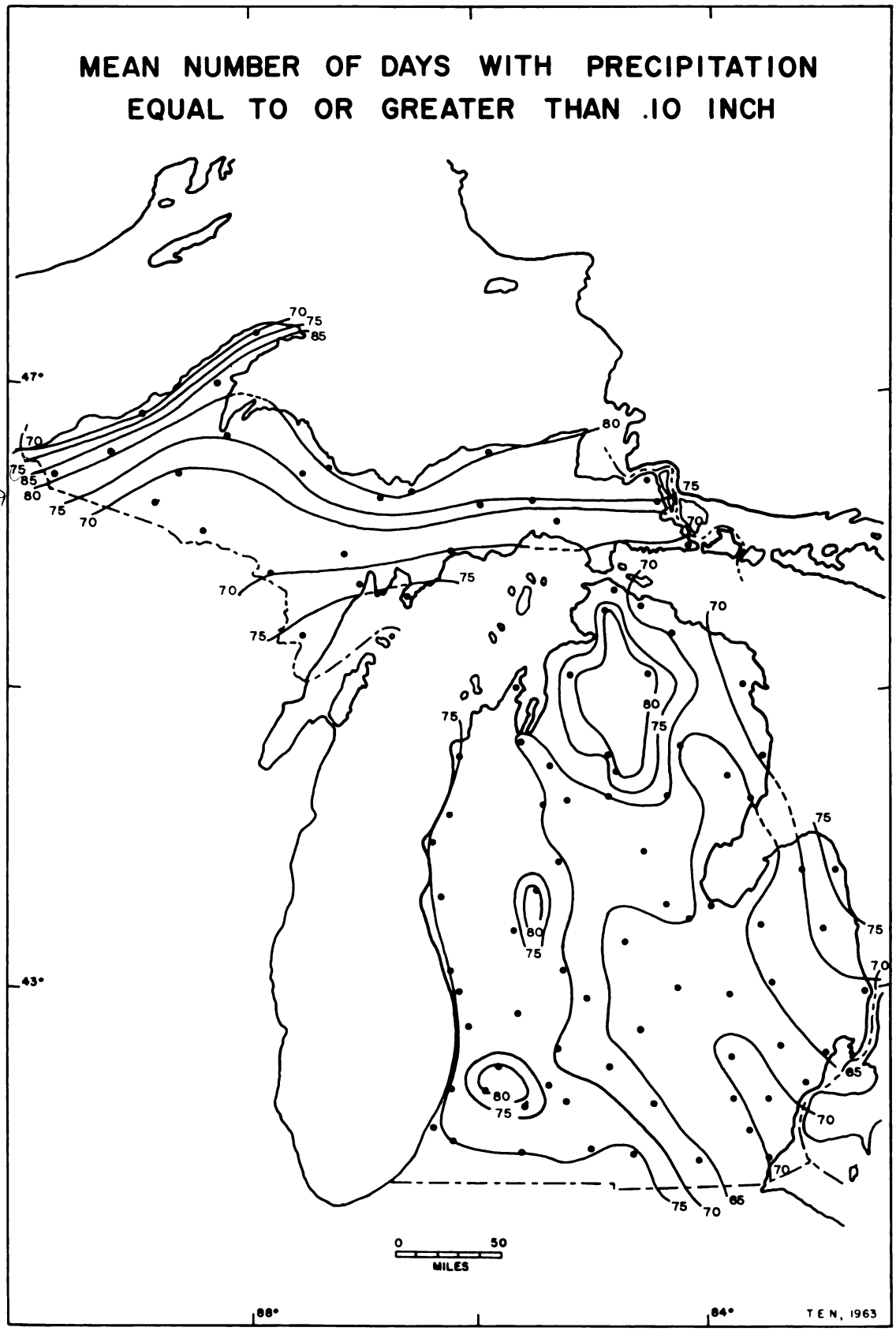

MEAN NUMBER OF DAYS WITH PRECIPITATION
EQUAL TO OR GREATER THAN .10 INCH
47°
43°
88°
84°
0
50
MILES
TEN, 1963

Figure 17

Figure 18 by means of the coefficient of variation.[1] The largest variations are in the extreme eastern section of the Lower Peninsula, in the vicinity of Mt. Clemens, Bay City, and Port Huron, with the latter station having the highest coefficient of variation (22.3%) for the study area. The least variability in the Lower Peninsula is in the northwest where Manistee (12%), Traverse City (13%), and East Jordan (11.6%) have only about one-half the variation of the southeastern stations. Benton Harbor and Eau Claire in the southwest have above average coefficients as does the Cadillac-Fife Lake-Lake City triangle in the Northern Upland, although each is less than 20%. A small cell of below average variability (less than 14%) is centered around Newaygo and Big Rapids. It is the only area of relatively low variability in the southern Lower Peninsula.

The Upper Peninsula has less precipitation variability than the Lower Peninsula. It is most variable in the west where a few coefficients exceed 16% (Ontonagon 16.1 and Kenton 16.2). From Marquette eastward variabilities are less than 14% at every station, with the extreme eastern section having the most reliable precipitation of any part of the study area (Sault Ste. Marie 9.4% and Dunbar 8.8%).

Comparison of the patterns for precipitation variabilities with precipitation totals (see Figure 12) yields no consistent relationships. High variabilities are associated with low precipitation (e.g., Saginaw Lowland) and they may be found in areas of high precipitation (e.g., southwestern Lower Peninsula). The same is true for low variabilities. On the basis of this analysis it cannot be assumed

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[1]See footnote page 43.

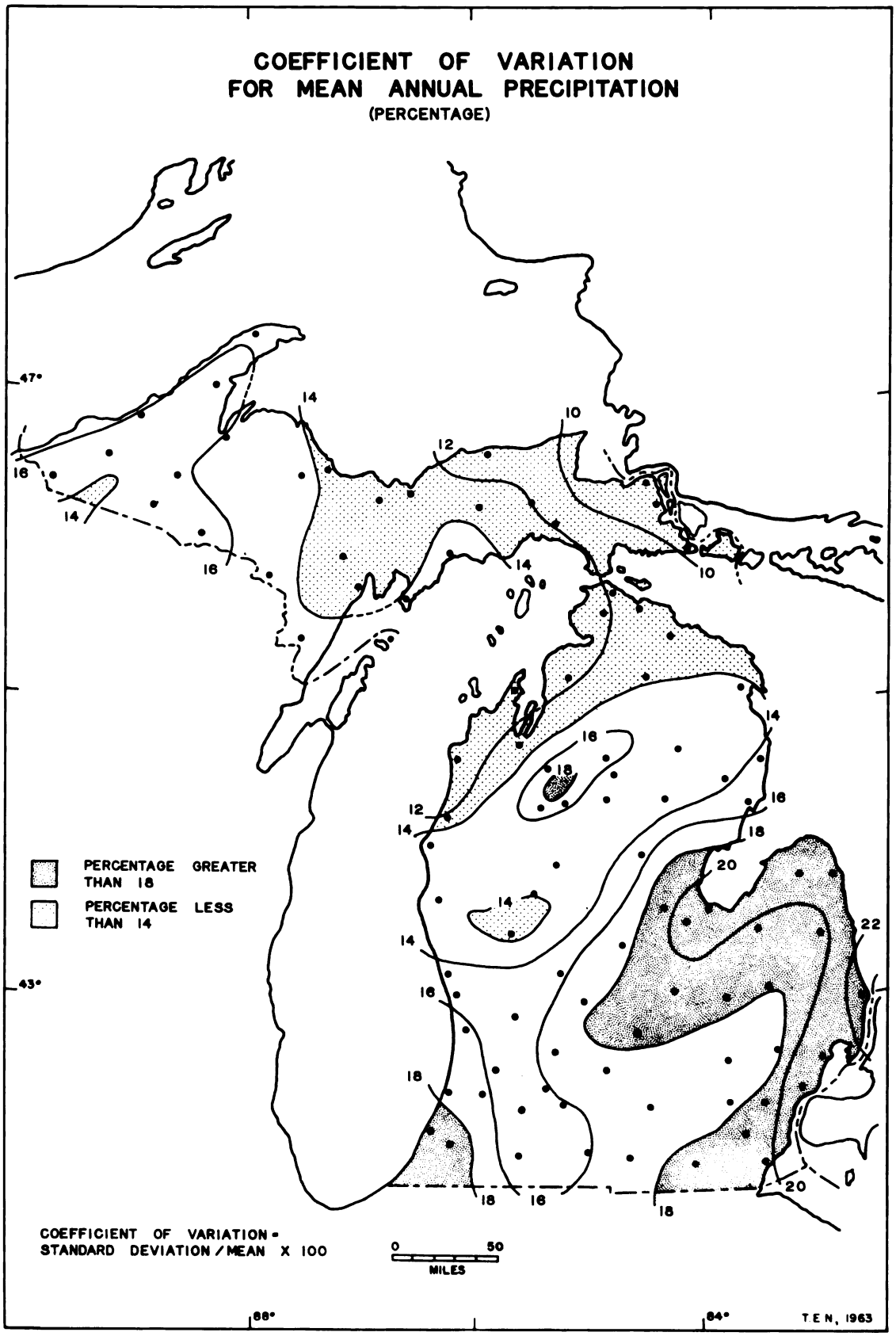

COEFFICIENT OF VARIATION
FOR MEAN ANNUAL PRECIPITATION
(PERCENTAGE)
47°
43°
68°
64°
PERCENTAGE GREATER THAN 18
PERCENTAGE LESS THAN 14
COEFFICIENT OF VARIATION = STANDARD DEVIATION / MEAN X 100
0 50
MILES
T E N, 1963

Figure 18

that a significant correlation exists between mean annual precipitation and precipitation variability within the study area.

Variabilities for individual months are, of course, without exception greater than for annual precipitation. A sample of 25 stations analyzed for the mid-season months indicates that January and April are the least variable, July is intermediate, and October is the most changeable from year to year. In January, the coefficients vary from 31% to 64%, in April from 38% to 67%, and in both months the majority of stations average around 50%. In July, percentages range from 42 to 73, with most stations clustering between 55% and 60%. In October, coefficients grade from 48% to 88% with a dispersal that makes difficult any determination of central tendency.

Monthly precipitation variabilities at individual stations are generally consistent with the distribution of mean annual precipitation variabilities. For example, Benton Harbor has very high coefficients in every month except January when it is lower than average. It also has highly variable annual precipitation. East Jordan, on the other hand, with annual precipitation variability well below the statewide average, is characterized by low coefficients of variation for the mid-season months.

The Temporal Precipitation Regime

The purpose of this section is to determine the temporal precipitation regime of the study area, or the periods of maximum and minimum precipitation. Because of the high variability of monthly rainfall from year to year (see previous section), the use of mean values to establish precipitation-regime types is not satisfactory

without further statistical refinement. The statistical method adopted[1] involves elimination of the extreme quartiles, and establishing single-month maxima only when the mean of the remaining 55%-fractile for the month with the greatest precipitation exceeds that of the preceeding and succeeding months by 20%. If the means of the 55%-fractile of any two months are within 20% of each other, a double-month maximum exists, providing both of these values are at least 20% higher than the amount received in the next highest month.

Plotting the values for monthly means, and illustrating the results in Figure 19, the following regime types may be delimited for the Lower Peninsula:

1. Late Spring-Early Summer Maximum. This type is characterized by either a single-month maximum in May or a double-month maximum in May and June. Its areal occurrence is south of a line connecting Benton Harbor, Lansing, and Port Huron, with a northern extension fringing Saginaw Bay.
2. Late Summer-Early Fall Maximum. The northern Lower Peninsula has a marked single-month maximum in September or a double-month maximum in August and September. Toward the north, the single-month maximum is more typical while toward the south the double-month subtype dominates. The type is confined largely to the area north of Saginaw Bay, with the exceptions of a peninsular extension toward the

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[1]This method was suggested by Dieter H. Brunnschweiler, "Precipitation Regime of the Lower Peninsula of Michigan," Papers of the Michigan Academy of Science, Arts, and Letters, Vol. XLVII, 1962, Pp. 367-381.

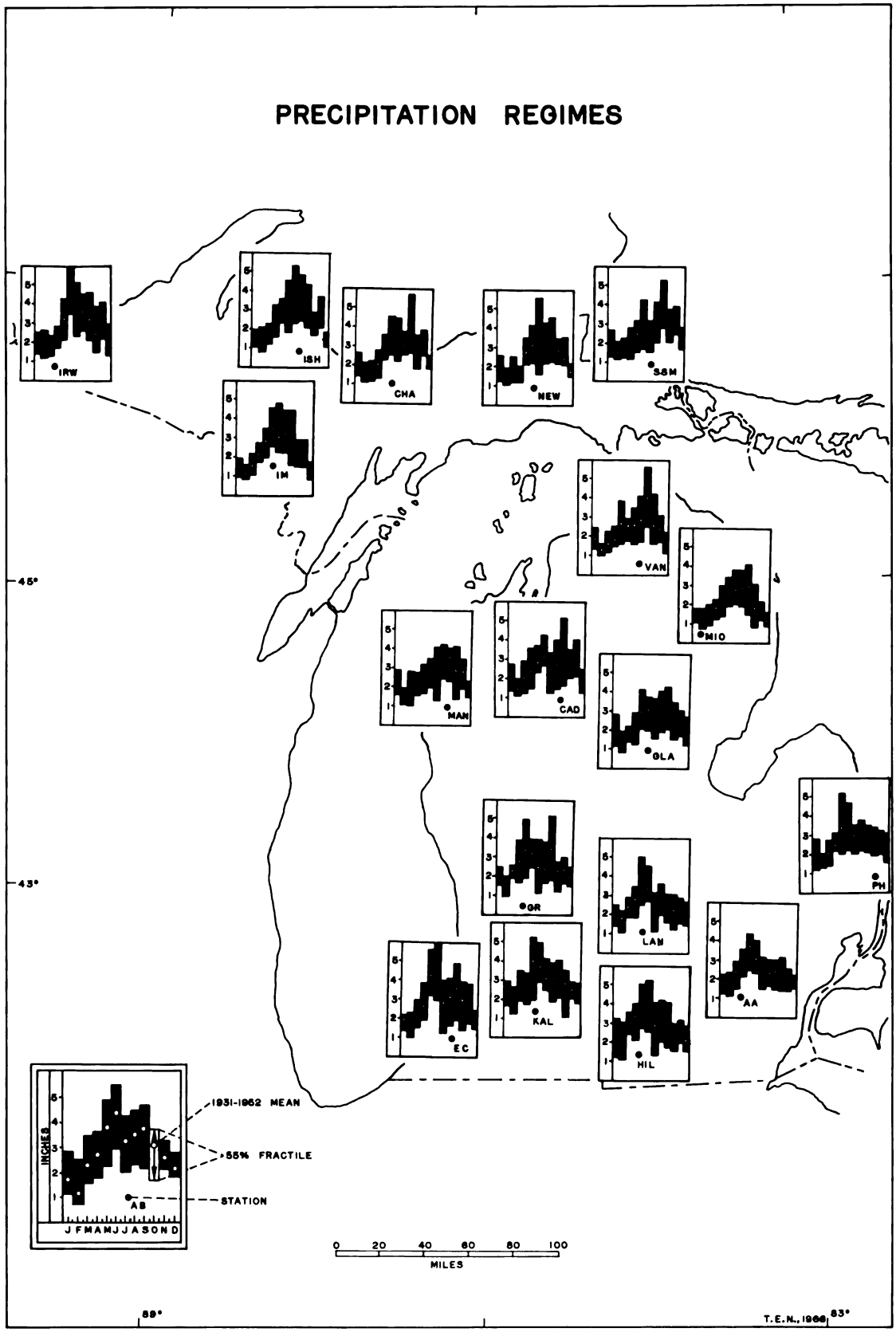

PRECIPITATION REGIMES
IRW
ISH
CHA
NEW
SSM
IM
VAN
MIO
MAN
CAD
OLA
PH
GR
LAN
AA
EC
KAL
HIL
45°
43°
89°
83°
INCHES
AS
J F M A M J J A S O N D
1931-1952 MEAN
55% FRACTILE
STATION
0 20 40 60 80 100
MILES
T.E.N., 1968

Figure 19

south in the center of the state and a small outlier centered around Michigan.

3. Transition Zone. The area between types 1 and 2 partakes of characteristics of both and, therefore, has extended peaks in May-June and August-September. The northern stations all have higher precipitation during fall than spring, while for the southern stations the reverse is true.

The Upper Peninsula may also be divided into three different types:

1. Early Fall Maximum. This type has a marked single-month maximum in September. It encompasses the entire eastern Upper Peninsula from Chatham and Fayette-Sack Bay eastward. In the extreme east, September maxima are very strongly marked, but, towards the west, June secondary maxima are also characteristic. It is comparable to the adjacent type 2 in the northern Lower Peninsula, except that in the Upper Peninsula September precipitation is always significantly higher than August precipitation.
2. Early Summer Maximum. The area to the west of L'Anse and Stambaugh has a well-defined June maximum. A subtype occurs in the Keweenaw Peninsula where there is a June-January double-month maximum. This is the only part of the study area that has maximum precipitation during a winter month. The early-summer type is similar to type 1 in the Lower Peninsula, the principal difference being that in the Upper Peninsula the maxima are always in June and are very strongly marked.

3. Mid-Summer Maximum-Transitional. A north-south corridor from Ishpeming to Escanaba and thence southwest to Stephenson and Iron Mountain lacks the well-defined maxima to the east and the west. Also, this type has either single-month maxima in July or August or double-month maxima involving both months. It is transitional between types 1 and 2 and its areal extent is much smaller.

The majority of the investigated stations in both peninsulas record minimum precipitation in February (see footnote page 47). However, in some of the more northerly Upper Peninsula stations the minima are delayed until March or April. Calumet and Houghton in the Keweenaw Peninsula subtype have well-defined March minima. The Grand Marais-Germfask area has double-month minima in March and April.

A common characteristic of most Michigan stations is a mid-summer slump in precipitation.[1] For all Lower Peninsula stations and many Upper Peninsula stations this is reflected in the July means, which are invariably lower than June or August averages. However, in the east-central Upper Peninsula the slump involves both July and August, with these months being significantly lower than June or September at Fayette-Sack Bay, Detour, Munising, and Grand Marais. At Marquette, July has less precipitation than June, but August is much drier than July or September.

An anomaly in terms of temporal distribution is the narrow corridor from Ishpeming south to Iron Mountain, Stephenson, and Escanaba. This is the only part of the study area that does not experience a

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[1] Ibid., P. 379.

mid-summer decrease in rainfall; instead, it has its maximum precipitation at this time. Ishpeming and Escanaba are unique in that they are the only stations recording July maxima. The explanation for the existence of this corridor may be sought in its transitional position between the June maxima to the west and the September maxima to the east.

The Distribution of Mean Annual Snowfall

Snow is the most commonly occurring solid hydrometeor in the study area, although it exhibits great regional and temporal variability. The period during which snow falls and remains on the ground varies somewhat from year to year, but, in general, it increases with higher latitude and higher elevation. During the six-month span from November to April, snow may be expected at any station in Michigan. In the northern Lower Peninsula and the Upper Peninsula it is also fairly common in May and October. In many years no measurable snowfall occurs at some stations during November and April; but the occasional very heavy falls during these months result in reasonably high averages in comparison to December, January, February, and March when measurable snow almost invariably occurs at all stations every year.

The mean annual snowfall of the state is illustrated in Figure 20. Amounts range from over 160 inches in the western Upper Peninsula to less than 30 inches in the southeast near Detroit and Monroe, for a very high intraregional difference of over 130 inches. The Upper Peninsula clearly has greater average snowfall than the Lower Peninsula. The heaviest falls occur on the higher elevations 10 to 30 miles inland from the southern shores of Lake Superior. The snowfall

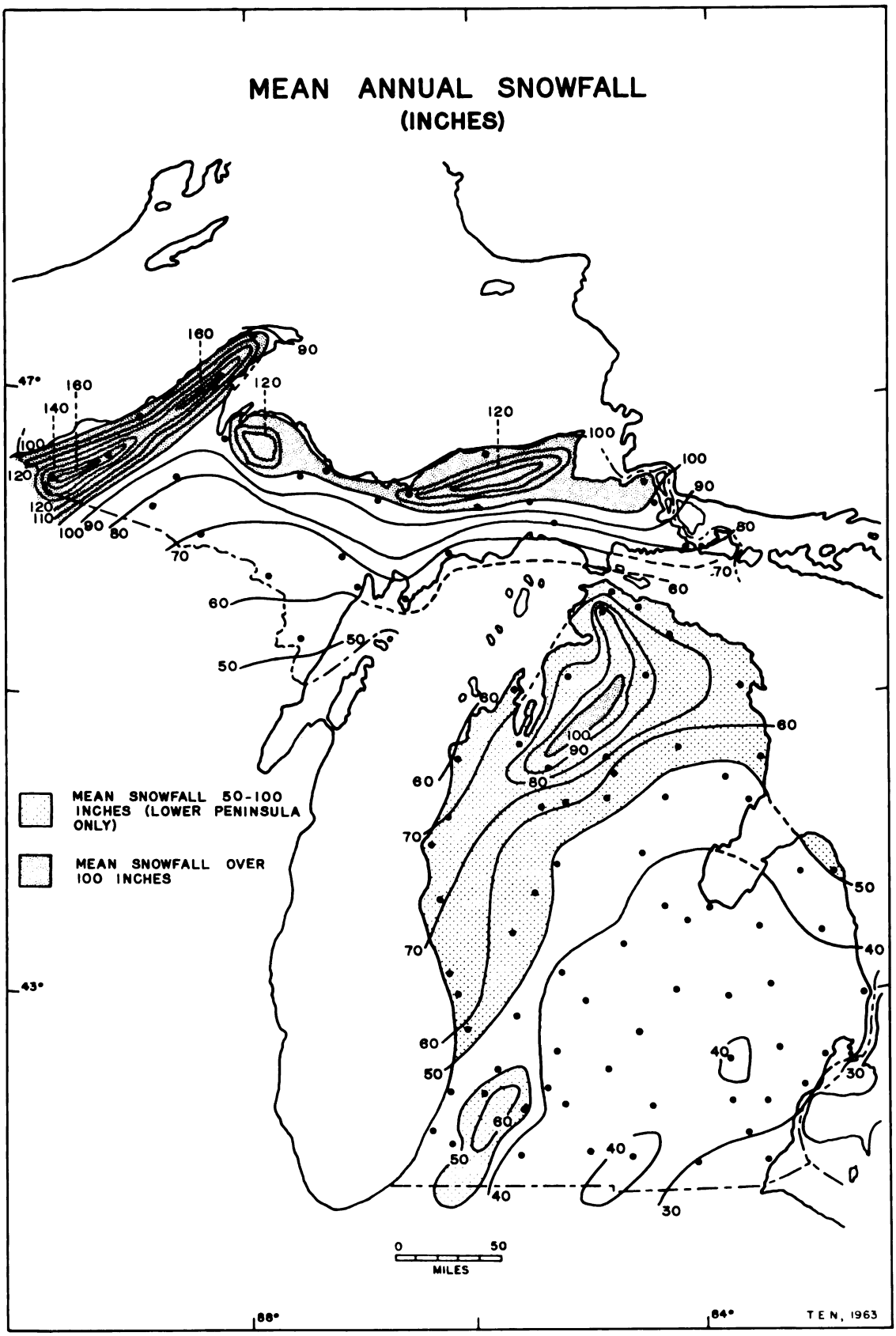

MEAN ANNUAL SNOWFALL
(INCHES)
MEAN SNOWFALL 50-100 INCHES (LOWER PENINSULA ONLY)
MEAN SNOWFALL OVER 100 INCHES
47°
43°
88°
84°
0 50
MILES
T E N, 1963

Figure 20

gradient from the Lake Superior shore towards the interior is very steep. For example, snowfall decreases from 160 inches at Ironwood to less than 60 inches at Stephenson within a distance of 145 miles.

For the Lower Peninsula as a whole, there is a marked decrease in totals from the northwest to the southeast. Although the difference between maximum and minimum (100 inches and 30 inches, approximately) is not as great as in the Upper Peninsula, it is still appreciable. The Lower Peninsula has only a small area with over 100 inches of snowfall, situated on the western rim of the Northern Upland in the vicinity of East Jordan, Vanderbilt, and Fife Lake. This is also the area of steepest snowfall gradients in the southern peninsula.

Snowbelts, or areas of exceptionally heavy snow accumulation, are a much discussed subject in the climatography of the Great Lakes region.[1] In this analysis a snowbelt is defined as an area of significantly above-average snowfall for its latitudinal position and with a relatively steep gradient from the center to the edge of the belt. Five snowbelts may be delimited in Michigan. Three are in the Upper Peninsula: (1) the western rim of the Northern Highlands (Keweenaw Peninsula-Porcupine Mountains-Gogebic Range). It is well-defined and comprises the largest snowbelt with the highest average

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[1]See, e.g., R. M. Dole, "Snow Squalls in the Lake Region," Monthly Weather Review, Vol. 56, No. 12, Dec. 1928, Pp. 512-513; C.L. Mitchell "Snow Flurries along the Eastern Shore of Lake Michigan," Monthly Weather Review, Vol. XLIX (1921), P. 502; J. T. Remick, "The Effect of Lake Erie on the Distribution of Precipitation in Winter," Bulletin American Meteorological Society, Vol. XXIII, Nos. 1 and 3, (1942), Pp. 1-4 and 111-117; and B. L. Wiggin, "Great Snows of the Great Lakes," Weatherwise, Vol. 3, No. 6, Dec. 1950, Pp. 512-513.

snowfalls; (2) the Huron Mountains snowbelt; and (3) the Grand Marais-Munising-Newberry snowbelt which receives amounts intermediate between the two western areas.

Two snowbelts are found in the Lower Peninsula: (1) the western rim of the Northern Upland between Vanderbilt and Fife Lake is the larger, better-defined, and has the heavier snowfall of the two; and (2) the Kalamazoo-Bloomington-Allegan triangle. Although snowfall in the latter area is much less than in the other belts, the triangle stands out for its above average snow in southern Michigan.

The variability of snowfall within the study area is somewhat greater than that for total precipitation. As determined by coefficients of variation (see footnote page 43), the range of variabilities for annual snowfall is from 19% at Sault Ste. Marie to 40% at Detroit (compared to 9% and 22% for mean annual precipitation at the same stations). In general, stations in the northern part of the state have less variation than those in the southern part. There is no apparent relationship between close proximity to the shore of a Great Lake and low snowfall variability or greater distance from a Lake and high variability.

Solid Precipitation Other Than Snowfall

Solid precipitation other than snow, namely, hail, sleet, and freezing rain (or glaze) is relatively rare in the study area but occurs with sufficient frequency to have noticeable climatic impact.[1]

Hail.- The primary significance of hail lies in its great

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[1]Data for sleet are reported with those for snowfall. Separate data for hail and freezing rain are not included in the official statistics of the U.S. Weather Bureau.

destructiveness, particularly to crops. It is responsible for more property damage in the United States than sleet, freezing rain, or tornadoes, and, in some years, causes almost as much damage as hurricanes.

During the period 1944 to 1953 only 15 hailstorms were recorded in Michigan, two of which were regarded as severe.[1] All occurred in June, July, or August with the latter month accounting for 9 of the 15. If the state's record of 15 occurrences is compared with 559 in Montana and 440 in Kansas (allowing for differences in area) for the same period, it is evident that damaging hailstorms are rare events in Michigan.

As far as regional distribution is concerned, the littoral sections of the state benefit from the stabilizing effects of the relatively cool water of the Great Lakes which inhibits the convection necessary to produce hail. Indicative of this stabilizing effect is the fact that the most severe hailstorms recorded in Michigan all occurred in the interior of the Lower Peninsula, at least 25 miles from the shore of a Great Lake.[2]

Hail normally occurs in association with severe thunderstorms. In the study area most thunderstorms take place in June, July, and August, although the other warm months usually experience a few. There is little regional difference in mean annual number of thunderstorms, with a range from 29 at Marquette and Alpena to 37 at Grand

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[1]Snowden D. Flora, Hailstorms of the United States, (Norman, Okla.: Univ. of Oklahoma Press, 1956), P. 3.

[2]The most destructive hailstorm in Michigan's history was in Gratiot County (near Alma weather station) on August 1, 1953; an estimated $500,000 damage occurred at this time. See Flora, op. cit., Pp. 22-23.

Rapids. The average number is approximately 33 per year, with northern and Lake-shore stations recording slightly less than this number and stations in the south being slightly above the state's average. It is obvious that throughout Michigan only a very small proportion of thunderstorms are accompanied by damaging hail.

Freezing Rain.- Freezing rain, or glaze, is not a form of precipitation but is the accumulation of a coating of ice on surface objects. It occurs when supercooled rain or drizzle strikes a cold surface and immediately changes to ice. Glaze is not common because the values of meteorological variables must be within a very narrow range for the phenomenon to occur.

The southern half of the Lower Peninsula averages as many glaze storms per year as any part of North America. The probability is high that a station in southern Michigan will experience one heavy glaze storm every three winters. In the northern Lower Peninsula one severe storm may be expected every 6 years. In the Upper Peninsula probabilities are high that more than 6 years will pass between two heavy freezing-rains.[1] The distribution of glaze storms in Michigan in indicative of the fact that surface warm fronts do not normally reach the Upper Peninsula during the winter. Moisture-bearing airmasses are usually so far aloft before reaching the northern part of the state that any rain produced freezes (and becomes snow or sleet) before striking a cold surface.

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[1]George H. T. Kimble, Our American Weather, (New York: McGraw-Hill, 1955), P. 16.

Moisture Elements Other Than Precipitation

Humidity

Relative humidity observations for Michigan's first-order weather stations are taken at 1:00 A.M., 7:00 A.M., 1:00 P.M., and 7:00 P.M.[1] Regional differences do exist, but they are not large if comparisons are based on the same hour in the same month. Detroit, Marquette, Escanaba, and Alpena have relative humidity values somewhat lower than Sault Ste. Marie, Muskegon, Flint, and Lansing. The highest average annual humidities are at Sault Ste. Marie which has 86% at 1:00 A.M., 86% at 7:00 A.M., 68% at 1:00 P.M., and 76% at 7:00 P.M. Detroit has the lowest mean relative humidity values with 77%, 79%, 59%, and 65%, respectively, for the same hours.[2] The western Upper Peninsula has slightly lower humidity than the eastern Upper Peninsula, whereas the eastern Lower Peninsula has somewhat lower moisture content in its atmosphere than the western Lower Peninsula. The fact that Marquette and Escanaba have relative humidities reasonably close to those of Detroit, while, at the same time, experiencing significantly lower temperatures, indicates that the northwestern part of the Upper Peninsula has lower absolute humidities than the other sections of the state.

Cloudiness

Seven first-order stations in Michigan report data for percentage

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[1]Official data are available for relative humidity, but only for first-order weather stations. No data are available for absolute humidity, specific humidity, or other moisture indices.

[2]Michigan Weather Service, Climate of Michigan --By Stations, (In cooperation with U.S. Weather Bureau), Lansing, Mich., Feb. 1963.

of possible sunshine received and for mean number of cloudy, partly cloudy, and clear days.[1] Examination of these data indicates that, in general, the northern and eastern Upper Peninsula is the cloudiest part of the state (i.e., has the lowest percentage of possible sunshine), and the eastern and southeastern part of the Lower Peninsula is the least cloudy. All parts of the state, however, receive less than 55% of possible sunshine, and at least two-thirds of the days are cloudy or partly cloudy.[2]

Sault Ste. Marie has the lowest percentage of possible sunshine (45), and Detroit has the highest (54). Of the other reporting stations, Marquette has 50%, Escanaba 53%, Alpena 51%, Grand Rapids 48%, and Lansing 52%.[3] It is apparent from the cited figures that regional differences in the study area are relatively small with respect to the ratio of actual to possible sunshine. A common characteristic of the state as a whole is the very low value of the percentages in comparison with other regions of the country. Michigan is situated in one of the cloudiest sections of the United States, with only the Pacific Northwest, parts of the eastern Great Lakes, and northern New England equalling or exceeding its mean cloud cover.

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[1]Cloudy, partly cloudy, and clear days are determined by the proportion of the sky that is covered by clouds. Sky cover is expressed as a range of from zero for no clouds to ten for complete sky cover. The number of clear days is based on average cloudiness of 0-3 tenths; partly cloudy days on 4-7 tenths; and cloudy days on 8-10 tenths. See, e.g., U.S. Dept. of Commerce, Weather Bureau, Local Climatological Data, Washington, D.C.

[2]Michigan Weather Service, Climate of Michigan--By Stations, op. cit.

[3]Ibid.

More conspicuous than regional differences, however, are the seasonal variations in cloudiness. In winter, no station within the state records more than two-fifths the amount of sunshine it could potentially receive for its latitude, and at some Lake-shore stations (e.g., Muskegon, Sault Ste. Marie, and Marquette) the duration of sunny hours is diminished by as much as 80% of the potential amount. During summer, the percentage of sunlight hours lost by cloud cover is greatly decreased, with most Lower Peninsula stations receiving about 70% of the possible sunshine and Upper Peninsula stations about 65%. Stations near the Great Lakes average more sunshine hours than those inland.

In spring and fall the ratios of actual to possible sunshine are intermediate between the low percentages of winter and the high percentages of summer. In the northern part of the state it is cloudier in the fall than in the spring, whereas the reverse is true in the southern part. Since, in the south, spring has more precipitation than fall, while fall is wetter than spring in the north, a positive correlation between cloudiness and precipitation may be inferred. However, there is no positive relationship between cloudiness and mean summer and mean winter precipitation. Winter is the cloudiest season but has the least precipitation, while summer, the sunniest season, has the greatest amount of rainfall.

In winter, Detroit and Escanaba are clearly favored by their locations on the lee side of the state with respect to Lakes Superior and Michigan, as evidenced by their significantly higher percentages of sunshine than the stations situated adjacent to these water bodies. No data are available for cloudiness above the Lake surfaces, but

there is no doubt that, in early winter, minimum percentages of sunshine would be recorded because of highly unstable conditions over the unfrozen water.[1] Lake-shore stations clearly exhibit a higher incidence of clouds in November and December than in the later winter months when large surfaces of the water bodies are frozen and assume, meteorologically, continental quality.

During summer the effect of the Lakes upon cloudiness is inverted. The relatively cool water tends to diminish convection, and the consequent increase in stability results in decreased cloud formation. Lake-shore stations record the highest percentages of possible sunshine for any part of the state at this time.

Analysis of mean number of cloudy, partly cloudy, and clear days (see footnote page 71) in the average year produces results similar to those for percentage of possible sunshine received. Escanaba has the fewest cloudy days per year (155), and most clear days (102), with the other 108 days being classified as partly cloudy. Sault Ste. Marie has the greatest number of cloudy days (207), and, with Flint, has the least number of clear days (65). Considering the entire study area, stations on the lee side with respect to Lakes Michigan and Superior have a lesser number of cloudy days and a greater number of clear days than the windward-side stations. Flint, a lee-side station, is the only anomaly in this pattern.

The effect upon cloudiness caused by close proximity to the cloud-producing surface of Lake Michigan is exemplified by conditions at Muskegon, which has 192 cloudy days per year, or 12 more than

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[1]Development of fogs over the Lakes ("Lake smokes") is often observed where areas inland within a few miles from the shore are clear.

lee-side Detroit. Yet Muskegon has 81 clear days per year compared to 80 at Detroit. Alpena, with a lee-side location, but near Lake Huron, has only 164 cloudy days per year (28 less than Muskegon) and 82 clear days (about the same as Muskegon). Although every station in the state has more clear days during the warmer half of the year, at Muskegon the clear days are very strongly concentrated in the summer and early fall months. Nearly 75% of the sunny days at this windward-side station occur from May to October. Escanaba, however, has only 57% of its clear days during this period.[1]

Fog

The frequency of days with dense fog[2] is considerably greater near the Great Lakes than it is in the interior of the study area. Muskegon, for example, averages 25 days per year with dense fog, while Grand Rapids, only 30 miles from Lake Michigan, has 19. Lansing, approximately 85 miles from Lake Michigan, averages 12 days per year with dense fog.

The highest frequencies are found at the eastern end of Lake Superior, as exemplified by Sault Ste. Marie with 47 days of dense fog annually. The lowest frequencies occur at high elevations in the Northern Highlands and Northern Uplands where averages are less than 5 days per year. Table 2 summarizes fog data for the first-order weather stations of Michigan.

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[1]Michigan Weather Service, Climate of Michigan--By Stations, op. cit.

[2]Dense fog is defined officially as any surface cloud that reduces visability to less than 50 yards. The Weather Bureau also recognizes thick fog, medium fog, and moderate fog, but official data are not published.

TABLE 2

MEAN NUMBER OF DAYS WITH DENSE FOG

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Alpena	1	1	2	2	2	2	1	1	2	3	2	1	20
Detroit	2	2	1	1	1	*	*	1	1	1	1	1	12
Escanaba	1	1	2	2	2	1	1	2	2	2	2	1	19
Flint	2	2	1	1	1	1	1	2	2	3	2	2	20
Grand Rapids	2	2	1	1	1	1	1	3	1	2	2	2	19
E. Lansing	1	1	1	*	1	1	1	1	2	1	1	1	12
Marquette	1	1	1	2	2	3	3	1	1	1	1	1	18
Muskegon	2	2	2	2	3	2	1	3	1	3	2	2	25
Sault Ste. Marie	2	2	3	3	3	4	5	7	7	6	2	3	47

* Less than one day

Winds and Tornadoes

Surface Winds

The surface winds of the study area are a part of the circumpolar westerly component of the general atmospheric circulation, and, therefore, are prevailingly from the west. Deviations in the prevailing pattern are caused by migratory pressure systems and local terrestrial factors.

Figure 21 indicates mean annual prevailing winds for eight first-order weather stations. The majority of months at most stations are dominated by northwesterly, westerly, or southwesterly winds. Although easterly, southerly, and northerly winds occur frequently they are

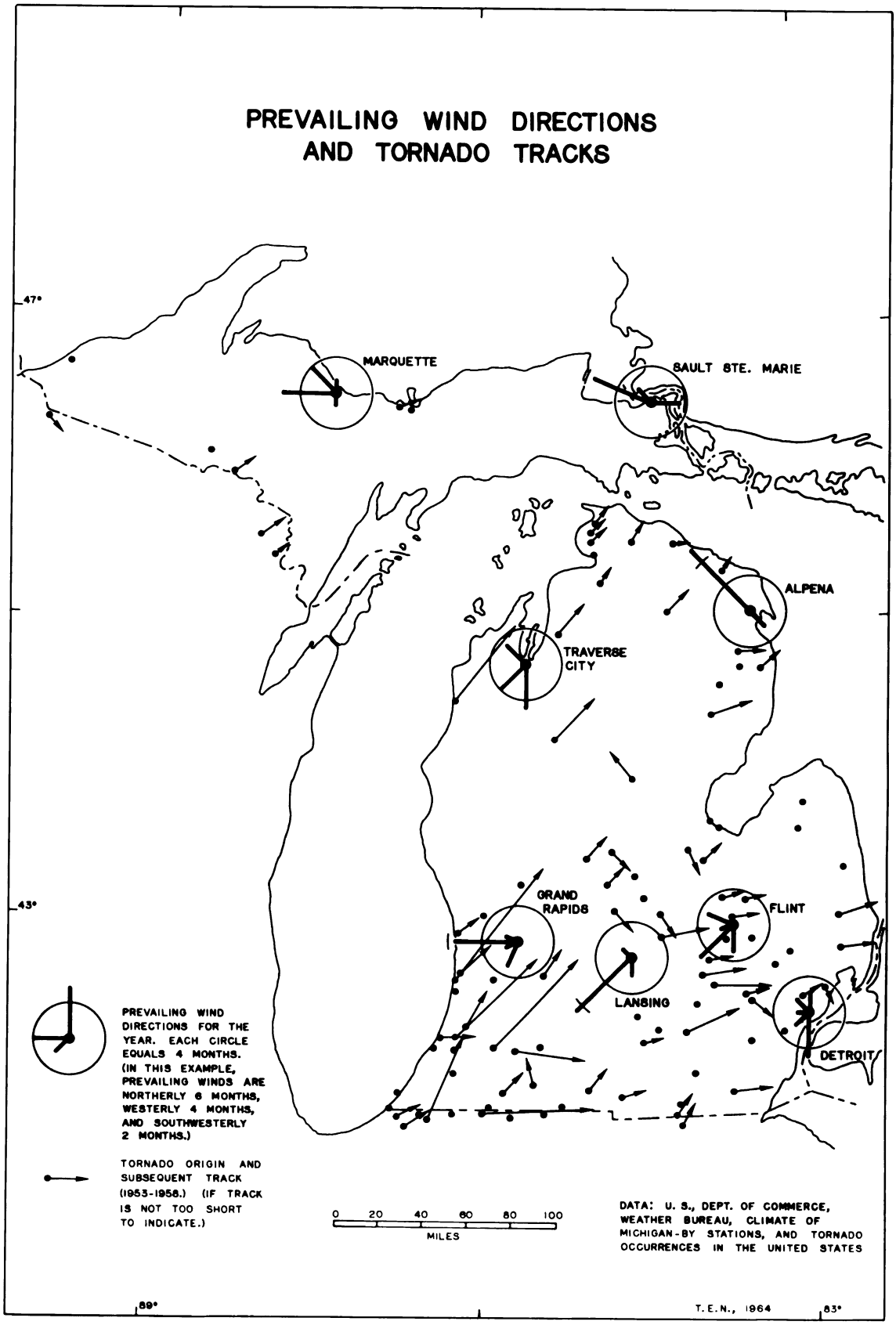

PREVAILING WIND DIRECTIONS
AND TORNADO TRACKS
47°
43°
89°
83°
MARQUETTE
SAULT STE. MARIE
ALPENA
TRAVERSE CITY
GRAND RAPIDS
FLINT
LANSING
DETROIT
PREVAILING WIND DIRECTIONS FOR THE YEAR. EACH CIRCLE EQUALS 4 MONTHS. (IN THIS EXAMPLE, PREVAILING WINDS ARE NORTHERLY 6 MONTHS, WESTERLY 4 MONTHS, AND SOUTHWESTERLY 2 MONTHS.)
TORNADO ORIGIN AND SUBSEQUENT TRACK (1953-1958.) (IF TRACK IS NOT TOO SHORT TO INDICATE.)
0 20 40 60 80 100
MILES
DATA: U. S., DEPT. OF COMMERCE, WEATHER BUREAU, CLIMATE OF MICHIGAN-BY STATIONS, AND TORNADO OCCURRENCES IN THE UNITED STATES
T. E. N., 1964

Figure 21

rarely the prevailing winds. In the southern part of the study area, the prevailing winds tend to be southwesterly (particularly in summer), while in the northern section they are generally northwesterly throughout the year.

Sault Ste. Marie and Alpena are the only first-order stations with prevailing easterly winds for any months of the year. However, at the former easterlies are typical during winter and at the latter they occur during summer. The explanation for this pattern may be sought in the relative location of the two stations and the mechanics of the lake and land breeze. In winter, especially when anticyclonic control prevails to the north of the study area, winds are often from the cold land toward the warm water of Lake Superior; therefore, they are easterly at Sault Ste. Marie. In summer the winds are reversed and join the prevailing westerly flow. The relative location of Alpena with respect to land and water is opposite that of Sault Ste. Marie. Consequently, in early summer, breezes are often from the cool surface of Lake Huron onto the warm land surface, and, therefore, easterly at Alpena.

Prevailing wind directions vary with the synoptic weather type and air mass that are present. Table 3 indicates the prevailing wind directions associated with air mass types at five Michigan stations. Listed are the prevailing wind direction (capital) and its relative frequency, and the combined frequency of winds from the dominant quadrant (direction spelled out). For example, at Detroit in January, with cA air masses present, westerly winds occur 30% of the time, and southwesterly, westerly, and northwesterly winds combined, 60% of the time.

TABLE 3

PREVAILING WIND DIRECTIONS ACCORDING TO AIR MASS TYPE[1]
(PERCENTAGE)

January

	cA	cP	NcP	mP	mT
Detroit	W- 30	SW- 18	S- 32	NE- 100	SW- 50
	West- 60	West- 52	South- 59	-	South- 100
Grand Rapids	W- 23	SW- 19	S- 25	NE- 33	W- 100
	West- 61	West- 50	South- 62	East- 66	-
Traverse City	SW- 28	SW- 20	SW- 27	NE- 100	W- 100
	West- 58	West- 44	South- 67	-	-
Escanaba	NW- 36	NW- 31	S- 36	N- 100	W- 100
	West- 77	West- 45	South- 57	-	-
Sault Ste. Marie	E- 32	E- 33	SW- 26	E- 50	W- 100
	East- 44	East- 53	South- 57	East- 75	-

July

	cP	mT	mP
Detroit	N- 30	S- 37	N- 100
	North- 51	South- 76	-
Grand Rapids	Calm- 19	S- 32	N- 100
	South- 38	South- 61	-
Traverse City	SW- 41	SW- 50	SW- 100
	South- 76	South- 96	-
Escanaba	N- 21	S- 48	S- 50
	North- 43	South- 88	South- 100
Sault Ste. Marie	W- 30	E- 40	S- 50
	West- 42	East- 85	South- 100

[1]Interpreted from U.S., Dept. of Commerce, Weather Bureau, Daily Weather Map, Washington , D.C., 1958-1962.

Note: Capital represents most frequently occurring wind; direction spelled out represents combined frequency of winds from the dominant quadrant.

The following generalizations may be made from Table 3: (1) cA air masses are normally associated with westerly, southwesterly, or northwesterly winds. Only at Sault Ste. Marie are winds typically from the east with cA air masses; (2) in January, winds associated with cP air masses behave similar to those with cA air masses. Again, Sault Ste. Marie is the only station with prevailingly easterly winds. In July, however, westerly winds occur with cP air at Sault Ste. Marie; (3) NcP air masses have a preponderance of southerly winds at all stations; (4) mP air masses are most commonly associated with northerly or northeasterly winds; and (5) mT air does not occur with sufficient frequency in January to permit valid inferences, but in July it is closely related to southerly winds, except at Sault Ste. Marie where easterly circulation dominates. The percentage of southerly winds associated with mT air masses generally increases northward.

Wind speeds in Michigan vary considerably according to the synoptic situation and local terrain conditions. In terms of mean monthly speed in miles per hour, however, there is little regional difference. Mean velocities vary from 7 to 13 miles per hour, with winter months having the higher wind speeds. The greatest mean velocities occur at lee-shore stations or in flat terrain. The southern part of the state has slightly higher wind speeds in winter than the northern section, while the opposite is true in summer. The northern half of the study area has a smaller range of differences between the mean wind velocities of winter and summer.

Tornadoes (High Velocity Wind Systems)

The highest wind speeds recorded in Michigan are associated

with the small and transient, but extremely intense, cyclone referred to as the tornado. During the period 1916-1958 the study area had 177 tornadoes occurring on 114 different days.[1] For the same period Illinois had 301 tornadoes, Missouri 446, and Kansas 1,041. Kansas, which lies in the center of the belt of maximum tornado frequency for North America, had more than three times as many tornadoes as Michigan during the mentioned period.

Figure 21 shows origins and tracks for all tornadoes observed in the study area during the six-year period 1953-1958. Most of the storms that were actually observed occurred in the southern half of the Lower Peninsula. Only 6 were recorded in the Upper Peninsula. The northwestern section of the Lower Peninsula, from Muskegon northward to Suttons Bay and inland to Cadillac, was also an area of minimal occurrence, with only one being observed. To the northeast of the latter area, and particularly on the lee-side of the Northern Upland, tornado densities are nearly equal to those in the southern part of the state. It is probable that the stabilizing effect of Lake Michigan is the most important cause of the frequency decrease in the Muskegon-Suttons Bay-Cadillac area. The majority of tornado tracks in Michigan are oriented from the southwest to the northeast.

The highest tornado frequency falls in June with 52 having been observed from 1916 to 1958. May ranks second with 46, and April, July, and August have from 16 to 19 occurrences. A tornado was observed at some place in the state during every month except December in

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[1]U.S., Dept. of Commerce, Weather Bureau, Tornado Occurrences in the United States, Technical Paper No. 20, Washington, D.C., 1960.

at least 1 of the 42 years of this period, but October, November, January, and February recorded only 1 or 2 each.[1]

Effects of the Great Lakes on Climatic Elements

From the preceding paragraphs it is clear that the Great Lakes are major modifying factors in the elemental patterns of Michigan's climate. The purpose of this section is to summarize the nature and magnitude of the modifications which these water bodies have on the climate of the study area.

The general nature of the relationships between the Great Lakes and the land surface of Michigan is illustrated in Figure 22 and Table 4. Both portray seasonal changes in the effects of Lake and land on the climate of the state. In summer, the relatively cold Lakes dampen convection by chilling the base layers of air masses, and thereby decrease lapse rates and promote atmospheric stability. At this time of year the Lakes often have higher barometric pressure over their surfaces than is found over the adjacent land. The land surface, heating rapidly and intensely during the daylight hours, labilizes the air over it by forcing it to rise convectionally, often with resultant precipitation. The difference in pressure between water and land results in the establishment of land and lake breezes, with on-shore flow of air during the day and off-shore flow at night. The Lake breeze often transports relatively cool air on-shore during the day, and thus reduces temperatures near the shores. This is particularly evident for daily maximum temperatures in summer which

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[1] Ibid., P. 34.

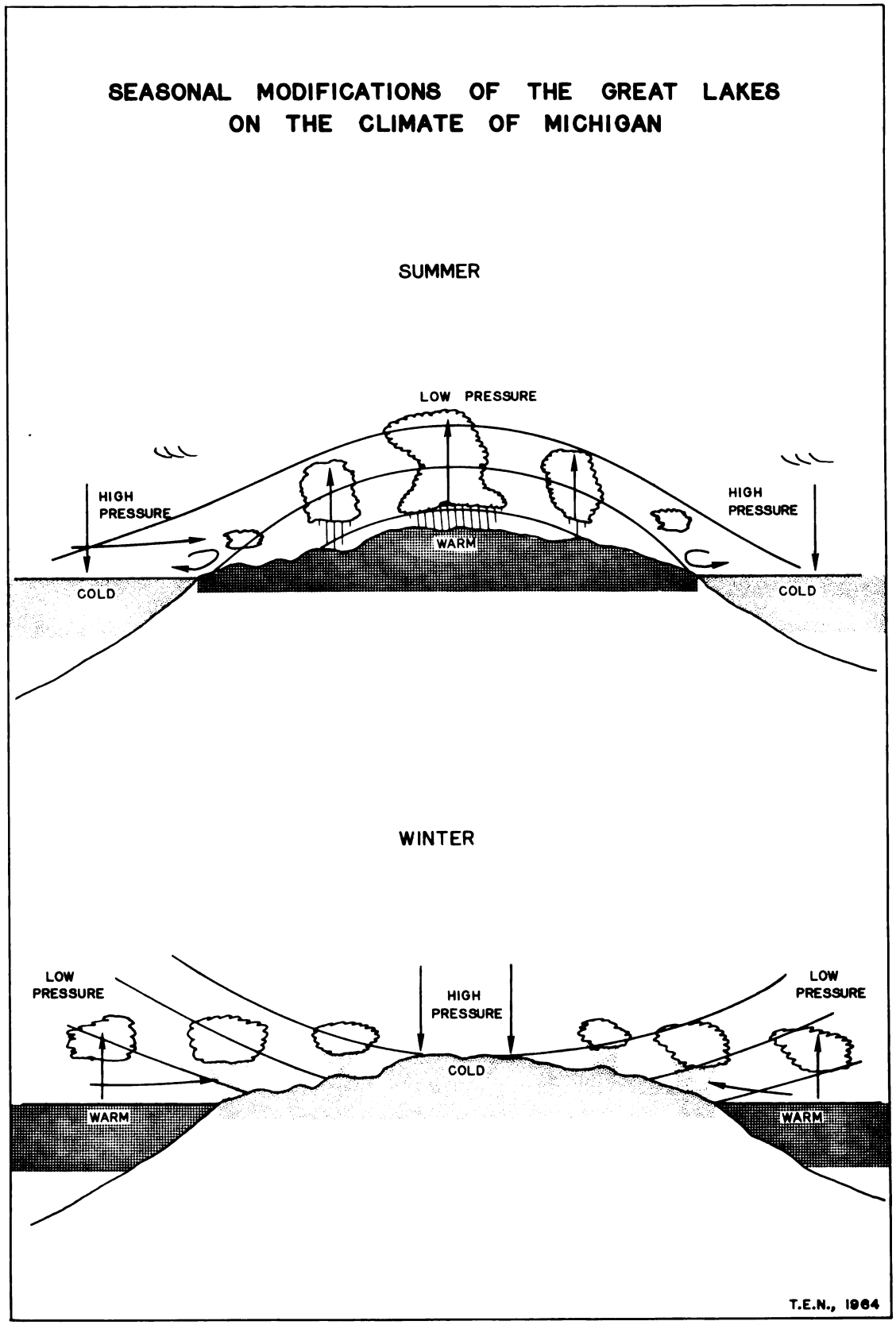

SEASONAL MODIFICATIONS OF THE GREAT LAKES
ON THE CLIMATE OF MICHIGAN
SUMMER
LOW PRESSURE
HIGH
PRESSURE
HIGH
PRESSURE
WARM
COLD
COLD
WINTER
LOW
PRESSURE
HIGH
PRESSURE
LOW
PRESSURE
COLD
WARM
WARM
T.E.N., 1964

Figure 22

TABLE 4

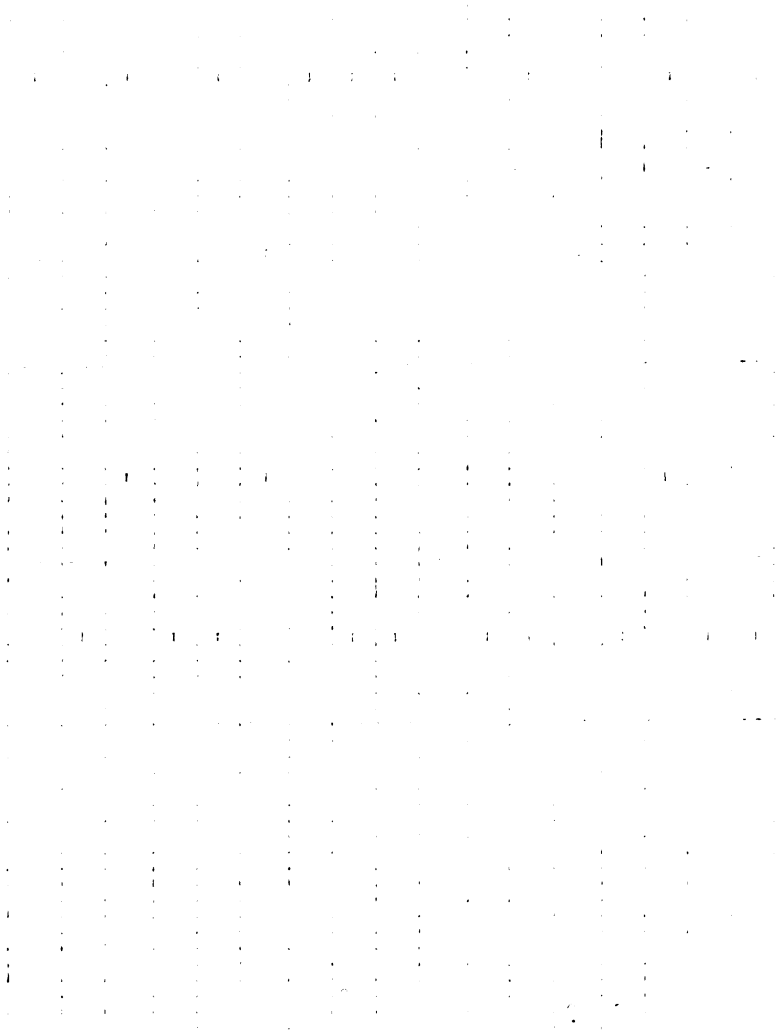
SEASONAL EFFECTS OF LAKE AND LAND ON THE CLIMATE OF MICHIGAN

Key
* = above average amount or frequency
- = below average amount or frequency
o = neutral, or slight effect

	Summer		Winter	
	Great Lakes	Land Surface	Great Lakes	Land Surface
Mean Monthly Temperature	-	*	*	-
Daily Maximum Temperature	-	*	*	-
Daily Minimum Temperature	*	-[1]	*	-
Mean Number of Days with Temperature 90° F., or above	-	*	o	o
Mean Number of Days with Temperature 0° F., or below	o	o	-	*
Convection	-	*	*	-
Cyclogenesis	-	o	*	o
Anticyclogenesis	*	o	-	o
Mean Monthly Precipitation	-	*	*	-
Mean Number of Days with Precipitation .10", or over	-	*	*	-
Mean Monthly Snowfall	o	o	*	-
Percentage of Possible Sunshine	*	-	-	*
Mean Number of Cloudy Days	-	*	*	-
Hail	-	*	o	o
Fog	*[2]	-	*	-
Tornadoes	-	*	o	o
Relative Humidity	o	o	*	-

[1]Depends on type of air and amount of cloud cover

[2]With mT air masses



are as much as 15 F.° lower near the shore than they are a few miles inland.

In late fall and early winter the Lakes are warm compared to the air masses over them and the adjacent land; therefore, they have effects opposite to those of summer. The Lakes labilize the lower layers of air masses, most markedly those of cP and cA, thereby steepening their lapse rates considerably and making them convectively unstable. There is also a much stronger vapor flux from the warm Lakes into the cold, dry air than from the cold Lakes into the warm air during summer. The combination of increased instability and greater humidity results in the formation of convectional cloudforms which, upon reaching land and being forced to rise by friction or orography, often release precipitation, most of which occurs as snow. In the interiors of the peninsulas, however, thermal high pressure cells are formed over the cold land with the typical characteristics of subsident air, namely, stability, limited formation of clouds, and little precipitation.

At various times of the year, when certain synoptic weather types prevail within the study area, the Lake-effect may produce unusual weather conditions. The most notable of these Lake-induced phenomena is the snow squall, a recurrent weather event of late fall and early winter. For example, snow squalls often develop along the eastern shore of Lake Michigan at Grand Haven, Muskegon, and Ludington, while at Chicago and Milwaukee on the western shore, skies are clear. A synoptic situation that may produce snow showers is the influx of cA or cP air in the cold sector of a cyclone passing through the Great Lakes area. It is necessary that the difference in temperature

between the air mass and water body be relatively high, and the isobars must be so oriented that air flows over a large extent of water before curving onto the land surface of the state.[1] The cold, dry air masses from the north absorb considerable moisture from the warm Lakes and large convective cloud systems are formed. The solid condensates precipitate as snow showers.

Often the snow squalls do not begin until the cyclone has moved to the east of Michigan, and a high pressure system is established over the Great Lakes. Thus, rising pressure is frequently accompanied by unstable weather with snow showers in the vicinity of the Lake shores.

For the very heavy snowfalls that sometimes occur near the Great Lakes, even more specific synoptic and meteorologic circumstances must prevail. These are as follows:[2]

1. a strong flow of cA or very cold cP air with a lee-shore lapse rate equal to, or greater than, the dry adiabatic rate to a height of at least 5,000 feet;
2. cyclonic curvature of the air flow pattern;
3. a great temperature differential (at least 20 F.^{o}) between air and water to build up the vertical thickness of unstable air, and to cause a rapid flux of moisture from the Lake surface to the air;
4. a long trajectory over water; and
5. sufficient wind shear to produce longitudinal convective cells.

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[1]R. M. Dole, op. cit., Pp. 512-513.

[2]B. L. Wiggin, op. cit., Pp. 123-126.

If the flow of cA air is of limited depth, all other factors being favorable, heavy cloudiness, but only a few snow flurries may result. An outbreak of cA air of great depth and anticyclonic curvature can produce snow squalls of high intensity and short duration, but relatively little snow accumulates on the ground.[1]

In early- and mid-summer, stations on the west shore of Lake Michigan receive significantly higher precipitation than do stations at similar latitudes and distances from the Lake on the east shore. Statistics to support this thesis are as follows:[2]

Mean Total Precipitation for May, June, and July

Wisconsin Stations	Inches	Michigan Stations	Inches
Green Bay.....	10.63	Frankfort.....	8.67
Manitowoc.....	10.80	Manistee.....	8.85
Sheyboygan.....	10.33	Ludington.....	8.84
Port Washington..	10.95	Hart.....	9.11
Milwaukee.....	10.11	Muskegon.....	8.56
Racine.....	10.50	Grand Haven.....	8.43

The east shore, or Michigan, stations have an average of 1.81 inches (or about 17%) less precipitation than the west shore stations. Although other causal factors might be active, it is probable that Lake Michigan is an important cause of these differences.

The continentality of Michigan, or the ratio between annual

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[1] Ibid.

[2] Cyrus H. Eshleman, "Do the Great Lakes Diminish Rainfall in the Crop Growing Season?" Monthly Weather Review, Vol. 49, No. 9, Sept. 1921, Pp. 500-503.

temperature ranges and latitude, is also modified significantly by the Great Lakes. Using the Conrad Coefficient-of-Continentality Index,[1] land control in the study area varies from 35% along the southeastern Lake Superior and northeastern Lake Michigan shores to 47% in the interior of the Northern Highlands.[2] The interior of the Lower Peninsula has a maximum coefficient of 43%. In general, continentality is lowest near the Lakes, particularly on the windward sides of the peninsulas, and increases rapidly away from the water bodies. The difference of about 12% for the entire state is of considerable climatic importance within an area as small as Michigan. As central Wisconsin, northern Minnesota, and Ontario have maximum coefficients approaching 60%, it is evident that continentality in the interior of the study area is significantly lowered by the presence of the Lakes.

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[1]The Conrad Coefficient-of-Continentality Index is determined by the formula $k = 1.7\,A/\sin(L + 10) - 14$, where A is the average annual temperature range in degrees Centigrade; L is the latitude in degrees; and k is the continentality coefficient, expressed as a percentage. k indicates the extent to which the air temperature of a region is influenced by a continent, or conversely, by a large water body. The higher the index value the greater the degree of continental control. The constants chosen for this formula are (1) Verkhoyansk, in northeastern Siberia, representing maximum continentality (100%), and (2) Thorshavn, in the Faeroe Islands, providing minimum continentality (0%).

[2]Richard J. Kopec, "Continentality Around the Great Lakes," Bulletin of the American Meteorological Society, Vol. 46, No. 2, Feb. 1965, Pp. 54-57.

CHAPTER III

THE RELATIONSHIPS BETWEEN SELECTED CLIMATIC ELEMENTS AND ATMOSPHERIC CONTROLS

The behavior of climatic elements in Michigan is determined by the atmospheric and terrestrial controls that dominate the area. It is the purpose of this chapter to investigate the relationships between the more significant atmospheric factors and selected elements characterizing the climate of the study area. Frequency studies of the atmospheric controls are also included in the analysis.

Frequencies of Migratory Cyclones and Anticyclones

Migratory cyclones and anticyclones were introduced in Chapter I. Table 5 summarizes the number of these systems passing through, or in close proximity to, the study area for each month during the ten year period, 1951-1960.[1] The mean number of occurrences of Highs and Lows for each month is indicated, along with the respective variances (S^2), standard deviations (S), and coefficients of variation (C.V.).[2]

Examination of Table 5 yields the following results:

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[1]Data from U.S., Dept. of Commerce, Weather Bureau, Monthly Weather Review, op. cit., 1951-1958; and Weather Bureau, Climatological Data: National Summary, Washington, D.C., 1959-1960.

[2]See Appendix B for the results of t-tests to determine the existence of significant differences between means.

TABLE 5

LOW AND HIGH PRESSURE SYSTEMS PASSING THROUGH MICHIGAN: 1951-1960

	Highs				Lows			
	X	S^2	S	C.V.	X	S^2	S	C.V.
January	2.20	.96	.98	44.5%	6.90	5.49	2.34	33.9%
February	2.00	2.60	1.61	80.5%	5.70	3.01	1.74	30.5%
March	2.30	1.21	1.10	47.8%	5.70	1.61	1.27	22.2%
April	2.10	1.09	1.05	50.0%	5.00	1.40	1.18	23.6%
May	3.80	2.36	1.54	40.5%	4.60	8.64	2.94	63.9%
June	3.90	2.69	1.64	42.1%	4.00	2.20	1.49	37.3%
July	3.80	1.76	1.33	35.0%	2.60	2.84	1.69	65.0%
August	3.80	2.16	1.47	38.7%	3.60	3.44	1.85	51.4%
September	3.60	2.04	1.43	39.7%	3.70	1.81	1.35	36.5%
October	3.30	2.01	1.42	43.0%	4.00	3.60	1.90	47.5%
November	1.60	1.24	1.11	69.4%	5.10	1.29	1.14	22.4%
December	1.50	2.05	1.43	95.3%	5.50	2.65	1.63	29.6%

Note:

X, S^2, S, and C.V. represent mean number of systems per month, variance, standard deviation, and coefficient of variation, respectively.

1. There are two significantly different periods of the year for relative frequency of occurrence of high pressure systems. A "winter" period consisting of November, December, January, February, March, and April has an average of nearly 2 Highs per month (1.95), with a range from 1.5 in December to 2.3 in March. No significant differences exist between the mean number of Highs for any of the winter months. The second period consists of the "summer" months of May, June, July, August, September, and October. It is characterized

by an average of 3.7 Highs per month with a range from 3.3 in October to 3.9 in June. Again, no significant differences exist between the mean number of Highs for any of the summer months. However, every winter month is significantly different from every summer month. On the basis of this evidence, it is concluded that Highs are more frequent in summer than in winter. Also, differences in frequency of occurrence for Highs, as expressed by the coefficient of variation, are greater in winter than in summer.

2. The frequencies of low pressure systems can likewise be divided into winter and summer periods. Maximum frequencies for Lows occur in winter (XI-IV), as opposed to the more frequent occurrence of Highs in summer. Unlike anticyclones, there is no sharp break between winter and summer for frequencies of cyclones. Change is gradual, and, consequently, few significant differences are found between successive months. The average frequency for winter is 5.65 Lows per month, and for summer it is 3.75. January has the greatest mean number (6.9), but does not differ statistically from December, February, or March. However, January clearly has a greater frequency of cyclones than April or November. December, January, and February have from 2 to 4 more Lows than the mid-summer months of June, July, and August. April does not differ significantly from May or June, but has nearly twice the average number

of Lows that July has. June (4.00) is also significantly different from July (2.60), these being the only successive months with a significant variation in mean number of Lows.

3. Tests were applied to individual months to determine the existence of statistically significant differences between the mean number of Highs and the mean number of Lows. Two well-defined periods are evident, the same as in the preceding analyses. Winter averages more Lows per month than Highs. There is, however, no meaningful variation between frequencies of Highs and Lows for most of the summer months. Although in each case a slight difference exists, only in July is it statistically valid. Thus, it may be concluded that in the winter Lows are more frequent than Highs, while in the summer the pressure types have similar frequencies. July is the only month in which the mean number of Highs significantly exceeds the mean number of Lows.

Relationships Between Air Masses and Climatic Elements

In the analysis of the relationships between air masses and climatic elements, the mid-season months (January, April, July and October) for the five-year period 1958-1962 were considered. United States Weather Bureau Daily Weather Maps[1] were examined and an air mass type assigned to each day of the period for Detroit, Grand Rapids

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[1]U.S., Dept. of Commerce, Weather Bureau, Daily Weather Map, Washington, D.C., 1958-1962.

Traverse City, Escanaba, and Sault Ste. Marie. Element statistics for each day were then grouped with the air mass that prevailed during that day.

Air Mass Frequencies

Table 6 shows the number of occurrences, in frequencies and percentages, for each air mass type in each of the mid-season months. It is clear that continental Arctic and continental Polar[1] air masses dominate Michigan in the winter. January percentages for these two air masses combined range from 75 at Detroit to 88 at Sault Ste. Marie. At Detroit and Grand Rapids cA is only slightly more frequent than cP, but at Escanaba and Sault Ste. Marie cA exceeds cP by 20%.[2]

The occurrence of maritime Tropical[3] air masses at the surface during January is rare in the study area, with only Detroit averaging at least one day per month during the period of investigation. The Upper Peninsula stations have mT air at the surface only once during the five-year period. Maritime Polar[4] air masses also occur infrequently but are more evenly distributed over the state than mT. Modified continental Polar[5] air masses are more common than mT or mP, but are present only about half as often as either cA or cP. Like mT, NcP is much more prevalent in the southern part of the state than in the northern part.

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[1]Hereafter abbreviated cA and cP.

[2]On the basis of this five-year sample it cannot be concluded that cA and cP always bear this relationship, because in 1959, 1961, and 1962 January mean temperatures were significantly lower than the long-term normals.

[3]Hereafter abbreviated mT. [4]Hereafter abbreviated mP.

[5]Hereafter abbreviated NcP.

TABLE 6

FREQUENCY AND PERCENTAGE OF OCCURRENCES OF AIR MASS TYPES
(1958-1962)

January

	cA		cP		NcP		mP		mT		Total	
	F*	%	F	%	F	%	F	%	F	%	F	%
Detroit	58	40.9	49	34.5	26	18.3	3	2.1	6	4.2	142	100
Grand Rapids	61	42.6	51	35.7	26	18.2	3	2.1	2	1.4	143	100
Traverse City	64	44.7	56	39.2	19	13.3	3	2.1	1	0.7	143	100
Escanaba	75	52.4	48	33.6	16	11.2	3	2.1	1	0.7	143	100
Sault Ste. Marie	79	55.2	47	32.9	14	9.8	2	1.4	1	0.7	143	100
Mean No. of Occurrences	67.4	. .	50.2	. .	20.2	. .	2.8	. .	2.2	. .	143	. .

April

	cP		NcP		mP		mT		Total	
	F	%	F	%	F	%	F	%	F	%
Detroit	93	64.1	23	15.9	5	3.4	24	16.6	145	100
Grand Rapids	97	66.9	22	15.2	5	3.4	21	14.5	145	100
Traverse City	108	74.5	23	15.9	5	3.4	9	6.2	145	100
Escanaba	123	84.2	15	10.3	7	4.8	1	0.7	146	100
Sault Ste. Marie	126	86.3	12	8.2	7	4.8	1	0.7	146	100
Mean No. of Occurrences	109.4	. .	19.0	. .	5.8	. .	11.2	. .	145	. .

* F represents frequency.

TABLE 6 -- Continued

July

	cP		mP		mT		Total	
	F	%	F	%	F	%	F	%
Detroit	103	69.1	0	0	46	30.9	149	100
Grand Rapids	104	70.3	1	0.7	43	29.0	148	100
Traverse City	118	79.2	1	0.7	30	20.1	149	100
Escanaba	122	81.9	2	1.3	25	16.8	149	100
Sault Ste. Marie	125	85.0	2	1.4	20	13.6	147	100
Mean No. of Occurrences	114.4	. .	1.2	. .	32.8	. .	148	. .

October

	cP		NcP		mP		mT		Total	
	F	%	F	%	F	%	F	%	F	%
Detroit	80	52.3	23	15.1	12	7.8	38	24.8	153	100
Grand Rapids	87	56.8	23	15.1	13	8.5	30	19.6	153	100
Traverse City	96	62.8	21	13.7	13	8.5	23	15.0	153	100
Escanaba	108	70.6	17	11.1	13	8.5	15	9.8	153	100
Sault Ste. Marie	108	70.6	18	11.8	14	9.1	13	8.5	153	100
Mean No. of Occurrences	95.8	. .	20.4	. .	13.0	. .	23.8	. .	153	. .

In April the cA air mass is no longer in evidence because the arctic front is not affecting the study area. The cP air mass assumes dominance over the entire state with percentages only slightly less than the combined percentages of cA and cP during January. Greater relative frequency of cP at the northern stations, as compared to the southern stations, continues in the spring. At Detroit about two-thirds of the days are characterized by cP air, but at Sault Ste. Marie it prevails on nearly 90% of the April days. NcP and mP air masses show little change from January, but mT frequencies increased significantly at the southern stations, with both Detroit and Grand Rapids gaining about 13% more mT days. However, Escanaba and Sault Ste. Marie still experience few surface mT incursions. A strong decrease is indicated for mT frequencies between southern and northern Michigan, with the steepest gradient occurring between Grand Rapids and Traverse City.

In July only cP and mT occur with sufficient frequency to establish parameters. cP is the dominant air mass in this month as in January and April. Nevertheless, the relative frequency of mT is greater than in any of the other mid-season months, with each station having at least 13% of its days dominated by mT, and Detroit and Grand Rapids having approximately 30% of their days characterized by mT. The mT gradient of decreasing frequency continues to be steepest between Grand Rapids and Traverse City.

In October the relative frequency of cP air masses is slightly less than in July and April. NcP occurs about as often in October as in April, and mP is more common in this month than in any other,

but is still the least frequent of all air mass types. mT air masses are less numerous than in July, but more frequent than in April. The mT gradient between Grand Rapids and Traverse City remains fairly steep, but differences are now greater between Traverse City and Sault Ste. Marie.

Temperature Characteristics of Air Masses

Means, variances, and standard deviations for air mass temperatures in each of the mid-season months are shown in Table 7. Although temperature differences between air masses are evident, it is important to determine whether these inequalities are statistically significant or, conversely, have a high probability of occurring by chance. If mean temperatures of unlike air masses are significantly different, it is very likely that physical dissimilarities do, in fact, exist between the air masses. The t-values obtained from difference-of-means tests in this analysis indicate that differentiation of air masses based on thermal characteristics is possible.[1]

In January the greatest inequalities (as indicated by very high t-values at the .05 level of confidence) are found between cA and the other air mass types. Mean temperatures of cP air also differ, in most cases, from those of the other air masses, but contrasts are not as well marked as for cA. Relatively little thermal differentiation is found between mT, mP, and NcP air at this time, partly because

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[1]To determine statistical significance for the temperature means of Table 7, difference-of-means tests were applied and the results checked with t-statistic distributions. Samples of these calculations and tests for Detroit and Sault Ste. Marie are shown in Appendix B. For a description of the t-statistic method see, e.g., Helen M. Walker and Joseph Lev, Statistical Inference, (New York: Henry Holt, 1953), Chapter 7.

TABLE 7

MEANS, VARIANCES, AND STANDARD DEVIATIONS FOR TEMPERATURES OF AIR MASS TYPE
(^{o} F.)

January

		cA	cP	NcP	mP	mT
Detroit	X	16.70	27.80	31.60	32.60	33.20
	S2	47.61	40.96	65.61	5.91	38.44
	S	6.90	6.40	8.10	2.40	6.20
Grand Rapids	X	14.20	25.90	28.30	30.70	28.00
	S2	51.84	30.25	75.69	4.84	1.00
	S	7.20	5.50	8.17	2.20	1.00
Traverse City	X	13.40	23.90	27.80	28.70	28.10
	S2	56.25	33.64	38.44	11.64	0.00
	S	7.50	5.80	6.20	3.30	0.00
Escanaba	X	9.90	22.50	26.90	25.70	26.00
	S2	64.00	36.00	19.36	1.17	0.00
	S	8.00	6.00	4.40	1.10	0.00
Sault Ste. Marie	X	7.10	19.60	24.30	23.50	25.00
	S2	64.00	51.84	16.00	0.25	0.00
	S	8.00	7.20	4.00	0.50	0.00

April

		cP	NcP	mP	mT
Detroit	X	43.50	53.50	50.14	61.90
	S2	39.69	36.00	106.09	86.49
	S	6.30	6.00	10.30	9.30
Grand Rapids	X	42.00	49.80	49.40	60.00
	S2	32.49	72.25	94.09	75.69
	S	5.70	8.15	9.70	8.70
Traverse City	X	40.30	48.00	45.40	55.20
	S2	64.00	49.00	129.96	86.49
	S	8.00	7.00	11.40	9.30
Escanaba	X	38.90	43.80	45.10	46.00
	S2	38.40	30.25	60.84	0.00
	S	6.20	5.50	7.80	0.00
Sault Ste. Marie	X	38.00	39.00	41.10	40.00
	S2	47.61	24.01	40.96	0.00
	S	6.90	4.90	6.40	0.00

Note:
X, S^2, and S represent mean, variance and standard deviation, respectively.

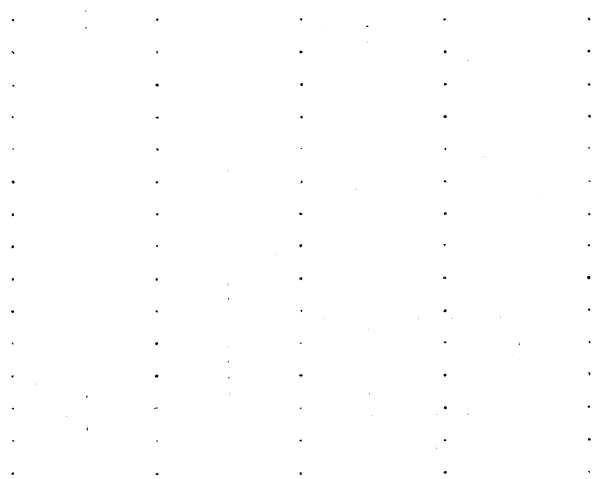




TABLE 7 -- Continued

July

		cP	mP	mT
Detroit	X	70.90	0.00	76.40
	S2	9.00	0.00	4.41
	S	3.00	0.00	2.10
Grand Rapids	X	69.00	68.00	73.50
	S2	21.20	0.00	15.21
	S	4.60	0.00	3.90
Traverse City	X	65.80	66.00	72.00
	S2	56.25	0.00	9.61
	S	7.15	0.00	3.10
Escanaba	X	64.80	66.00	70.40
	S2	18.50	1.00	3.61
	S	4.30	1.00	1.90
Sault Ste. Marie	X	62.30	62.00	68.80
	S2	25.00	4.00	10.29
	S	5.00	2.00	3.20

October

		cP	NcP	mP	mT
Detroit	X	49.10	56.30	60.80	62.40
	S2	45.85	47.02	20.36	38.56
	S	6.80	6.90	4.51	6.20
Grand Rapids	X	48.30	54.80	58.00	60.40
	S2	30.05	40.61	16.31	36.87
	S	5.50	6.40	4.04	6.07
Traverse City	X	46.10	50.30	56.50	57.00
	S2	62.60	61.58	20.60	45.87
	S	7.90	7.90	4.50	6.80
Escanaba	X	45.90	50.90	54.20	55.50
	S2	49.56	23.25	11.44	22.35
	S	7.04	4.80	3.40	4.70
Sault Ste. Marie	X	43.70	50.40	52.90	52.70
	S2	51.96	45.28	34.52	24.48
	S	7.20	6.70	5.90	4.90

of inherent similarities and also because of the limited number of observations for mP and mT.

Using Grand Rapids as an example, it can be seen that cA air masses are much colder than the other types in January; cA has an average temperature of 16.7° F. with a standard deviation (S) of 6.9 F.°,[1] while cP, the next coldest type, has a mean of 25.9° F. with a standard deviation of 5.5 F.°[2] Thus, cA produces lower temperatures than cP a very high percentage of the time at Grand Rapids.

In April cP varies significantly from NcP and mT, the other principal types. For example, at Grand Rapids the mean temperature for cP air masses is 42.0° F. with a standard deviation of 5.7 F.°, and for NcP the respective values are 49.8° F. and 8.5 F.° NcP and mT also differ from each other in the Lower Peninsula, but not in the Upper Peninsula. No differences are found between NcP and mP or mP and mT at any of the five stations.

Of the three air masses recognized in July, mP occurs too infrequently to establish its mean temperature. However, cP and mT air mass temperatures are consistently and highly differentiated at each station. For example, at Grand Rapids cP has a thermal mean of 69.0° F. with a standard deviation of 4.6 F.°, while mT temperatures average 73.5° F. with the standard deviation being 3.9 F.° For two-thirds of the mean daily temperatures (plus and minus one standard deviation) the range for cP is 64.4-73.6° F. and for mT it is 69.6-77.4° F.

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[1]About two-thirds of mean daily temperatures are between 9.8° F. and 23.6° F. with cA air masses present.

[2]Approximately two-thirds of cP's mean daily temperatures are within the range of 20.4° F. - 31.4° F.

In October the same general pattern prevails, with cP mean temperatures well below those of the other types. At Grand Rapids cP averages 48.3° F. with a standard deviation of 5.5 F.°, and NcP has a mean of 54.8° F. with an S-value of 6.4 F.° Difference-of-means tests indicate that this inequality is significant. NcP temperatures also vary statistically from those of mP and mT at all stations except Sault Ste. Marie. However, mT and mP show no significant thermal differentiation at any station.

Precipitation Characteristics of Air Masses

Precipitation characteristics of the various air masses are more difficult to analyze than those of temperature because of their non-continuous nature and lack of normality. Also, the presence of a warm or an occluded front may cause precipitation to originate in an air mass not in contact with the surface. In spite of these problems an attempt was made to summarize precipitation data relating to air mass type.

Table 8 indicates the number of days which have a trace, or more, of precipitation (or all days on which measurable precipitation occurs), and the frequency of days which register at least .05 inches of precipitation. Table 9 gives the total amount of precipitation for each air mass, and also the average precipitation per day for days on which precipitation is actually recorded.

In January no well-defined differences in precipitation frequencies are observed among the various air masses. mT has the highest percentage of days with at least a trace of precipitation, but this air mass, as noted earlier, is at the surface only rarely at this time of year. cA, cP, and NcP are all approximately equal

TABLE 8

PRECIPITATION FREQUENCIES FOR AIR MASS TYPES

January
(N=155)

		cA		cP		NcP		mP		mT		Total	
		T	.05	T	.05	T	.05	T	.05	T	.05	T	.05
Det.	F	44	8	35	13	19	7	3	0	6	3	116	32
	%	75.8	13.8	72.0	28.0	73.1	26.9	100	0	100	50	74.8	20.6
G.R.	F	48	23	38	18	18	8	3	0	2	2	127	52
	%	78.7	37.7	74.5	38.0	69.2	30.8	100	0	100	100	81.9	33.5
T.C.	F	53	25	36	18	12	7	2	1	1	1	122	53
	%	82.8	39.1	64.3	32.1	63.2	36.8	67	33	100	100	78.7	34.2
Esc.	F	50	14	31	9	9	2	3	1	1	0	104	29
	%	66.7	18.6	64.6	18.8	56.3	12.5	100	33	100	0	67.0	18.7
S.S.M.	F	71	28	33	11	13	5	2	0	1	0	130	47
	%	89.9	35.4	70.2	23.4	92.9	35.7	100	0	100	0	83.9	30.3

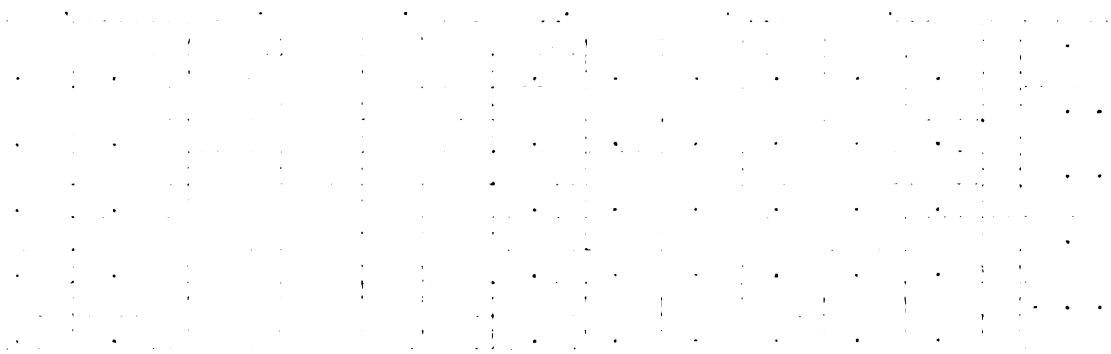
April
(N=150)

		cP		NcP		mP		mT		Total	
		T	.05	T	.05	T	.05	T	.05	T	.05
Det.	F	56	21	18	11	4	2	18	11	98	45
	%	60.2	22.6	78.2	47.8	80.0	40.0	75.0	45.8	65.3	30.0
G.R.	F	57	18	17	11	4	1	15	12	94	42
	%	58.8	18.6	77.2	50.0	80.0	20.0	71.4	57.1	62.7	28.0
T.C.	F	53	22	16	6	5	3	7	5	84	36
	%	49.1	20.3	69.6	26.1	100	60.0	77.8	55.6	56.0	24.0
Esc.	F	59	31	10	8	5	3	1	1	77	43
	%	48.0	25.2	66.7	53.3	71.4	42.9	100	100	51.3	28.6
S.S.M.	F	63	29	9	6	6	3	1	1	81	39
	%	50.0	23.0	75.0	50.0	85.7	42.9	100	100	54.0	26.0

Notes:

F, T, and .05 represent day-frequencies, days with at least a trace of precipitation, and days with at least .05 inches of precipitation, respectively.

Frequency values in the total column do not always agree with the summation of frequencies for individual air masses, because mixed air masses are not listed individually but are included in the totals.



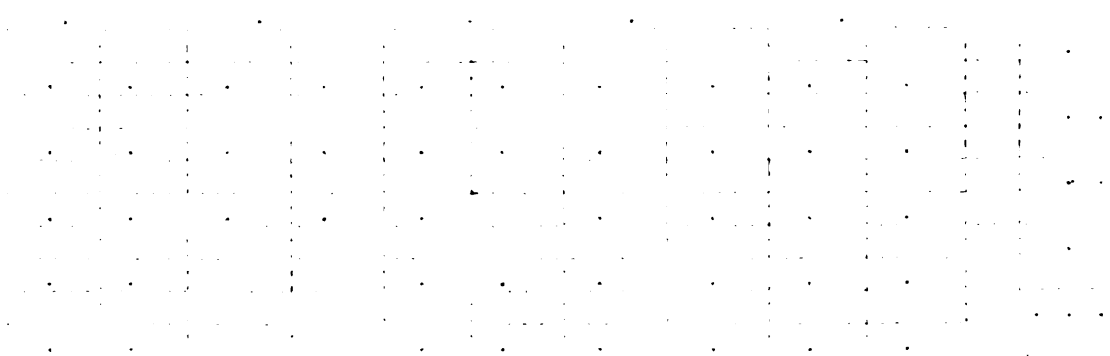


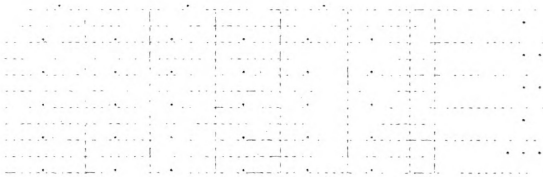
TABLE 8 -- Continued

July
(N=155)

		cP		mT		Total	
		T	.05	T	.05	T	.05
Det.	F	38	17	31	20	74	37
	%	36.9	16.5	67.3	43.5	47.7	24.8
G.R.	F	35	12	33	19	72	31
	%	33.7	11.5	76.7	44.2	46.5	21.1
T.C.	F	36	18	20	12	64	30
	%	30.5	15.3	66.7	40.0	41.3	20.2
Esc.	F	55	27	16	8	76	35
	%	45.1	22.1	64.0	32.0	49.0	23.8
S.S.M.	F	55	30	14	6	77	36
	%	44.0	24.0	70.0	30.0	49.7	24.8

October
(N=154)

		cP		NcP		mP		mT		Total	
		T	.05	T	.05	T	.05	T	.05	T	.05
Det.	F	29	4	11	7	9	6	26	18	76	36
	%	36.7	5.1	45.8	29.2	75.0	50.0	68.4	47.3	49.3	23.4
G.R.	F	38	9	10	5	12	8	20	9	82	31
	%	43.7	10.3	43.5	21.7	92.3	61.5	66.7	30.0	53.2	20.1
T.C.	F	51	28	10	6	11	5	17	14	89	54
	%	53.1	29.1	47.6	28.6	84.6	38.5	73.9	60.9	57.8	35.1
Esc.	F	49	14	9	7	11	7	9	8	79	37
	%	45.4	12.9	52.9	41.2	84.6	53.8	60.0	53.3	51.3	24.0
S.S.M.	F	67	24	10	6	11	4	12	10	81	39
	%	62.0	22.2	55.6	33.3	78.5	28.6	92.3	76.9	54.0	26.0



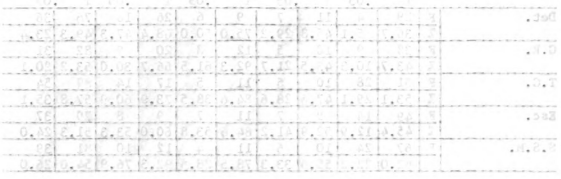


TABLE 9

TOTAL AND AVERAGE PRECIPITATION FOR AIR MASS TYPES
(INCHES)

January

	cA		cP		NcP		mP		mT		Total	
	T	A	T	A	T	A	T	A	T	A	T	A
Det.	0.92	.02	3.79	.11	1.94	.10	.03	.01	3.07	.51	9.75	.08
G.R.	2.95	.06	6.11	.16	1.97	.11	.01	.003	.13	.07	11.17	.09
T.C.	3.36	.06	3.35	.09	0.83	.07	.05	.03	.12	.12	7.71	.06
Esc.	1.99	.04	1.34	.04	0.10	.01	.10	.03	Tr.	Tr.	3.53	.03
S.S.M.	4.30	.06	2.38	.07	1.02	.08	.04	.02	.01	.01	7.75	.06

April

	cP		NcP		mP		mT		Total	
	T	A	T	A	T	A	T	A	T	A
Det.	6.77	.12	4.47	.25	.17	.04	4.47	.25	15.88	.16
G.R.	4.86	.09	6.12	.36	.23	.06	5.73	.38	16.94	.18
T.C.	5.18	.10	3.74	.23	1.54	.31	1.20	.17	11.66	.13
Esc.	9.31	.16	3.25	.33	.30	.06	.18	.18	13.04	.17
S.S.M.	6.73	.11	1.65	.18	.17	.03	.17	.17	8.72	.11

Note:

T represents total precipitation for five-year period, and A represents average precipitation per occurrence. Tr indicates a trace of precipitation.

TABLE 9 -- Continued

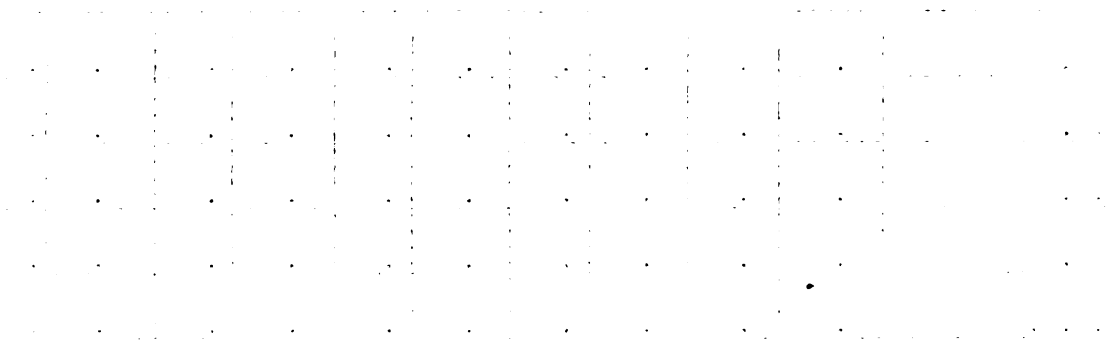
July

	cP		mT		Total	
	T	A	T	A	T	A
Detroit	5.32	.14	5.68	.18	11.00	.15
Grand Rapids	4.40	.13	8.10	.25	12.50	.17
Traverse City	7.44	.21	5.28	.26	12.72	.22
Escanaba	14.21	.26	5.09	.32	19.30	.27
Sault Ste. Marie	8.91	.16	1.35	.10	10.26	.13

October

	cP		NcP		mP		mT		Total	
	T	A	T	A	T	A	T	A	T	A
Det.	0.65	.02	1.51	.14	3.79	.42	4.81	.19	10.76	.14
G.R.	2.06	.05	1.03	.10	3.48	.29	6.26	.32	12.83	.16
T.C.	6.82	.13	1.00	.10	1.44	.13	4.24	.25	13.50	.15
Esc.	4.29	.09	2.50	.28	0.76	.07	2.63	.29	10.18	.13
S.S.M.	5.09	.08	2.16	.22	1.05	.10	5.28	.44	13.58	.17





in precipitation effectiveness. However, the inter-station differences for cA frequencies allow some interesting interpretations. The percentage of days with at least .05 inches of precipitation is only 13.8 at Detroit and 18.6 at Escanaba, but rises to 37.7 at Grand Rapids, 39.1 at Traverse City, and 35.4 at Sault Ste. Marie. Detroit and Escanaba have been previously identified as lee-side stations with respect to Lakes Superior and Michigan, while Grand Rapids, Traverse City, and Sault Ste. Marie have windward-side locations with consequent unstable stratification in the lower layers of the cA air masses. These differences are indicated by precipitation averages for the Arctic air mass: (1) .06 inches per day at Grand Rapids, Traverse City, and Sault Ste. Marie; (2) .04 inches per day at Escanaba; and (3) .02 inches per day at Detroit.

In April the relative frequency of days with precipitation is approximately the same for NcP, mP, and mT, and they have, in most cases, higher percentages than cP air masses. cP-days have much lower average precipitation than either NcP- or mT-days. The low precipitation yield on cP-days may already reflect the stabilizing effect of the Great Lakes which change their role as convective platforms into that of heat sinks in mid-spring.

In July mT air masses have more frequent precipitation than cP air masses, especially in terms of number of days with at least .05 inches. These variations are least pronounced in the Upper Peninsula where relative frequencies are almost as large for cP as for mT. However, average precipitation per occurrence is significantly higher with mT than with cP at every station except Sault Ste. Marie.

In October NcP, mP, and mT all have greater relative frequencies of days with precipitation than cP. In terms of average rainfall, mT air masses are consistently high throughout the state. NcP and mP also have some high averages, but vary more from station to station than does mT. NcP is unusual in that it has greater mean precipitation at the Upper Peninsula stations than at the southern stations. This may be explained by the relative warmth of the Great Lakes (specifically Lakes Michigan and Huron) over which NcP air masses must pass before reaching the northern peninsula, and the consequent vapor flux from water to air. cP air, as usual, has lower average precipitation per occurrence than the other air masses, except at Traverse City where both mP and NcP are lower. Again, this distribution may be explained by the location of Traverse City relative to warm Lake Michigan and the consequent labilization of cP air masses in its vicinity.

In summary, frequencies, totals, and averages indicate that the precipitation effectiveness of the various air masses is clearly different. mT is, for the entire year, the most consistent producer of precipitation, although mP and NcP are nearly as effective but have greater regional and temporal variability. cP and cA air masses generally yield much less precipitation, but at windward-side stations in the fall and winter, when the Lakes are warm relative to the air, cP and cA become more effective.

Frequency of Frontal Activity

Changes in air mass type within the study area normally take place after the passage of a front. Table 10 shows frontal passages through Michigan for the same period (1958-1962) and the same months as in the preceding analyses.

TABLE 10

FREQUENCY OF FRONTAL PASSAGES IN MICHIGAN
(MEAN NUMBER PER MONTH)

January

	Cold	Warm	Occluded	Total
Det.	4.0	2.4	2.0	8.4
G.R.	4.0	1.8	2.0	7.8
T.C.	3.8	1.6	1.4	6.8
Esc.	3.8	1.2	1.2	6.2
S.S.M.	3.6	1.2	1.1	5.9

April

	Cold	Warm	Occluded	Total
Det.	3.0	2.8	1.8	7.6
G.R.	3.0	2.2	1.6	6.8
T.C.	2.4	1.6	1.6	5.6
Esc.	2.4	0.6	1.4	4.4
S.S.M.	2.2	0.2	1.6	4.0

July

	Cold	Warm	Occluded	Total
Det.	4.6	1.2	.0	5.8
G.R.	4.6	1.2	.0	5.8
T.C.	4.0	1.2	.2	5.2
Esc.	4.0	1.2	.2	5.4
S.S.M.	3.8	1.0	.2	5.2

October

	Cold	Warm	Occluded	Total
Det.	4.2	3.8	0.8	8.8
G.R.	4.0	3.6	0.8	8.4
T.C.	4.2	3.8	0.8	8.8
Esc.	4.2	3.6	1.0	8.8
S.S.M.	4.2	3.2	1.0	8.4

In Michigan, cold fronts are more frequent than warm fronts and occluded fronts are least common. This conforms to the high frequency of occurrence for cA and cP air masses which typically arrive in the lee of cold fronts. Cold fronts pass through the study area most frequently in July, least frequently in April. Warm fronts reach their maximum prevalence in October, and occur least often in July.

In terms of averages, regional differences are not great, but are sufficiently large to be significant. This is particularly evident for warm fronts in January and April. In January, warm fronts occur twice as often at Detroit as at Sault Ste. Marie. In April the differences are even greater with Detroit averaging nearly 3 passages while Sault Ste. Marie records only one warm front every five years. Occluded fronts do not vary regionally to any extent, except in January when they occur twice as often at Detroit as at Sault Ste. Marie.

With respect to total frontal passages, the southern stations (Detroit and Grand Rapids) have more occurrences than the northern stations (Traverse City, Escanaba, and Sault Ste. Marie), with the exception of October when all stations have approximately the same totals. The greatest regional contrast in total frontal activity is in April when Detroit has 7.6 frontal passages while Sault Ste. Marie experiences only 4.0.

Relationships between Synoptic Weather Types and Climatic Elements

The purpose of this section is to determine frequencies of

occurrence for each of the synoptic weather types outlined in Chapter I, and to relate the weather types to observed values of temperature and precipitation. The method of analysis is similar to that used for air masses; i.e., the four mid-season months, the five-year sample period (1958-1962), and the Daily Weather Map form the statistical base. The synoptic maps for the observation period were examined and one of the 11 weather types assigned to each day. Temperature and precipitation data for each day were then grouped with the prevailing weather type.

Synoptic Weather-Type Frequencies

Relative frequencies of occurrence for the 11 synoptic weather types are given in Table 11. Due to the small area considered in comparison to the magnitude of the weather systems, frequencies for a given weather type do not differ markedly from station to station. However, great differences do exist in the frequencies of the various weather types at a given station.

The pattern of frequencies changes from month to month, as may be illustrated by the case of Detroit. In January nHs (northern High to the south of the Lakes) is the most common weather type, occurring on 42 of 153 days. In April nHs dominates on only 26 of 150 days, and ranks third to mLl (Montana Low through the Lakes) and sLl (southern Low through the Lakes). During July, 7 of 155 days, and in October, 8 of 154 days are characterized by nHs which is much more frequent during winter and spring. The neH (New England High) type is not found at any station during January, April, or July, but is fairly common during October (13 of 154 days). The gLe (Gulf Low to the east of the Lakes) occurs typically in winter.

TABLE 11

DAY-FREQUENCIES OF SYNOPTIC WEATHER TYPES AT FIVE SELECTED STATIONS
(1958-1962)

January

	aLn*	aL1	mL1	sL1	gLe	nHn	nHs	wH1	n&eH	nH1	neH	Total
Detroit	12	16	27	18	10	18	42	4	4	2	0	153
Grand Rapids	12	16	26	18	10	19	42	4	4	2	0	153
Traverse City	12	16	25	18	10	20	42	4	4	2	0	153
Escanaba	11	16	25	18	10	20	43	4	4	2	0	153
Sault Ste. Marie	12	16	25	18	10	20	42	4	4	2	0	153

April

	aLn	aL1	mL1	sL1	gLe	nHn	nHs	wH1	n&eH	nH1	neH	Total
Detroit	10	1	29	34	2	9	26	14	14	11	0	150
Grand Rapids	10	1	29	34	2	9	26	14	14	11	0	150
Traverse City	11	1	28	33	2	10	26	14	14	11	0	150
Escanaba	11	1	28	33	2	10	26	14	14	11	0	150
Sault Ste. Marie	11	1	28	33	2	10	26	14	14	11	0	150

* See Pp. 26-28 for explanation of code.

TABLE 11 -- Continued

July

	aLn	aLl	mLl	sLl	gLe	nHn	nHs	wHl	n&eH	nHl	neH	Total
Detroit	24	2	32	1	0	5	7	18	30	36	0	155
Grand Rapids	23	2	32	2	0	5	7	18	30	36	0	155
Traverse City	22	2	32	2	0	5	7	18	29	36	0	155
Escanaba	23	2	32	2	0	5	7	18	30	36	0	155
Sault Ste. Marie	23	2	32	2	0	5	7	18	30	36	0	155

October

	aLn	aLl	mLl	sLl	gLe	nHn	nHs	wHl	n&eH	nHl	neH	Total
Detroit	17	3	32	12	0	12	8	45	9	3	13	154
Grand Rapids	17	3	32	12	0	12	8	45	9	3	13	154
Traverse City	17	3	32	12	0	12	8	45	9	3	13	154
Escanaba	17	3	33	12	0	12	7	45	9	3	13	154
Sault Ste. Marie	17	3	33	12	0	12	7	45	9	3	13	154

The dominating types for each month, listed in descending order of day-frequencies per month, are:

1. January: nHs (8.4); mL1 (5.4); nHn (3.6); sL1 (3.6), and aL1 (3.2).
2. April: sL1 (6.8); mL1 (5.8), and nHs (5.2).
3. July: nH1 (7.2); mL1 (6.4); n&eH (5.0), and aLn (4.8).
4. October: wH1 (9.0); mL1 (6.4), and aLn (3.4).

mL1 is the only type that occurs frequently in all four months. It is the most consistent weather type in the synoptic calendar with an average frequency of about 6 days in each of the investigated months.

The January pattern of weather type frequencies reveals a slight imbalance between meridional circulation, as represented by nHs, sL1, aL1, and gLe, and zonal circulation, as represented by mL1, nHn, and aLn. In terms of number of days, the systems resulting from meridional circulation dominated during the selected period. In April the meridional systems (specifically sL1, nHs, and nH1) continue to be more frequent than the zonal types. By July, however, a fundamental change occurs, and zonal systems (principally mL1, aLn, and wH1) are clearly dominating. July is characterized by a conspicuous scarcity of meridional-flow types. The only meridional system occurring with any appreciable frequency in mid-summer is nH1. In October zonal control governs circulation to the extent that meridional influence is almost excluded. For every meridional type, 4 zonal types are observed, with the wH1, mL1, and aLn systems predominant during the period of investigation. There are, however, more meridional cyclones than during July, but the meridional High (nH1), prominent in

mid-summer, occurs only 3 times in the five-year interval.

A comparison of the data used in this analysis with the data attained for a different observation period (1953-1957)[1] indicates a high degree of uniformity between the two periods, and probably in any two five-year periods. A test for significant differences between the periods with the Chi Square method yielded the following results:[2] (1) in January and October the two sets of data are significantly different, with the dissimilarity greater in October than in January; and (2) in April and July the sets of data are statistically equal. In January the variation between periods is explained almost wholly in terms of two synoptic systems: nHs and nHn (northern High to the north of the Lakes). During the 1953-1957 period nHs and nHn occurred with nearly equal frequency, whereas in the 1958-1962 period nHs dominated more than twice as many days as nHn. Genetically, a predominance of greater meridional, over zonal, circulation is indicated during the latter period. In October the inequality between periods is due to the varying frequencies of the cyclonic weather types, specifically mLl, aLn, and gLe. Each of the anticyclonic types has approximately the same frequency in both periods. The variations in occurrence of the different Lows may again be attributed to alterations in the upper-air circulation which prevailed in the two periods.

A comparison of all cyclonic and anticyclonic weather types for the two periods shows very small differences. In January the total number of Lows was 84 for the 1953-1957 span and 83 for the

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[1]Hodgins, Genetic Climatology of the Great Lakes Region, op. cit.

[2]For tables of Chi Square computations see Appendix B.

1958-1962 period. January Highs for the former period equalled 71, and for the latter they totaled 70. In July the 1953-1957 and 1958-1962 figures for Lows were 57 and 59, and for Highs 95 and 96, respectively. October also conformed to the pattern with 66 Lows for the latter, and 88 Highs compared to 90. The frequencies for April deviated slightly from this remarkable uniformity, with the 85 Lows of 1953-1957 exceeding by 9 and 76 Lows of 1958-1962, and the 64 Highs of the former period being 10 less than the 74 Highs of the latter interval. However, the April variations do not represent statistically significant differences, as determined by the Chi Square method. An interpretation of the cause of these temporal similarities in numbers of Highs and Lows must be based primarily on the apparent constancy of circumpolar westerly circulation which controls cyclogenesis and anticyclogenesis within the study area and adjacent regions.

Temperature Characteristics of Synoptic Weather Types

Table 12 gives the mean temperature of each synoptic weather type for five first-order weather stations in January, April, July, and October. Variances and standard deviations included in the table were computed to permit testing for differences of means.[1] The results of the latter indicate highly significant differences of mean temperature between nHs and all of the other types during January (with the single exception of two occurrences of nHl at Sault Ste. Marie). This clearly demonstrates that nHs is a distinct physical type in terms of its thermal characteristics. nHs is established far to the

[1]See Appendix B for table summarizing January difference of means tests (t-statistic) for Detroit.

TABLE 12

TEMPERATURE MEANS (°F.), VARIANCES, AND STANDARD DEVIATIONS
AS RELATED TO SYNOPTIC WEATHER TYPES

January

	Detroit			Grand Rapids			Traverse City			Escanaba			Sault Ste. Marie		
	X	S^2	S	X	S^2	S	X	S^2	S	X	S^2	S	X	S^2	S
aLn	30.7	10.6	3.3	26.9	18.5	4.3	27.3	14.4	3.8	24.6	45.9	6.8	22.3	7.4	2.7
aL1	29.1	57.8	7.6	26.4	53.9	7.4	26.3	57.7	7.6	21.1	60.5	7.8	15.3	96.4	9.8
mL1	29.5	23.3	4.8	24.8	32.9	5.7	24.4	46.6	6.8	20.2	82.8	9.1	19.2	81.5	9.0
sL1	30.0	40.7	6.4	26.2	45.2	6.7	24.9	46.4	6.7	21.7	65.2	8.1	20.2	55.3	7.4
gLe	30.8	6.2	2.5	27.2	3.4	1.8	23.5	14.1	3.8	22.8	20.2	4.5	18.9	50.5	7.1
nHn	23.8	30.4	5.5	21.3	47.2	6.9	18.7	51.4	7.2	16.9	37.8	6.2	9.4	91.5	9.6
nHs	14.3	28.2	5.3	11.7	41.9	6.5	11.0	48.4	6.9	6.4	59.6	7.7	4.9	63.1	7.9
wH1	28.3	0.7	0.8	26.0	16.5	4.1	19.3	4.7	2.2	16.5	19.3	4.4	18.5	10.3	3.2
n&eH	32.0	6.5	2.6	28.0	12.5	3.5	27.0	6.5	2.6	25.8	33.7	5.8	15.0	106.0	10.3
nH1	20.0	1.0	1.0	17.0	1.0	1.0	14.5	0.3	0.5	21.0	1.0	1.0	6.5	0.3	0.5
Mean Low	29.8	30.2	5.5	26.0	34.0	5.8	25.2	39.9	6.3	21.7	61.5	7.8	19.1	63.8	8.0
Mean High	18.7	58.9	7.7	16.2	68.0	8.2	14.6	63.4	8.0	11.3	86.2	9.3	7.5	83.2	9.1
Diff.	11.1			9.8			10.6			10.4			11.6		

Note:
X, S^2, and S represent mean temperature, variance and standard deviation, respectively.

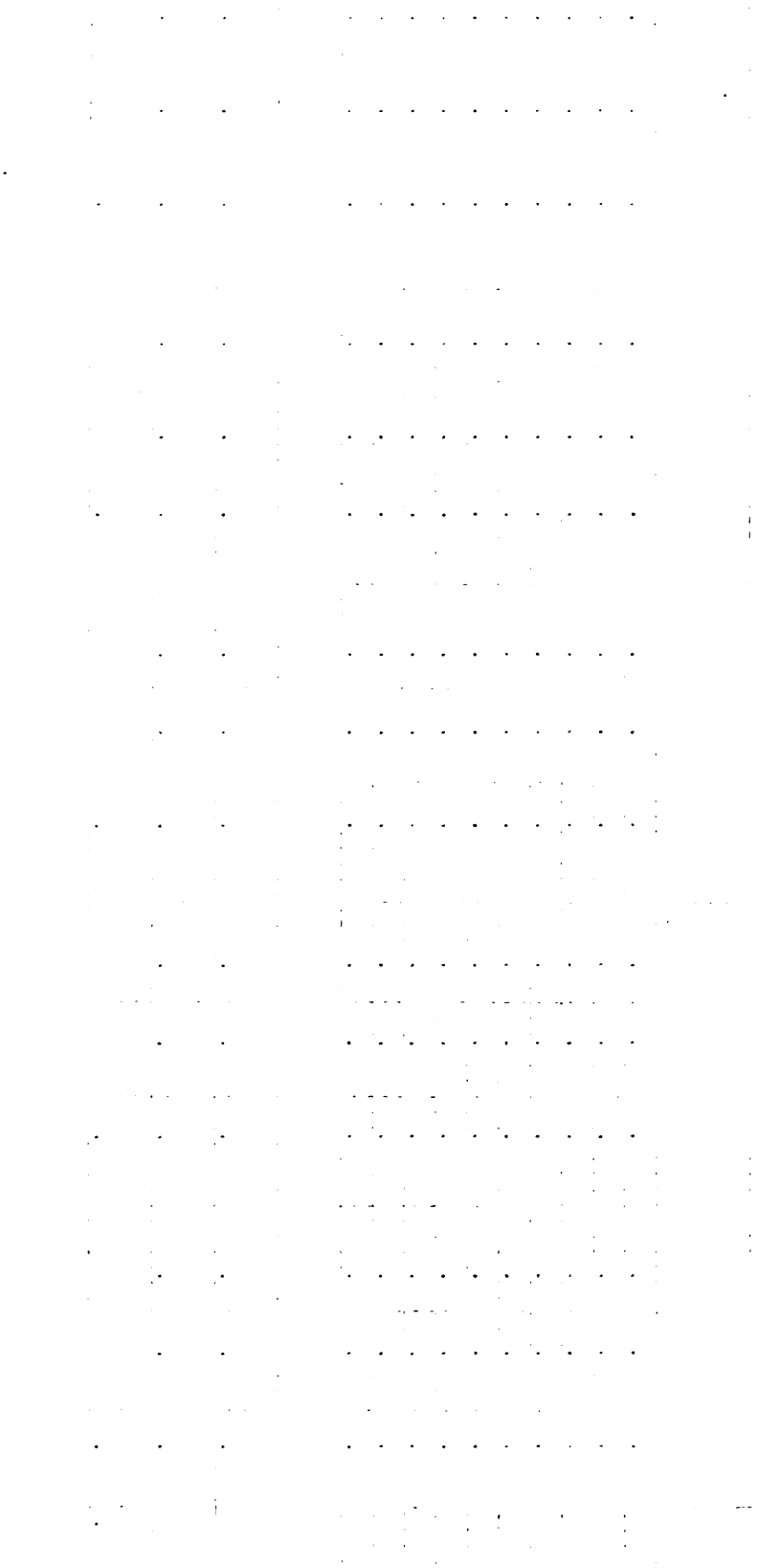


TABLE 12 -- Continued

April

	Detroit			Grand Rapids			Traverse City			Escanaba			Sault Ste. Marie		
	X	S^2	S	X	S^2	S	X	S^2	S	X	S^2	S	X	S^2	S
aLn	54.4	26.0	5.1	51.0	51.6	7.2	49.0	64.0	8.0	45.3	31.7	5.6	43.2	52.9	7.3
aLl	53.0	0.0	0.0	49.0	0.0	0.0	45.0	0.0	0.0	42.0	0.0	0.0	36.0	0.0	0.0
mLl	52.8	77.2	8.8	49.1	81.1	9.0	45.3	80.7	9.0	41.8	43.6	6.6	39.7	48.5	7.0
sLl	47.5	77.5	8.8	44.0	60.1	7.8	40.9	50.5	7.1	38.2	23.7	4.9	37.3	33.0	5.8
gLe	40.0	4.0	2.0	43.0	4.0	2.0	43.0	1.0	1.0	42.5	6.3	2.5	43.0	1.0	1.0
nHn	42.1	69.5	8.3	43.0	69.8	8.4	38.6	75.6	8.7	38.0	48.6	7.0	37.0	35.4	5.9
nHs	41.1	36.2	6.0	39.5	36.7	6.1	36.7	55.2	7.4	35.5	43.7	6.6	33.8	34.0	5.8
wHl	48.1	29.1	5.4	46.1	33.7	5.8	43.0	47.9	6.9	39.2	29.1	5.4	39.0	37.6	6.1
n&eH	61.6	126.9	11.3	58.1	125.2	11.2	53.2	94.5	9.7	45.5	31.7	5.6	45.0	40.7	6.4
nHl	43.0	35.3	5.9	43.1	56.9	7.5	40.9	66.9	8.2	38.8	23.5	4.8	35.8	22.2	4.7
Mean Low	50.3	78.6	8.9	46.9	72.8	8.5	43.8	70.3	8.4	40.7	23.6	4.8	39.2	45.3	6.7
Mean High	46.7	113.8	10.7	45.2	38.2	6.2	41.8	100.9	10.1	38.9	48.4	7.0	37.6	50.6	7.1
Diff.	3.6			1.7			2.0			1.8			1.6		

TABLE 12 -- Continued

July

	Detroit			Grand Rapids			Traverse City			Escanaba			Sault Ste. Marie		
	X	S^2	S	X	S^2	S	X	S^2	S	X	S^2	S	X	S^2	S
aLn	74.6	10.6	3.3	71.7	11.4	3.4	69.4	17.1	4.1	68.9	14.0	3.7	66.3	19.0	4.4
aL1	77.0	4.0	2.0	72.5	20.3	4.5	71.0	36.0	6.0	67.5	6.3	2.5	65.5	30.3	5.5
mL1	74.3	17.0	4.1	71.4	24.4	4.9	67.5	19.6	4.4	65.8	24.4	4.9	62.3	32.8	5.7
sL1	72.0	0.0	0.0	69.5	0.3	0.5	67.5	0.3	0.5	61.5	6.3	2.5	63.0	9.0	3.0
nHn	70.2	6.2	2.5	69.6	12.6	3.6	65.8	3.8	1.9	64.6	7.0	2.7	64.6	1.0	1.0
nHs	68.6	9.6	3.1	64.6	9.0	3.0	63.4	3.8	1.9	61.9	11.2	3.4	60.0	2.6	1.6
wH1	71.8	9.2	3.0	69.6	16.1	4.3	68.1	21.0	4.6	65.3	20.7	4.6	64.1	28.2	5.3
n&eH	74.5	18.2	4.3	72.8	13.2	3.6	69.3	26.6	5.2	66.5	20.6	4.5	64.4	33.6	5.8
nH1	69.1	16.0	4.0	68.1	17.3	4.2	64.9	34.4	5.9	64.2	28.4	5.3	61.4	32.4	5.7
Mean Low	74.5	12.0	3.5	71.4	19.0	4.4	68.3	20.2	4.5	66.9	20.1	4.5	64.0	29.6	5.4
Mean High	71.3	20.3	4.5	69.7	14.9	3.9	66.8	30.5	5.5	65.0	22.1	4.7	62.9	30.2	5.5
Diff.	3.2			1.7			1.5			1.9			1.1		

TABLE 12 -- Continued

October

	Detroit			Grand Rapids			Traverse City			Escanaba			Sault Ste. Marie		
	X	S^2	S	X	S^2	S	X	S^2	S	X	S^2	S	X	S^2	S
aLn	58.2	62.5	7.9	55.9	32.0	5.7	52.4	49.6	7.0	51.6	27.4	5.2	48.3	25.8	5.1
aL1	49.7	7.9	2.8	49.0	0.7	0.8	43.7	16.6	4.1	42.7	10.6	3.3	40.7	33.3	5.8
mL1	58.0	63.4	8.0	54.7	71.3	8.4	51.5	66.1	8.1	48.8	44.9	6.7	48.5	48.1	6.9
sL1	61.0	35.5	6.0	56.8	37.2	6.1	53.6	48.4	7.0	53.0	43.5	6.6	51.0	47.5	6.9
nHn	52.9	43.7	6.6	51.5	59.8	7.7	48.0	59.8	7.7	47.0	27.7	5.3	44.8	35.5	6.0
nHs	39.9	11.0	3.3	38.9	23.0	4.8	37.3	37.3	6.1	34.9	11.2	3.3	34.6	5.8	2.4
wH1	49.3	33.2	5.8	47.4	30.2	5.5	45.1	39.9	6.3	45.7	41.4	6.4	42.3	34.7	5.9
neH	61.7	9.7	3.1	60.6	19.8	4.5	58.5	27.0	5.2	56.0	9.7	3.1	55.9	25.0	5.0
n&eH	61.7	28.3	5.3	58.3	44.4	6.6	53.0	54.7	7.4	50.0	7.8	2.8	48.0	11.8	3.4
nH1	41.3	27.6	5.3	39.7	34.6	5.9	40.3	25.2	5.0	38.0	24.0	4.9	35.3	25.1	5.0
Mean Low	58.2	60.6	7.8	55.1	53.9	7.3	51.7	60.5	7.8	50.0	44.2	6.7	48.5	41.5	6.4
Mean High	51.7	72.0	8.5	49.9	42.7	6.5	47.4	73.5	8.6	46.7	56.1	7.5	44.4	55.9	7.5
Diff.	6.5			5.2			4.3			3.3			4.1		

north of the study area over northern Canada. Due to its subsequent trajectory to the west and south of the Great Lakes, it delivers air to Michigan from the northern (or northeastern) quadrant of the anticyclone, which is the coldest section of the system.

It is interesting to note that nHn, which originates in approximately the same area as nHs, is about 10 F.° warmer than the latter (except at Sault Ste. Marie), but is, nevertheless, the second coldest type in the winter. nHn passes to the north of the study area, and, consequently, air from its southern, or warmer, side flows into Michigan.

The cyclonic systems have similar temperatures during January, although aLn (Alberta Low to the north of the Lakes) is consistently, but not always significantly, warmer than most of the other types. Temperatures recorded during n&eH (northern and eastern Highs separated by a Stationary Front) dominance equal those of the cyclonic rather than those of the anticyclonic types. n&eH consists of a trough of low pressure situated between a northern (continental) High and an eastern (maritime) High. For this reason it is significantly warmer than the other Highs in the southern part of the state (maritime as opposed to continental control). However, in the northern section, poleward of the mean position of the stationary front, n&eH and the other Highs are truly anticyclonic and exhibit continental qualities; therefore, temperature differences are less.

In April the pattern of thermal contrasts changes considerably. nHs continues to be generally colder than the other types, but does not differ statistically from nHn and nHl at most stations. Large

variations exist between nHs and aLn, mL1, and n&eH. Although nHn, as in January, is still slightly warmer than nHs, there is a lessening of the temperature differential between the poleward and equatorward sides of the northern Highs. nHn does not differ from nHs and nH1 at this time, but is significantly colder than all of the cyclonic types except aL1.

n&eH has the largest variances (S^2) of any weather type during April, and has considerably higher temperatures than all other systems with the exception of aLn at Traverse City, Escanaba, and Sault Ste. Marie. The extremely large variances of n&eH at the three southernmost stations may be explained by the varying positions of the stationary front separating the northern and eastern Highs, with a consequent alternating dominance of continental (polar) and maritime (tropical) influences. The stationary front is nearly always equatorward of the Upper Peninsula stations, and, therefore, the northern stations have lower temperatures and smaller variances than those in the south.

In April, unlike January, the sL1 system is substantially colder than aLn and mL1, except at Sault Ste. Marie where it is statistically equal to mL1. sL1 does not differ significantly from nHn, wH1, and nH1. It mean temperatures at this time of the year more closely resemble those of the Highs than the Lows.

In July thermal inequalities due to different weather types are of smaller degree than in the other months. The temperature range between the means of the coolest and warmest systems is only 6 F.^{o} at Detroit, and of similar magnitude at the other stations. However, variances are much lower for most weather types than they are in April and October (the thermal transition months), and, therefore

significant differences do exist. nHs is still the coldest type, but differs only slightly from nHn and nHl. nHn is nearly as often statistically equal to other types as it is different. n&eH, again, is more similar to cyclonic than anticyclonic types. Cyclonic weather types all exhibit very little thermal contrasts during summer.

In October the behavior of temperature, as a consequence of different synoptic types, is comparable to that of April. nHs weather again is much colder than all other types with the exception of nHl. The frequency of nHs in October is much less than in April or January; nevertheless, its temperatures are significantly lower than those of the other types. nHn is slightly colder than the other weather systems, but is statistically equal to mLl, sLl, and n&eH at most stations. The neH (New England High) type appears for the only time during the 1958-1962 period in this month. Its mean temperatures are similar to those of n&eH in the southern part of the state, but are distinctly higher at the northern stations. Unlike the somewhat similar n&eH type, there is no stationary front separating diverse air masses in the neH type, and consequently little thermal contrast is found between the northern and southern sections of the system. neH is associated with warm, maritime air masses, and is responsible for many of the days of fine weather ("Indian Summer") occurring in the study area at this time of year. Very few significant thermal inequalities between Lows are observed in October. Only the rarely occurring aLl system stands out as a distinctly cold type.

In summary it may be emphasized that nHs is associated with the lowest temperatures observed in the study area. Its thermal effect differs strongly from all other systems, with the exceptions of nHn

and nHl during several seasons. n&eH, which is unique in that it is the only type with a stationary front bisecting the state, is normally the warmest system in the southern part of Michigan, but to the north of the front its temperatures are approximately the same as during the regime of cyclonic types. Among the various Lows temperature differences are too small, in most cases, to be of statistical significance. However, aLn is normally slightly warmer than the other cyclonic types, except in October when sLl tends to have the highest temperatures.

Thermal contrasts between the warmest types and coldest types for each month (omitting types with less than 5 occurrences) are as follows:[1]

1. January: n&eH (warmest) - nHs (coldest) equals 17.7 F.°
2. April: n&eH - nHs equals 20.5 F.°
3. July: aLn - nHs equals 6.0 F.°
4. October: n&eH and neH - nHs equals 21.8 F.°

It is notable that the thermal transition months, April and October, have the greatest temperature inequalities. This is indicative of the greater contrast between unlike air masses during spring and fall. The relatively high temperature differential in January is explicable almost entirely in terms of the extremely low temperatures occurring with nHs and its associated air mass, cA.

Precipitation Characteristics of Synoptic Weather Types

Table 13 indicates total amounts of precipitation and the average precipitation per day associated with individual synoptic weather

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[1]For Detroit. Other stations would differ only slightly.

TABLE 13

TOTAL AND AVERAGE PRECIPITATION
FOR SYNOPTIC WEATHER TYPES

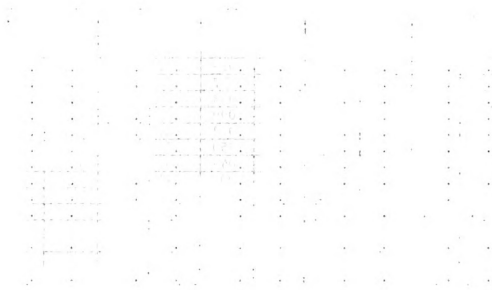
January

	Detroit		Grand Rapids		Traverse City		Escanaba		Sault Ste. Marie	
	T	A	T	A	T	A	T	A	T	A
aLn	.64	.053	.60	.050	.22	.018	.17	.015	.20	.017
aL1	.18	.011	.22	.014	.59	.037	.14	.009	.84	.053
mL1	2.62	.097	2.81	.108	1.57	.063	1.29	.052	2.60	.104
sL1	4.19	.233	4.51	.251	1.79	.099	.96	.053	1.37	.076
gLe	.55	.055	.39	.039	.22	.022	.28	.028	.24	.024
nHn	.21	.011	.48	.025	1.00	.050	.50	.025	.50	.025
nHs	.84	.020	2.10	.050	2.02	.048	.41	.010	1.75	.042
wH1	.04	.010	.01	.003	.03	.008	.12	.030	.11	.028
n&eH	.01	.003	Tr.	Tr.	.09	.023	.13	.033	.30	.008
nH1	Tr.	Tr.	.08	.040	.18	.090	.17	.085	.05	.025
Mean Low	8.18	.099	8.53	.104	4.39	.054	2.84	.036	5.25	.065
Mean High	1.10	.016	2.67	.037	3.32	.046	1.33	.018	2.44	.034

April

	Detroit		Grand Rapids		Traverse City		Escanaba		Sault Ste. Marie	
	T	A	T	A	T	A	T	A	T	A
aLn	1.43	.143	.32	.032	1.27	.115	.27	.025	.28	.025
aL1	.04	.040	Tr.	Tr.	.06	.060	.03	.030	.01	.010
mL1	2.90	.100	3.78	.130	1.48	.053	2.38	.085	2.74	.098
sL1	8.28	.243	8.62	.254	7.02	.213	6.92	.210	3.94	.119
gLe	.46	.230	.01	.005	0.00	.000	0.00	.000	0.00	.000
nHn	.15	.016	.16	.018	0.00	.000	.17	.017	.16	.016
nHs	.32	.012	.75	.029	.56	.022	.60	.023	.70	.027
wH1	.37	.026	.49	.035	.11	.008	.44	.031	.37	.026
n&eH	1.61	.115	2.59	.185	1.30	.093	2.36	.169	1.54	.110
nH1	.26	.023	.06	.005	.02	.002	0.00	.000	.08	.007
Mean Low	13.11	.173	12.73	.168	9.83	.131	9.60	.128	6.97	.093
Mean High	2.71	.037	4.05	.055	1.99	.027	3.57	.048	2.85	.038

Note:
Refer to Table 9 for explanation of T, A, and Tr.



	Detroit		Grand Rapids		Traverse City		Escanaba		Sault Ste. Marie	
	T	A	T	A	T	A	T	A	T	A
$\bar{x}_{Lg}$	1.43	.143	.38	.032	1.27	.115	.27	.029	.38	.025
s_{Lt}	.04	.040	Tr.	Tr.	.06	.050	.03	.030	.01	.010
$\bar{x}_{Lt}$	2.40	.100	2.38	1.20	2.07	.085	2.38	.085	2.24	.094
s_{Le}	6.58	.263	6.32	.258	5.05	.213	5.02	.210	3.96	.119
$\bar{x}_{Le}$	.04	.270	.01	.007	.00	.000	0.00	.000	0.00	.000
s_{Hn}	.15	.015	.16	.010	0.00	.000	.17	.017	.18	.018
s_{Ha}	.32	.013	.25	.010	.36	.023	.80	.029	.70	.027
s_{Ht}	.37	.025	.49	.022	.11	.008	.46	.021	.37	.025
s_{Hsh}	1.81	.115	1.61	.056	.30	.003	2.36	.146	1.56	.110
s_{Hl}	.28	.023	.04	.002	.02	.002	3.02	.000	.08	.002
Mean L_{Sh}	13.11	.113	13.13	.144	9.83	.131	9.66	.128	8.97	.093
Mean H_{Sh}	4.71	.027	4.03	.021	1.99	.027	3.37	.048	2.85	.038

Refer to Table 9 for explanation of T, A, and Tr.

TABLE 13 -- Continued

July

	Detroit		Grand Rapids		Traverse City		Escanaba		Sault Ste. Marie	
	T	A	T	A	T	A	T	A	T	A
aLn	2.47	.103	2.32	.101	1.67	.076	.98	.043	.85	.037
aL1	.04	.020	.22	.110	.02	.010	1.20	.600	.47	.235
mL1	4.72	.148	4.24	.133	6.13	.192	7.08	.221	5.51	.172
sL1	.20	.200	0.00	.000	.10	.050	.05	.025	.18	.090
nHn	.23	.040	1.42	.282	Tr.	Tr.	.03	.006	Tr.	Tr.
nHs	.16	.022	.31	.044	Tr.	Tr.	1.77	.252	Tr.	Tr.
wH1	.12	.007	.02	.001	1.17	.065	1.39	.007	.56	.311
n&eH	3.28	.109	4.11	.137	2.63	.091	3.91	.130	2.41	.080
nH1	.04	.001	.14	.004	1.10	.031	3.32	.092	.72	.020
Mean Low	7.43	.126	6.78	.115	7.92	.137	9.31	.158	7.01	.119
Mean High	3.83	.040	5.99	.062	4.90	.052	10.42	.109	3.69	.038

October

	Detroit		Grand Rapids		Traverse City		Escanaba		Sault Ste. Marie	
	T	A	T	A	T	A	T	A	T	A
aLn	.55	.034	.03	.002	.02	.001	.28	.016	1.43	.084
aL1	.36	.120	.35	.117	.26	.087	.24	.080	Tr.	Tr.
mL1	4.64	.145	6.99	.218	5.18	.162	5.96	.181	7.73	.234
sL1	4.15	.346	3.50	.292	3.39	.283	2.28	.190	1.31	.109
nHn	.02	.002	.23	.020	.52	.043	.23	.020	.34	.028
nHs	Tr.	Tr.	.31	.039	1.03	.129	.01	.001	.10	.014
wH1	.17	.004	.45	.010	1.34	.030	.54	.012	1.11	.025
neH	.84	.065	.52	.040	.57	.044	1.45	.112	1.40	.108
n&eH	.39	.043	.63	.070	.05	.066	0.00	.000	.04	.004
nH1	Tr.	Tr.	Tr.	Tr.	.22	.073	.27	.090	Tr.	Tr.
Mean Low	9.70	.152	10.87	.170	8.85	.138	8.76	.135	10.47	.161
Mean High	1.42	.016	2.14	.024	3.73	.041	2.50	.028	2.99	.034

types. It is obvious from the data that mLl is the most consistent originator of precipitation in the study area, because it is the only system which has high totals and averages in every season. While mLl is particularly important during July and October (months dominated by zonal circulation) it loses little of its precipitation efficiency in January and April.

The meridional sLl is not as consistent regionally or temporally as mLl, but is of great importance as a source of precipitation in the southern part of the state. In January it is the most productive system, in terms of both total and average precipitation, at Detroit and Grand Rapids. However, its effectiveness decreases rapidly northward, and in the Upper Peninsula mLl yields more precipitation during January than does the southern Low. The explanation lies in the fact that the center and associated fronts of the sLl system rarely reach the northern part of the state.

In April sLl is a much more important originator of precipitation than any other system, although, again, both total and average rainfall decrease northward. sLl reaches its peak frequency in spring and gradually abates until it becomes a very rare type in July. The lack of sLl occurrences in July can be considered a major cause for the marked decrease in precipitation falling in mid-summer over most of the study area in comparison to the late spring-early summer and late summer periods.

n&eH is the only other weather type that is a fairly consistent producer of precipitation. It is of only minor significance in January and October, but accounts for a considerable proportion of April and July rainfall. As previously stressed, n&eH has many of the qualities

of a low pressure system, and most of the precipitation associated with it is derived from the stationary front separating unlike air masses.

The high pressure systems, in spite of their generally stable structures, yield some fairly high precipitation totals. For example nHn at Grand Rapids in July, wHl at Traverse City and Escanaba in July, and wHl and nHs at Traverse City in October exhibit moderately high precipitation totals. The areal distribution of precipitation associated with nHs in January is unusual, and is a consequence of the behavior of cA air masses in the same month.[1] Three stations with windward-side locations with respect to Lakes Superior and Michigan (Grand Rapids, Traverse City, and Sault Ste. Marie) have distinctly higher total and average precipitation during the nHs regime than do two leeward-side stations (Detroit and Escanaba). neH, which occurs only during October in this investigation, is also irregular in that its associated precipitation at the two Upper Peninsula stations is nearly twice that recorded at the Lower Peninsula stations. The explanation lies in the lacustrine trajectory of the northward-flowing air over the relatively warm Lakes. The Lakes do not appreciably affect the air in the Lower Peninsula, but add to the humidity and instability of the air that reaches the northern stations under neH circulation.

Analysis of Combined Cyclonic and Anticyclonic Weather Types

Mean temperatures, variances, and standard deviations were also determined for the combined Highs and the combined Lows, as well as

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[1]See page 105.

total and average precipitation for the composite systems. The results are presented in the last three rows of Table 12 and the last two rows of Table 13.

In January the mean temperature during cyclonic control is higher than that prevailing with anticyclonic conditions. Sault Ste. Marie has the maximum thermal contrast between the combined Low and combined High (11.6 F.°) while Grand Rapids has the least difference (9.8 F.°). The large sample allows us to conclude that the average Low is associated with much higher temperatures than the average High. However, it is notable that one anticyclonic type, n&eH, occurring 4 times out of a possible 153, actually has higher temperatures than any cyclonic type, and does not differ significantly from any of them. As previously mentioned, n&eH may also be included with the cyclonic types in terms of temperature, precipitation, and, within much of the study area, even pressure characteristics. This indicates an inherent deficiency of statistical analysis--revealing a statistically significant difference when, in several cases, there is no such difference--and represents an excellent reason for classifying Lows and Highs into more specific synoptic weather types.

In April temperature differences between the composite Lows and Highs are somewhat diminished. Detroit has the greatest contrast between systems with 3.6 F.°, and Sault Ste. Marie has the least variation, 1.6 F.° Lows continue to be warmer than Highs. The uniqueness of n&eH is clearly indicated during this spring month, because if it is included with the Lows, thermal inequalities between the pressure systems are greatly accentuated. At the three Lower Peninsula stations the much higher mean temperatures of n&eH contrast sharply with all

of the other systems. In the Upper Peninsula, however, n&eH temperatures are comparable to those of aLn.

In July the absolute differences between the composite Lows and Highs are even less than in April. Variations range from 3.16 F.° at Detroit to only 1.09 F.° at Sault Ste. Marie. Nevertheless, because of very small standard deviations (S), these inequalities are statistically significant for every station except Sault Ste. Marie. If n&eH is incorporated with the combined Lows, the thermal contrasts are magnified considerably.

Mean temperatures during the cyclonic regime are significantly higher than those of the anticyclonic regime at all five stations in October. Differences between Lows and Highs vary from 6.5 F.° at Detroit to 3.3 F.° at Escanaba. In October, as in January, it is reasonable to conclude that the average Low is appreciably warmer than the average High. However, n&eH and neH should be included with the Lows as far as temperature characteristics are concerned. If they are, differences between Highs and Lows are substantially increased.

The precipitation data for the combined Lows and Highs are shown in the last two rows of Table 13. Lows clearly are the major precipitation producers in the study area during all seasons, in terms of both total amount and average per occurrence. The only case in which total precipitation from anticyclonic control is greater than that from cyclonic control is Escanaba in July, and even here, average cyclonic rainfall is more than average anticyclonic rainfall. In most instances average cyclonic precipitation is at least twice that produced by anticyclones. Furthermore, if n&eH and neH are

incorporated with the Lows, these differences are accentuated.

Association of Air Masses, Synoptic Weather Types, and Climatic Elements

Each of the synoptic weather types investigated in the previous section has one or more air masses associated with it, as well as an assemblage of climatic elements. If these phenomena are grouped, certain quantifiable interrelationships may be deduced. This is attempted in Table 14 by presenting frequency, temperature, and precipitation values that apply to air masses and synoptic weather types occurring on the same day. In this analysis only the Detroit data are used because of the lack of significant inter-regional differences.

Because the weather type is a dynamic element-complex and the air mass is relatively static, the former may be considered on a genetically higher level than the latter. Thus, the place of origin, the subsequent trajectory, and the sense of the circulation within the synoptic system determine the air masses which will be encountered within its sphere of influence.

Examination of Table 14 indicates that each of the Lows, n&eH, and neH are multiple air-mass types. The other Highs--nHn, nHs, wHl, and nHl--are basically single air-mass types, except in January when the northern Highs are composed of either cA or cP air. Therefore, it may be concluded that some of the temperature variation during the persistence of a particular synoptic type can be accounted for by a change of air masses. In April, e.g., n&eH was observed with 6 days

TABLE 14

SYNOPTIC WEATHER TYPES, ASSOCIATED AIR MASSES, AND VALUE OF SELECTED CLIMATIC ELEMENTS FOR DETROIT (1958-1962)

Key

	cA	
aLn	Frequency	Mean Temp. °F.
	S^2 Temp.	Tot. Prec."
	S Temp.	Avg. Prec."

	cA		cP		NcP		mP		mT	
aLn			8	29.7	4	32.8				
			9.0	.13	.57	.51				
			3.0	.016	.76	.128				
aL1	4	23.0	4	27.0	8	33.1				
	28.5	.11	19.5	.04	56.0	.03				
	5.3	.028	4.4	.01	7.5	.004				
mL1	1	23.0	10	28.7	9	31.2	1	34.0	1	32.0
	0	.17	28.0	1.52	13.4	.50	0	.01	0	.42
	0	.17	5.3	.152	3.7	.056	0	.010	0	.420
sL1	2	23.5	10	28.6	2	32.0			4	35.8
	6.3	.26	26.8	1.41	1.0	.87			51.2	1.64
	2.5	.130	5.2	.141	1.0	.440			7.2	.410
gLe			5	30.4	1	31.0	1	31.0	1	34.0
			6.2	.27	0	.02	0	Tr.	0	Tr.
			2.5	.054	0	.02	0	Tr.	0	Tr.
nHn	11	20.6	5	27.2	1	32.0	1	33.0		
	13.7	Tr.	15.4	.18	0	.02	0	.01		
	3.7	Tr.	3.9	.036	0	.02	0	.01		
nHs	37	13.7	5	19.0						
	25.7	.64	21.2	.20						
	5.1	.017	4.6	.04						
wH1			4	28.3						
			.69	.04						
			.83	.010						
n&eH			3	33.0	1	29.0				
			4.7	0	0	.01				
			2.2	0	0	.01				
nH1	1	19.0	1	21.0						
	0	Tr.	0	0						
	0	Tr.	0	0						

TABLE 14 -- Continued

April

	cP		NcP		mP		mT	
aLn	4	50.0	3	54.7	1	64.0	1	58.0
	10.0	.78	7.86	.36	0	0	0	.29
	3.2	.195	2.80	.12	0	0	0	.29
aL1	1	53.0						
	0	.04						
	0	.04						
mL1	10	45.5	7	55.0	2	49.5	8	60.5
	22.9	.50	50.3	1.38	0	.14	38.8	.75
	4.8	.050	7.1	.197	0	.070	6.2	.093
sL1	19	42.2	6	53.0	1	47.0	8	56.1
	28.9	2.68	9.36	2.36	0	Tr.	89.8	3.24
	5.4	.141	3.1	.393	0	Tr.	9.5	.405
gLe	1	38.0			1	42.0		
	0	.43			0	.03		
	0	.430			0	.030		
nHn	8	39.4					1	64.0
	10.4	.12					0	.03
	3.2	.015					0	.030
nHs	23	39.9	3	50.0				
	26.2	.15	26.0	.17				
	5.1	.007	5.1	.057				
wH1	12	46.5	1	54.0				
	12.1	.37	0	Tr.				
	3.5	.030	0	Tr.				
n&eH	6	54.3	2	52.5			6	71.8
	43.5	1.25	4.0	.20			19.0	.16
	6.6	.208	2.0	.100			4.6	.027
nH1	11	43.0						
	35.3	.26						
	5.9	.023						

TABLE 14 -- Continued

July

	cP		mT	
aLn	14	74.1	10	75.3
	9.4	1.46	3.2	1.01
	3.1	.104	1.8	.101
aL1			2	77.0
			0	.04
			0	.020
mL1	18	72.2	14	77.1
	12.0	3.09	8.0	1.63
	3.5	.172	2.8	.116
sL1	1	72.0		
	0	.20		
	0	.020		
nHn	5	70.2		
	6.2	.23		
	2.5	.046		
nHs	7	68.6		
	9.6	.16		
	3.1	.023		
wH1	18	71.8		
	9.2	.12		
	3.0	.007		
n&eH	9	71.2	19	76.3
	13.8	.15	13.4	3.00
	3.7	.017	3.7	.157
nH1	35	68.9	1	77.0
	15.1	.04	0	0
	3.9	.001	0	0

TABLE 14--Continued

October

	cP		NcP		mP		mT	
aLn	6	54.2	5	55.2			5	66.4
	50.1	.39	31.8	0			21.8	.16
	7.1	.065	5.6	0			4.7	.032
aL1			3	49.7				
			8.0	.36				
			2.8	.120				
mL1	6	49.3	5	55.4	2	60.5	18	61.7
	28.2	.53	37.4	.16	6.3	.17	49.3	3.40
	5.3	.088	6.1	.032	2.5	.085	7.0	.189
sL1			2	60.5	5	60.5	4	62.0
			72.3	.41	30.9	2.85	22.5	.89
			8.5	.21	5.6	.570	4.7	.222
nHn	12	52.9						
	43.7	.02						
	6.6	.002						
nHs	8	39.9						
	11.0	Tr.						
	3.3	Tr.						
wH1	42	48.6	1	58.0			2	60.5
	27.0	.10	0	.05			0	.02
	5.2	.002	0	.050			0	.010
neH			5	60.2	4	61.5	4	63.8
			18.2	.07	.75	.77	.19	0
			4.3	.014	.87	.193	.43	0
n&eH	3	60.3	2	62.5			4	62.3
	26.2	Tr.	0	.05			30.7	.34
	5.1	Tr.	0	.025			5.5	.085
nH1	3	41.3						
	27.6	Tr.						
	5.3	Tr.						

of cP air at a mean temperature of 54.3° F., 2 days of NcP at 52.5° F., and 6 days of mT air at 71.8° F. The large thermal contrasts between mT and the other air masses help to explain the extremely large variances (S^2) associated with the n&eH weather type.

cA and cP air masses are associated with both Highs and Lows approximately in proportion to their frequency of occurrence. However, NcP, mP, and mT tend to occur more with the Lows and only occasionally with the Highs. This may be explained by the fact that Lows are usually multi-air-mass systems, due to centripetal advection within the cyclone. Highs, on the other hand, with their divergent flow are likely to consist only of the air mass that is characteristic of their place of origin. Most Highs which traverse the study area originate over the land surfaces to the west or north, and, therefore, are associated with the continental air masses of those regions.

A further conclusion derived from Table 14 is that the mean temperature of an air mass is not the same for all weather types with which it occurs. In January the cA air mass is associated most often with nHs, and has very low mean temperatures (13.7° F.) with this type. For nHn, the only other synoptic type with which cA regularly occurs, the mean temperature is 7 F.° higher. However, the cA air masses occurring with nHn are much colder than those of any other air mass associated with this system. cP air masses also reach their lowest mean temperatures during the January persistence of nHs. The Polar air mass is nearly 10 F.° colder with nHs than it is with the Lows. NcP, mP, and mT, which are found mainly with the Lows, have approximately the same temperature regardless of the synoptic type.

In April, cP air masses are coldest when associated with nHs and nHn. However, differences are slight except those between the northern Highs and n&eH-aLn. The thermal behavior of NcP is similar with all weather types, and mP occurs too infrequently to permit valid inferences. The mean temperatures of mT air masses are more variable, ranging from 56.1° F. with sLl, 60.5° F. with mLl, to 71.8° F. with n&eH, the only three systems with which it is regularly found. If the prevailing weather situation under sLl regime is considered, one notices that the southern Low is a major precipitation type (see Table 13), is associated with cloud-covered skies, and must have much lower temperatures than the clearer days under n&eH dominance.

In July temperature differences are lessened. Nevertheless, cP air occurring with the northern Highs is still several degrees cooler than with the other synoptic types. There is only slight thermal variation in mT air masses as a result of their association with contrasting weather types. Undoubtedly, humidity and precipitation dissimilarities are more important as differentiating factors between air masses in summer than are temperature characteristics.

In October cP air controlled by nHs (and to a lesser extent, nHl) is much colder than it is with the other Highs or the Lows. For example, the mean of cP with nHs is 39.9° F. and with aLn it is 54.2° F., for a difference of 14.3 F.° NcP, which is not well represented in October, is slightly warmer under anticyclonic (neH, n&eH, and wHl) regime than it is with cyclonic domination. mP occurs more frequently at this time than in any other investigated month, and its temperatures are nearly identical with each synoptic type. The

thermal characteristics of mT are also similar with all weather types with the exception of aLn which produces temperature averages 3-5 F.° higher than the other types.

Table 14 also shows that the precipitation yield of an air mass is not the same for all synoptic weather types. It is not surprising that air masses associated with cyclonic circulation produce significantly higher average precipitation than those with anticyclonic control. In January cA occurs most frequently with northern Highs, but its few occurrences with Lows account for almost as much precipitation as with the Highs. The same is true for cP air masses which record their highest averages with mL1 (.152") and sL1 (.142"). However, cP yields little precipitation with the Alberta Lows. NcP has a very large percentage of its precipitation under the regimes of aLn and sL1. All of the hydrometeors occurring with mT dominance in January are produced by sL1 and mL1, both of which have very high averages.

In April much of the precipitation occurring with cP air masses may be attributed to sL1 and n&eH, although aLn also has a high average. The Highs contribute very little. With NcP regime mL1 and sL1 are the major producers. Most of the rainfall originating in mT air masses is from the Lows with sL1 accounting for the largest part (3.24") and having the highest average (.405").

In July cP yields considerable precipitation under aLn and mL1 regime, but very minor quantities with the infrequently occurring sL1 system. The Highs record only modest amounts, although none are dry. However, nH1, which with 35 occurrences is the most frequent

type in July, produced only .04" of rainfall in 5 years for an average of .001" per occurrence. This is the lowest average precipitation in any month for any type having a minimum frequency of 5 days. mT air masses have high precipitation totals and averages with 3 different synoptic types. Highest yields are with n&eH which has a total of 3.00" and an average of .157". mL1 and aLn also account for considerable rainfall with mT air. No precipitation is derived from mT by the Highs.

In October cP air masses give up most of their moisture with the aLn and mL1 systems, both of which produce only moderate totals. wH1, which dominates on 42 days of the 5-year period, yields only .10", or an average of .002" per occurrence. Like nH1 in July, the association of wH1 with cP air masses is responsible for very dry conditions. Most of the precipitation occurring with NcP is associated with aL1, mL1, and sL1. The Highs produce only moderate amounts with this type. mP air masses are found with only 3 synoptic types, and all of them yield some rainfall. However, sL1, with a frequency of only 5 days but a total of 2.85" and an average of .570" per occurrence, is easily the most significant producer of precipitation with mP. The association of mP air with sL1 circulation gives the highest average precipitation for this analysis. mT air masses produce precipitation while under the control of 5 different weather types. The highest totals and averages are accounted for by mL1, sL1, and n&eH.

CHAPTER IV

THE RELATIONSHIPS BETWEEN SELECTED CLIMATIC ELEMENTS AND TERRESTRIAL CONTROLS

The purpose of this chapter is to investigate the relationships between selected climatic elements and certain terrestrial factors that are hypothesized to be directly related to the behavior of these elements within the study area. The climatic elements used in this analysis are mean monthly temperature, mean monthly precipitation, and mean monthly snowfall. The terrestrial controls examined are (1) distance from a Great Lake according to prevailing wind direction, (2) latitude, and (3) elevation. The method of investigation is multiple regression and correlation analysis.

Three hypotheses are tested by means of regression and correlation analysis:

1. variations in the selected climatic elements from place to place in Michigan are directly related to distance from a Great Lake, measured in terms of prevailing wind direction;
2. variations in the selected climatic elements from place to place in Michigan are directly related to latitude; and
3. variations in the selected climatic elements from place to place in Michigan are directly related to elevation.

Regression equations were formulated for mean monthly temperature,

mean monthly precipitation, and mean monthly snowfall.[1] One equation was solved for each monthly temperature and precipitation variable, whereas for snowfall equations were developed only for the six months during which snow normally occurs. A sample of 51 stations was used for the regression equations developed for mean monthly temperature. For mean monthly precipitation the sample size was 55 stations, and for mean monthly snowfall 49 stations were represented. The reason for the smaller samples used in the temperature and snowfall analyses was the unavailability of satisfactory data for several stations which had been used in the precipitation analysis. A thirteen-year observation period (1949-1961) was used for each of the elements.[2]

In addition to the regression equations, correlation coefficients and residuals from regression were computed. Three types of correlation coefficients were obtained from computer analysis of the data:

1. coefficients of simple correlation (r_{12}), which measure the degree of association between the dependent variable and one of the independent variables;
2. coefficients of partial correlation ($r_{12.34}$), which measure the relationship between the dependent variable and one independent variable when variation in the remaining independent variables is held constant statistically; and

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[1]For illustrations and descriptions of the regression and correlation equations used in this analysis, see Appendix C; also see, Walker and Lev, op. cit., Pp. 318-319.

[2]The data for these analyses were obtained on punched cards from the National Weather Records Center. The data were repunched on IBM cards with the terrestrial variables added. The cards were then scaled, programmed (Library Routine K 16-M), and the regression and correlation equations solved on the Michigan State University Integral Computer (MISTIC).

3. coefficients of multiple correlation ($R_{1.234}$), which describe the degree to which all three of the independent variables are related to the dependent variable.[1]

Residuals from regression for each climatic element were also calculated for individual stations. A residual from regression, for any particular observation, is the difference in magnitude between an actual value and an estimated value that has been determined by the regression equation. Stated within the context of this analysis, a residual is defined as that part of the value of a given climatic element that is independent of the areal association between the given element and the three terrestrial (independent) variables included in the investigation.[2]

Residuals from regression may be expressed in a variety of ways. The normal procedure is to subtract the estimated value of Y (the climatic element-dependent variable) from the observed value of Y (or vice versa). The residuals used in this analysis, however, are standardized by dividing the above result by the standard error of estimate (S_{y_c}) which is a statistical measure of the variability of the estimates. Thus, the formula for their computation is Yn - Yc / S_{y_c}. A desirable characteristic of this type of residual is that the values may be placed in classes, the limits of which are usually set by some even or common multiple of the standard error of estimate. Since almost all residuals fall within three standard errors of estimate

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[1]Walker and Lev, op. cit., Pp. 321-322.

[2]See Edwin N. Thomas, "Maps of Residuals from Regression: Their Characteristics and Uses in Geographic Research," Dept. of Geography, State Univ. of Iowa, Iowa City, Iowa, 1960, P. 10.

from the mean, on both positive and negative sides, the number of classes need never be very large.[1]

Relationships between Mean Monthly Temperature and Selected Terrestrial Variables

Table 15 indicates the results of the regression and correlation analysis for mean monthly temperature on the three terrestrial variables (distance from a Great Lake according to prevailing wind direction, latitude, and elevation). The coefficients of multiple correlation (R) obtained in this analysis are comparatively high, indicating the existence of a strong relationship between monthly temperature and the terrestrial controls. The coefficients of multiple correlation range from a high of .972 in November to .896 in August.[2] There is no significant difference between these R values at the .05 level of confidence,[3] but the winter values are consistently higher, in the absolute sense, than the summer values. The coefficient of determination (R^2) is an important parameter because it represents the proportion of the variance of mean monthly temperature that is attributable to the relationship between temperature and the three terrestrial variables.[4] In other words, it indicates the proportion of the mean temperature variation in Michigan that is explained by

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[1] Ibid., Pp. 21-22.

[2] Coefficients of plus 1.00 and minus 1.00 indicate, respectively, perfect direct and inverse correspondence of variations from place to place. A coefficient of zero indicates a complete lack of mathematical relationship between the variables.

[3] Unless otherwise stated all testing is at the .05 level of confidence.

[4] Walker and Lev, op. cit., Pp. 243-244.

TABLE 15

CORRELATION COEFFICIENTS BETWEEN MEAN MONTHLY TEMPERATURE AND SELECTED TERRESTRIAL VARIABLES

	$R_{1,234}$	$R^2_{1,234}$	r_{12}	r_{13}	r_{14}	$r_{12,34}$	$r_{13,24}$	$r_{14,23}$	S_{yc}
January	.971*	.943*	.343*	-.931*	-.486*	-.308*	-.957*	-.781*	1.05
February	.965*	.930*	.346*	-.937*	-.408*	-.286*	-.952*	-.634*	1.10
March	.968*	.937*	.380*	-.956*	-.346*	-.188	-.958*	-.509*	1.05
April	.951*	.904*	.415*	-.950*	-.244*	-.007	-.937*	-.138	1.06
May	.934*	.871*	.380*	-.931*	-.134	-.075	-.921*	.178	1.23
June	.933*	.870*	.456*	-.931*	-.178	.152	-.912*	.062	1.22
July	.925*	.856*	.445*	-.922*	-.262*	.116	-.900*	-.172	1.17
August	.896*	.803*	.358*	-.889*	-.290*	-.084	-.870*	-.230	1.37
September	.943*	.888*	.387*	-.921*	-.392*	-.074	-.920*	-.517*	1.11
October	.935*	.875*	.404*	-.908*	-.412*	.001	-.907*	-.534*	1.02
November	.972*	.945*	.370*	-.884*	-.582*	-.139	-.951*	-.865*	0.73
December	.971*	.943*	.320*	-.888*	-.562*	-.350*	-.953*	-.849*	0.88

The subscripts (1,2,3,4) refer as follows: (1) Mean Monthly Temperature; (2) Distance from a Great Lake, according to prevailing wind direction; (3) Latitude; and, (4) Elevation.

S_{yc} equals Standard Error of Estimate (^{o}F.)

* equals coefficient significantly different from zero

distance from a Great Lake, latitude, and elevation. In the case of mean monthly temperature the explained variance is large; 95 per cent for November and 80 per cent for August, to note the extremes. It may be inferred that predictability of mean temperatures in terms of these variables is very good.

Examination of the simple correlation and partial correlation coefficients indicates how much each of the terrestrial variables influences temperature separately. Both simple and partial coefficients show that latitude makes the greatest contribution to the explanation of the variation in mean monthly temperature. For latitude, the correlation coefficients are consistently negative, indicating an inverse relationship between latitude and temperature. Distance from a Great Lake and elevation also have importance in the explanation of the variance, although appreciably less than latitude. The distance variable is of predictive aid during the months of December, January, and February when its partial correlation coefficients are significantly different from zero. The partial correlation coefficients for elevation vary statistically from zero during January, February, March, September, October, November, and December. During November, December, January, and February they contribute greatly to the definition of temperature variations in the study area. Neither distance from a Great Lake nor elevation has partials significantly different from zero during the warmer months (April to August), and latitude also has slightly lower partial correlation coefficients at this time.

The standard errors of estimate (S_{y_c}), which are the standard deviations of the predicted temperatures with the independent variables

held constant, are small for all months. Values range from 1.37° F. in August to 0.73° F. in November. In November, if the independent variables are arbitrarily set at 60 miles for distance from a Great Lake, 44° 30' for latitude, and 950 feet for elevation, and this produced, by regression, an estimated temperature of 35.5° F., expectations are that 67 per cent of all places in Michigan having that same combination of terrestrial variables would have mean November temperatures of 35.5° F., plus or minus .73° F. If, for the same month, two standard errors of estimate are taken instead of one, expectations would be that about 95 per cent of mean November temperatures, for the given set of terrestrial variables, would fall within the limits of 35.5° F., plus or minus 1.46° F.

Relationships between Mean Monthly Precipitation and Selected Terrestrial Variables

Table 16 gives the results of the regression and correlation analysis for mean monthly precipitation on the three terrestrial variables. The correlation coefficients for mean monthly precipitation are considerably different from those for mean monthly temperature. For every month, without exception, the precipitation coefficients are lower and there is more variation in their magnitudes from month to month. The highest coefficient of multiple correlation is .796 for April, and the lowest is .499 for May. Coefficients of multiple determination range from .633 in April to .249 in May, indicating that in the former month about 63 per cent of the variation in precipitation is accounted for by the terrestrial variables while in the latter month only about 25 per cent is explained.

TABLE 16

CORRELATION COEFFICIENTS BETWEEN MEAN MONTHLY PRECIPITATION AND SELECTED TERRESTRIAL VARIABLES

	$R_{1.234}$	$R^2_{1.234}$	r_{12}	r_{13}	r_{14}	$r_{12.34}$	$r_{13.24}$	$r_{14.23}$	S_{yc}
January	.681*	.464*	-.004	-.571*	-.284*	-.394*	-.644*	-.274*	.294
February	.695*	.483*	-.005	-.624*	-.220	-.252*	-.587*	-.160	.265
March	.701*	.491*	.271*	-.698*	-.121	-.087	-.667*	-.020	.229
April	.796*	.633*	.340*	-.781*	.029	-.038	-.763*	.242*	.325
May	.499*	.249*	-.140	.274*	.454*	.001	.207	.433*	.351
June	.586*	.343*	-.324*	.222	.518*	-.276*	.025	.510*	.423
July	.621*	.385*	-.092	.123	.620*	-.023	.020	.612*	.491
August	.532*	.283*	.062	.368*	.323*	.308*	.437*	.313*	.370
September	.703*	.494*	-.462*	.668*	.129	-.310*	.572*	.225*	.385
October	.738*	.545*	.107	-.696*	-.096	-.343*	-.732*	.006	.266
November	.502*	.252*	-.481*	.352*	.057	-.382*	.164	-.011	.319
December	.500*	.250*	-.019	-.270*	-.418*	-.201	-.293*	-.408*	.328

The subscripts (1,2,3,4) refer as follows: (1) Mean Monthly Precipitation; (2) Distance from a Great Lake, according to prevailing wind direction; (3) Latitude; and, (4) Elevation.

S_{yc} equals Standard Error of Estimate (inches)

* equals coefficient significantly different from zero

There is no consistent seasonal pattern of multiple correlation coefficients, but the period from January to April has fairly high coefficients, as do September and October. All of the multiple correlation coefficients are significantly different from zero; therefore, mathematical relationships may be said to exist between precipitation and the combined terrestrial variables in each month.

Analysis of simple and partial correlation coefficients indicates further important differences between precipitation and temperature. Latitude continues to be the most important terrestrial factor over the course of the year, but it is relatively insignificant during May, June, and July (partial coefficients of .207, .025, and .020, respectively). Latitude is also of lesser significance in November and December (partials of .164 and .293). In all other months, however, it has the highest simple and partial coefficients, and, thus, accounts for most of the variation in precipitation due to the terrestrial controls. In the months for which its simple correlation coefficients are high the coefficients are also negative, denoting a decrease of precipitation toward the north in these months. During the months from May to September (and also November) the simple coefficients are positive, indicating that precipitation increases toward the north during this period.

Distance from a Great Lake does not account for as high a proportion of the variance as latitude, but its partials are significantly different from zero in 7 of the 12 months and its simple coefficients in 5 of the 12 months. The highest partial correlation coefficient for the distance variable is -.394 in January, and in

November this variable has a higher partial (-.382) than either latitude or elevation. In all of the months in which its correlation partials are significant, except August, distance is negatively correlated with precipitation, denoting that precipitation tends to lessen with increasing distance from the Lakes in those months. The one exception to this rule is August when distance is meaningfully, and positively, correlated with precipitation, indicating that rainfall tends to increase with increasing distance from a Great Lake.

In terms of both simple and partial correlation coefficients, elevation is not an important factor in the clarification of the distribution of precipitation variations during the winter months. However, beginning in April and continuing through September, elevation has fairly high simple and partial coefficients. In May, June, and July it has higher partials than either latitude or distance from a Great Lake. The simple correlation coefficients for these months are approximately the same as the partials, and are positive, inferring that there is greater precipitation at higher elevations during May, June, and July. During these latter three months the elevation variable has the only simple and partial correlation coefficients that are significantly different from zero.

The Relationships between Mean Monthly Snowfall and Selected Terrestrial Variables

Table 17 shows the results of the regression and correlation analysis for mean monthly snowfall on the three terrestrial variables. Coefficients of multiple correlation for snowfall occupy a position intermediate between those of temperature and precipitation. They are

TABLE 17

CORRELATION COEFFICIENTS BETWEEN MEAN MONTHLY SNOWFALL AND SELECTED TERRESTRIAL VARIABLES

	$R_{1.234}$	$R^2_{1.234}$	r_{12}	r_{13}	r_{14}	$r_{12.34}$	$r_{13.24}$	$r_{14.23}$	S_{yc}
January	.834*	.695*	-.710*	.691*	-.056	-.622*	.603*	-.306*	3.69
February	.756*	.571*	-.559*	.706*	.020	-.364*	.612*	-.146	2.80
March	.880*	.775*	-.551*	.860*	.230*	-.311*	.813*	.199	2.07
April	.800*	.641*	-.501*	.788*	-.044	-.228*	.721*	-.023	1.75
November	.869*	.756*	-.653*	.768*	.370*	-.538*	.702*	.444*	2.76
December	.867*	.751*	-.695*	.773*	.002	-.601*	.718*	-.251*	3.67

The subscripts (1,2,3,4) refer as follows: (1) Mean Monthly Snowfall; (2) Distance from a Great Lake, according to prevailing wind direction; (3) Latitude; and, (4) Elevation.

S_{yc} equals Standard Error of Estimate (inches)

* equals coefficient significantly different from zero

significantly higher than those for precipitation, but slightly less than those for temperature. However, snowfall coefficients resemble those of temperature more closely in terms of magnitude, lack of great variation from month to month, and consequent statistical significance.

The highest multiple correlation coefficient for snowfall is .880 in March and the lowest is .756 in February. With the exception of the latter month, every multiple correlation coefficient is equal to or exceeds .800. The degree of explanation of snowfall variations in terms of the terrestrial factors is, therefore, moderately high, with percentages ranging from nearly 78 in March to 57 in February. Inasmuch as these multiple correlation coefficients are not only significantly different from zero, but also from the coefficients for precipitation, in every month but April, it is reasonable to assume that there is a stronger relationship between mean snowfall and the three terrestrial variables than between mean precipitation and the same variables.

Analysis of the simple and partial correlation coefficients indicates definite contrasts between snowfall and the other two dependent variables. Distance from a Great Lake is considerably more important in the snowfall correlations than for either precipitation or temperature. The simple correlation coefficients between snowfall and each of the terrestrial variables are over .500 in every month, and reach a high of .710 in January. Partial coefficients are also high for the months of January, November, and December, when, in each case, they exceed .530.

Simple correlation coefficients for distance from a Great Lake are statistically different from zero in each of the six months.

Partials, however, are significantly different in February and March only. In January both simple and partial correlation coefficients for snowfall on distance are higher than the simple and partial coefficients for snowfall on latitude, suggesting that distance from a Great Lake is equal to, or slightly more important than, latitude in accounting for the variation in January mean snowfall in Michigan. The simple correlation coefficients for snowfall on distance are negative in all months, indicating that snowfall tends to decrease with increasing distance from a Great Lake.

Latitude is an important interpretative factor in snowfall correlations, as it was in the temperature and precipitation analyses. In fact, it is the most important of the terrestrial controls in all months except January. The range for simple correlation coefficients of latitude is from .860 in March to .691 in January, and for the partials, .813 to .603 in the same months, respectively, with all coefficients being positive. This connotes a significant relationship between snowfall and latitude within the study area with snowfall totals becoming larger with increasing latitude.

On the basis of its simple and partial correlation coefficients, elevation does not appear to play a major role in the clarification of snowfall variations from place to place in the study area. Partial correlation coefficients are significantly different from zero in November, December and January, but they range from only .251 to .444 during these months. In January the simple correlation coefficient is negative, suggesting that snowfall actually decreases with higher elevation! The difficulty here is an operational one, and involves

failure to provide measurements of local relief and exposure which are more important than raw elevation in the determination of snowfall conditions (local relief and exposure are more difficult to quantify, however). A further difficulty is that some stations with high elevations are situated at a considerable distance from a Great Lake with interposing higher elevations between, and, therefore, are in areas that experience a snow-shadow effect.

Summary and Conclusions

It is obvious that temperature, precipitation, and snowfall are related in different degrees to the three terrestrial controls. In all cases, the coefficients of multiple correlation are significantly different from zero, proving that relationships do exist and often are very strong. Most of the simple and partial correlation coefficients also indicate associations between the various climatic elements and the individual terrestrial factors.

Latitude is the most consistently significant terrestrial control in terms of explaining variation in the selected climatic elements, although its relative importance is different for temperature, precipitation, and snowfall. Elevation also is important in the explanation of element variations, but is not as consistent as latitude. For temperature the highest partial coefficients relating to elevation are in winter, at which time they are over -.700. In the case of precipitation, elevation partials are highest in the summer months, but of lesser magnitude than the winter temperature partials, and, in addition, are positively correlated. The partials for elevation and snowfall show very little relationship.

Distance from a Great Lake is approximately equal to elevation as an explanatory factor, but does not have the high partial correlation coefficients that exist between elevation and winter temperatures. Distance is significantly related to all three climatic elements, but its strength is best evidenced in the snowfall correlations. The partial correlations between distance and temperature are not significantly different from zero except during the winter months when the two are negatively correlated, indicating that the Lakes play a small role in raising mean temperatures near their shores. Partial correlation for precipitation on distance are slightly higher than those for temperature and distance, but are similar in that the higher correlations are obtained in the winter season. Simple and partial coefficients for distance are generally negative, revealing that precipitation tends to be greater near the Great Lakes.

When R is relatively low, the amount of variation in the climatic element that is explained by the terrestrial variables is also low. If R^2 does not equal or exceed .500, less than 50 per cent of the variation in the climatic element is explained by the terrestrial factors. In the cases of temperature and snowfall, R^2 is significantly greater than .500 in every month. For precipitation, however, R^2 is significantly larger than .500 in April only, although it does slightly exceed .500 in the absolute sense during October.

Three conditions may be cited as possible reasons for the difference in the magnitude of correlation coefficients between temperature and precipitation:

1. random disturbances not related to distance, elevation, or

latitude may occur more frequently in the distribution of precipitation;

2. the precipitation regression equations almost certainly do not contain sufficient independent variables, or do not include those variables which would greatly increase the amount of explained variance. Meteorological variables, for example, might be added if they were thought to vary significantly over the study area in patterns unrelated to distance, latitude, and elevation. The inclusion of other terrestrial factors such as local relief, exposure, and rain-shadow position might increase the amount of explanation;
3. regional patterns not directly associated with the three terrestrial variables used in this analysis may exist in the case of precipitation, and these areal distributions may have stronger impact on the variations in precipitation than do the selected terrestrial factors. It is possible that different atmospheric controls, bearing no consistent relationships to distance, latitude, or elevation, may be dominant in the various sections of the state.

Analysis of Residuals from Regression

The purpose of this section is to analyze the areal distributions of the variations in mean temperature, mean precipitation, and mean snowfall that are not explained by their correlations with the selected terrestrial variables. The results of the preceding analyses, and their areal distribution, are presented by maps of residuals from

regression.

Residuals from regression for temperature, precipitation, and snowfall are shown in Figures 23-27. The residuals were standardized $(Yn - Yc / S_{yc})$[1] and, therefore, range from -3.00 to plus 3.00. Interpretation of the residual maps should be based on the fact that positive residuals connote that the actual mean temperature (or precipitation, or snowfall) is greater than the estimated temperature (or precipitation, or snowfall) and, thus, the temperatures within the areas enclosed by positive isolines are underestimated. Negative residuals indicate that the temperature calculated by regression is greater than the observed temperature, and, consequently temperatures in areas enclosed by negative isolines are overestimated. The greater the value of the residual, the greater the amount of over- or underprediction.

Residuals from Regression for Mean Monthly Precipitation

Winter.- Figures 23 and 24 indicate the monthly pattern of residuals from regression for mean precipitation. The grouping in these maps is by season, with each row representing a season. In winter (December, January, and February) the pattern of residuals shows regional concentrations. The eastern Upper Peninsula has positive residuals, including many of high value, in all winter months. The western Upper Peninsula has negative values except along the Lake Superior littoral at Ontonagon and Ironwood. This implies that precipitation, as estimated from its relationships with the three terrestrial variables, is consistently overestimated in the west-central part of the Peninsula, and underestimated in the east and the

[1]Actual mean temperature less estimated mean temperature, divided by the standard error of estimate.

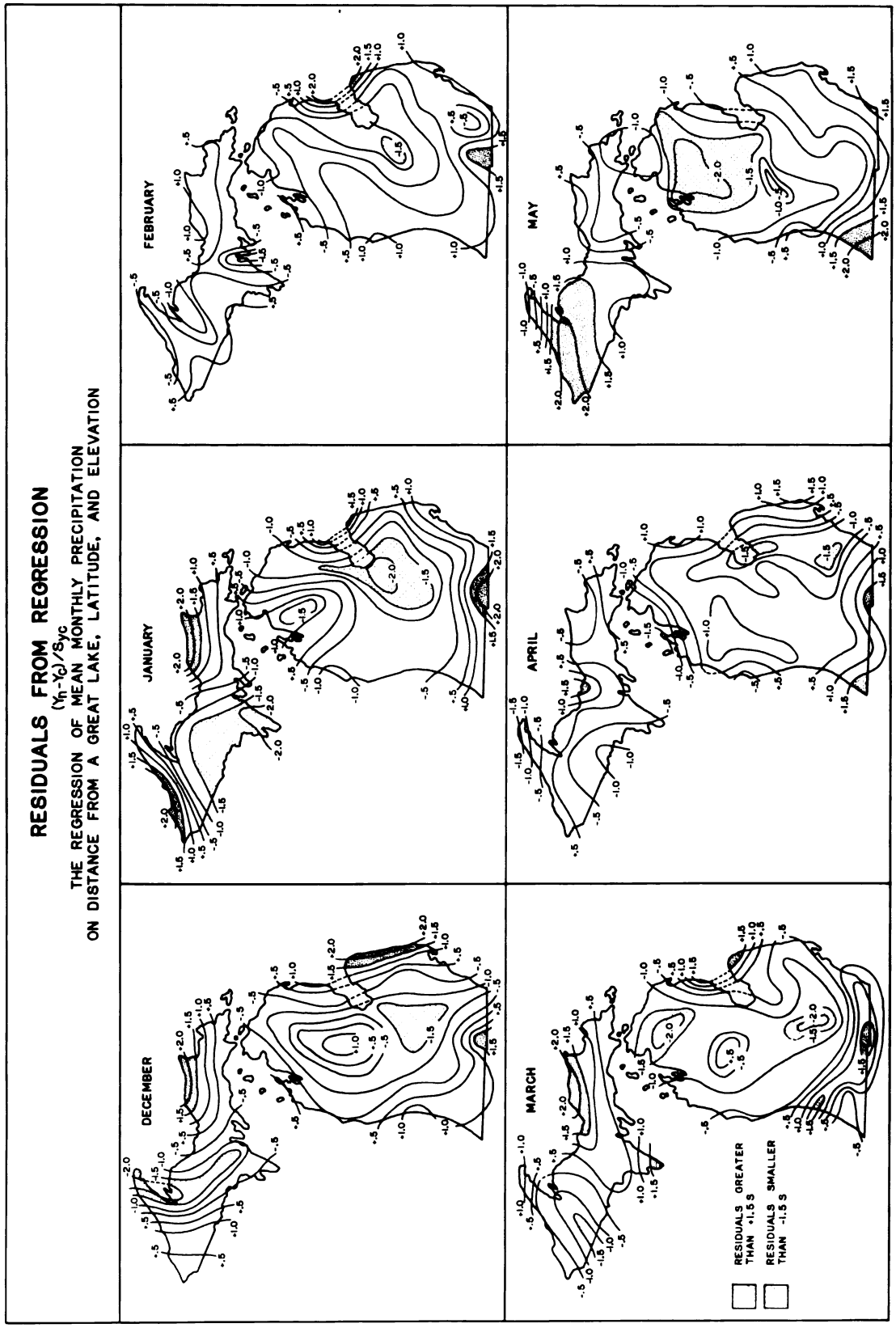

RESIDUALS FROM REGRESSION
$(Y_n-Y_c)/S_{yc}$
THE REGRESSION OF MEAN MONTHLY PRECIPITATION
ON DISTANCE FROM A GREAT LAKE, LATITUDE, AND ELEVATION
DECEMBER
JANUARY
FEBRUARY
MARCH
APRIL
MAY
RESIDUALS GREATER THAN +1.5 S
RESIDUALS SMALLER THAN -1.5 S

Figure 23

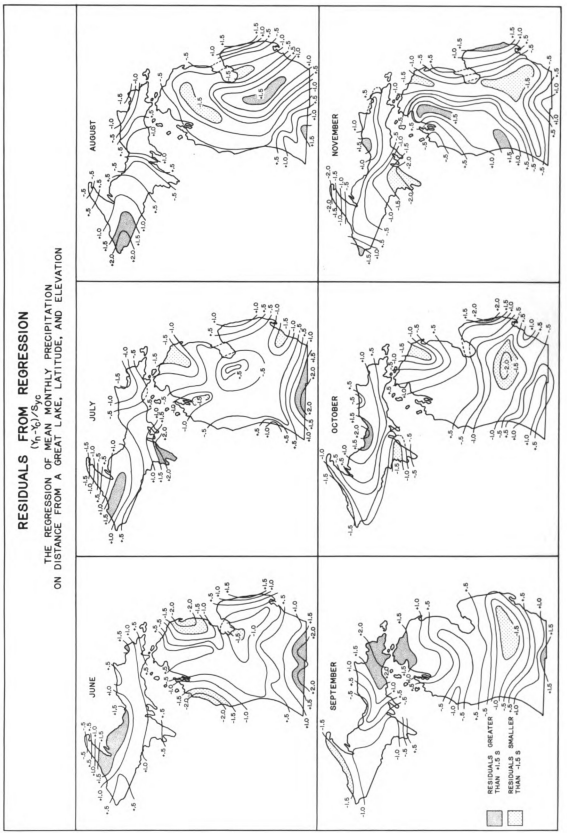

RESIDUALS FROM REGRESSION
$(Y_n - Y_c)/S_{Yc}$
THE REGRESSION OF MEAN MONTHLY PRECIPITATION
ON DISTANCE FROM A GREAT LAKE, LATITUDE, AND ELEVATION
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
RESIDUALS GREATER THAN +1.5 S
RESIDUALS SMALLER THAN -1.5 S

Figure 24

extreme west. Escanaba averages the largest negative residuals, with L'Anse and Kenton also having high values. It is notable that these stations are leeward of the highest land in the study area, and consequently might be expected to experience a rainshadow effect.

In the Lower Peninsula there are three areas where regression consistently predicts too much or too little precipitation. The two areas that are underestimated (positive residuals) are (1) along the Lake Huron shore as represented by Port Huron, Harbor Beach, and Harrisville, and (2) the extreme south-central section, particularly in the vicinity of Hillsdale. The only area of consistently overestimated precipitation is the Saginaw Lowland.

A comparison of the maps of residuals for winter precipitation and the map for mean winter precipitation (see Figure 13) reveals a general correspondence between the two. In the Upper Peninsula the areas for which calculated values are too low are also the areas of maximum winter precipitation, and the area of least winter precipitation (west-central section) is roughly coincident with the belt of greatest overestimation. In the Lower Peninsula the correspondence is less consistent. However, the Saginaw Lowland is both an area of overprediction and minimal winter precipitation, and the extreme south is an area of positive residuals and above average winter precipitation. The one section of the state where these relationships do not hold true is the northern Lower Peninsula. The Lake Huron littoral, although an area of underestimation, does not have above average rainfall, but its mean precipitation is greater than the area to the west.

Spring.- The residual patterns for the spring months (March, April, and May) are characteristic of the transitional nature of the season. This is particularly evident in the Upper Peninsula. The March residuals do not differ greatly from those of winter, except for a pocket of positive residuals near Stephenson in the extreme south. By April, however, the positive residuals characteristic of the eastern Upper Peninsula in winter are found farther westward in the vicinity of Munising and Chatham. Negative residuals disappear from the map in the western Upper Peninsula and reappear in the eastern section, although they are of low value in April. By May the transition from winter to summer is nearly complete. High positive residuals now dominate the west, while average value negatives are in evidence over the eastern half of the Peninsula.

In the Lower Peninsula regional groupings of residuals are better defined than they were in winter. The high positive residuals, or areas of underestimation, are now in the extreme south and along the Lake Huron littoral, while the remainder of the Peninsula is dominated by negative residuals, and its precipitation is thus less than the values calculated by regression.

Comparison of the patterns of residuals from regression and mean spring precipitation (see Figure 14) again indicates a high degree of correspondence. In general, precipitation is least in the eastern and extreme northern Upper Peninsula, which are the areas of negative precipitation residuals in May. The western Upper Peninsula, which receives heavy May precipitation, is an area of high positive residuals in this month. In the Lower Peninsula, the area of maximum precipitation in the south corresponds to one of the two major zones of high

positive residuals, while the northern section, the area of lowest precipitation, is dominated by negative residuals.

Summer.- The residual pattern established in May continues to characterize the summer with only slight differences. During June, precipitation over almost the entire Upper Peninsula is underpredicted, as evidenced by the solid block of positive residuals. Eagle Harbor, on the northern tip of the Keweenaw Peninsula is the only Upper Peninsula station with a positive residual in June, and this is only -.5. In July and August, however, this pattern changes, as negative residuals dominate the eastern Upper Peninsula while positive residuals remain in the west.

The residual pattern for precipitation in the Lower Peninsula remains essentially as it was in May, i.e. strongly positive in the south and strongly negative in the north. Two elements of the summer pattern differ slightly from the May situation. The highest negatives are now concentrated along the shores of northern Lake Michigan and northern Lake Huron, especially in June and July. Also, in July, and even more so in August, cells of positive residuals develop in the center of the Peninsula where negative residuals were found earlier in the spring. These cells may represent the convectional centers of the state during these months of maximum thunderstorm activity.

Comparison of the residual patterns for summer precipitation and the map of mean summer precipitation (see Figure 15) again reveals a close correspondence. The western Upper Peninsula, the area of highest summer precipitation in the state also has the highest positive residuals. The periphery of the eastern Upper Peninsula has below average summer precipitation, and during July and August is dominated by negative

residuals.

In the Lower Peninsula the same general relationship between residual pattern and mean precipitation is found. The only major exception is the cell of above average precipitation around Grayling in the Northern Upland which is not indicated in the pattern of residuals. It might be inferred that this cell is the result of higher elevations found in the area, and that this is taken into account in the regression equations. The southern Lower Peninsula, which has high positive residuals, is the area of greatest mean summer precipitation. The northern Lower Peninsula littoral, which is the area of lowest precipitation, is an area of negative residuals.

Fall.- The change in residual patterns between August and September, the first month of fall, is the most drastic for any two consecutive months. The eastern Upper Peninsula and the northern Lower Peninsula which are strongly negative in August become strongly positive in September. The western Upper Peninsula which is highly positive in August becomes negative in September. The August cell of high positive residuals over the south-central Lower Peninsula is replaced in September by a high-value negative cell. The only area that corresponds reasonably well to the August pattern is the extreme southern Lower Peninsula which is positive in both months.

The October pattern of residuals does not differ greatly from September except for small, but not insignificant, details. In the Upper Peninsula the high positive residuals which are located in the extreme east during September migrate to the north-central area around Munising and Chatham. In the Lower Peninsula there are two slight

shifts that are of significance. In the northeastern extremity of the Peninsula, a wedge of negative residuals pushes southward into the position occupied by positive residuals in September. And, in October, there is reestablishment of the high positive residuals along the southern Lake Huron littoral (Port Huron-Harbor Beach).

The November pattern of residuals resembles that of December very closely, differing only slightly in the orientation and magnitude of the isolines. The principal differences between November and October are (1) the reappearance of high positive residuals in the extreme western Upper Peninsula, and (2) the establishment of a meridional, as opposed to zonal, orientation of the positive and negative residuals in the Lower Peninsula, with the positive values dominating most of the western half and the negatives incorporating most of the eastern half.

Comparison of the residual patterns for fall precipitation and the map of mean fall precipitation (see Figure 16) again shows close correspondence between areas of above average precipitation and high positive residuals, and areas of below average precipitation and negative residuals. In the Lower Peninsula, where there is almost perfect accordance between the residuals and mean precipitation values, both residual isolines and isohyets have a marked meridional orientation. The only exceptions to the general agreement between patterns are (1) the Gogebic Range-Porcupine Mountains area where above average precipitation is not evidenced by high positive residuals (except in November), and (2) along the Lake Huron shore where high positive residuals are not associated with above average precipitation. However,

the latter area does have slightly greater precipitation than the area to the west.

Conclusions

It is evident that the residuals from regression for precipitation are distributed in concentrations of negative and positive values. Areas enclosed by positive isolines have a strong tendency to be areas of above average precipitation, while those enclosed by negative isolines are likely to receive below average precipitation.[1]

In all of the above analyses it was noted that residual patterns and mean seasonal precipitation correspond closely. The residuals, however, add the following information to the analysis of precipitation distribution: (1) they represent the variation that remains after the effects of distance from a Great Lake, latitude, and elevation have been removed by regression analysis (i.e. factors expressing the relationship between precipitation and the terrestrial controls). Regression explained 63 per cent of the variation in April but only about 25 per cent in May and December; (2) the remaining variation is not attributable to the selected terrestrial factors, but must be accounted for by other climatic controls if precipitation bears a cause-and-effect

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[1]To ascertain that each of these regions has statistically significant differences from adjacent regions, they should be subjected to analysis of covariance. Analysis of covariance allows the testing of a regional classification while, at the same time, considering the effect of the relationships between variables within the various regions. If the regional classification is significant the covariance analysis will result in an increase in explained variance for the dependent variable. A substitute procedure for analysis of covariance is to examine the residual patterns for all three months of a season, and if the pattern is similar in all, to make the plausible assumption that regional differences do exist in that season and are significant. See Thomas, op. cit., P. 5.

relationship to other physical phenomena, as may be assumed; and (3) although the residuals do not inform us what these unknown factors are, their regional groupings do indicate that the factors are areally differentiated within the study area.

In the search for the factors that cause the unexplained variation in Michigan's precipitation, the following are suggested:

1. the location of the polar-front - this factor is one of the most important in the analysis of precipitation genesis, because its position determines, to a very large extent, the course of cyclonic storms and their associated rainfall. However, the polar front is usually oriented zonally, and, therefore, most of the variation in precipitation caused by its position, other than that which is locally induced, should be accounted for by latitude;
2. the tracks of synoptic weather systems - as indicated earlier, certain of the synoptic weather systems are responsible for most of the precipitation within the study area. It is possible that regional differences might occur because of position relative to the principal tracks of the major precipitation-inducing pressure centers, and this could account for some of the unexplained variation. Again, however, most of these systems have mean trajectories from west-to-east, and their variations should, thus, be accounted for by latitude. It was also shown in a preceding section that amounts of precipitation during specific synoptic situations depend on location with respect to a Great Lake

(e.g. differences between lee-side stations such as Escanaba and Detroit, and windward-side stations as Grand Rapids, Traverse City, and Sault Ste. Marie). Therefore, some of the variation caused by synoptic influences should be explained by distance from a Great Lake;

3. random disturbances - the occasional scattering of residuals, as opposed to their regional grouping, suggests that some of the unexplained variation in precipitation may be due to randomness. Some of the possible random disturbances are related to well-known physical causes such as locally varying degrees of convection. However, other scattering may occur by chance alone, and have no discernible physical basis;
4. combined effects of close proximity to a Great Lake and steep elevation gradients - several of the areas in which precipitation was underestimated (positive residuals) are located at fairly high elevations on the windward side of the state relatively close to the water of a Great Lake. These are nearly always areas of above average precipitation. It is hereby postulated that the combined effects of high elevation and close proximity to a Great Lake result in heavier precipitation than predicted by the regression equations;
5. location with respect to isthmuses - the precipitation patterns of the southern Lower Peninsula (particularly the southwestern portion) and the western Upper Peninsula,

> although separated by several hundred miles of latitudinal distance, are markedly similar in both mean annual and seasonal precipitation. This is best exemplified by the patterns of increase during the spring when these two areas receive considerably more rainfall than the remainder of the state. For example, in May the western Upper Peninsula and the southern Lower Peninsula clearly have much higher precipitation than the eastern Upper Peninsula or northern Lower Peninsula. During summer (June, July, and August) this areal differentiation remains as definitive as in May.

The southern Lower Peninsula and western Upper Peninsula obviously differ in terms of latitude and elevation, as well as location with respect to synoptic weather system trajectories. Although they are similar in terms of distance from a Great Lake, neither differs greatly from the northern Lower Peninsula or eastern Upper Peninsula in this respect. We may, therefore, postulate that the most significant physical factor in the similarity of precipitation patterns for these areas is their location adjacent to the southern extremities of the isthmuses connecting the Peninsulas to the continent. These land bridges, in both cases increasing in width toward the south, allow maritime tropical (mT) and modified continental polar (NcP) air masses to enter the southern Lower Peninsula and western Upper Peninsula without first passing over the surface of a Great Lake. In the fall when the northern Lower Peninsula and the eastern Upper Peninsula have higher precipitation totals than the western Upper Peninsula and the southern Lower Peninsula, the Lakes are relatively warm compared to the air passing over them, and, therefore, tend to promote instability.

In summary, it is evident that the northern Lower Peninsula and the eastern Upper Peninsula have the highest degree of Lake-control over their precipitation regimes of any sections of the study area. The southern Lower Peninsula and western Upper Peninsula, conversely, have the highest degree of land-control, particularly with respect to the entrance of mT and NcP air masses into the state. These differences are fundamental to the analysis of regional precipitation variations.

Residuals from Regression for Mean Monthly Snowfall

Residuals from regression for the six months during which snow normally falls in the study area are shown in Figure 25. In the interpretation of these residuals it should be noted that the percentage of variation explained by regression was considerably higher for snowfall than for precipitation (from 57 to 78 per cent as compared to 25 to 63 per cent).

One of the outstanding features visible on these maps is the strong concentration of high positive residuals centered around Munising in the Upper Peninsula, extending to Ishpeming in the west and to Grand Marais in the east. The underestimated snowfall here may be explained by the prevailing northerly winds which bear moist, unstable air after crossing 200 miles of the relatively warm surface of Lake Superior. Also, the configuration of the shoreline acts as a funnel concentrating moist air into the Munising area.

In the western Upper Peninsula, from L'Anse to Kenton and Stambaugh, and thence curving toward Stephenson and Escanaba, lies a zone of consistently negative residuals (corresponding roughly to an area of high

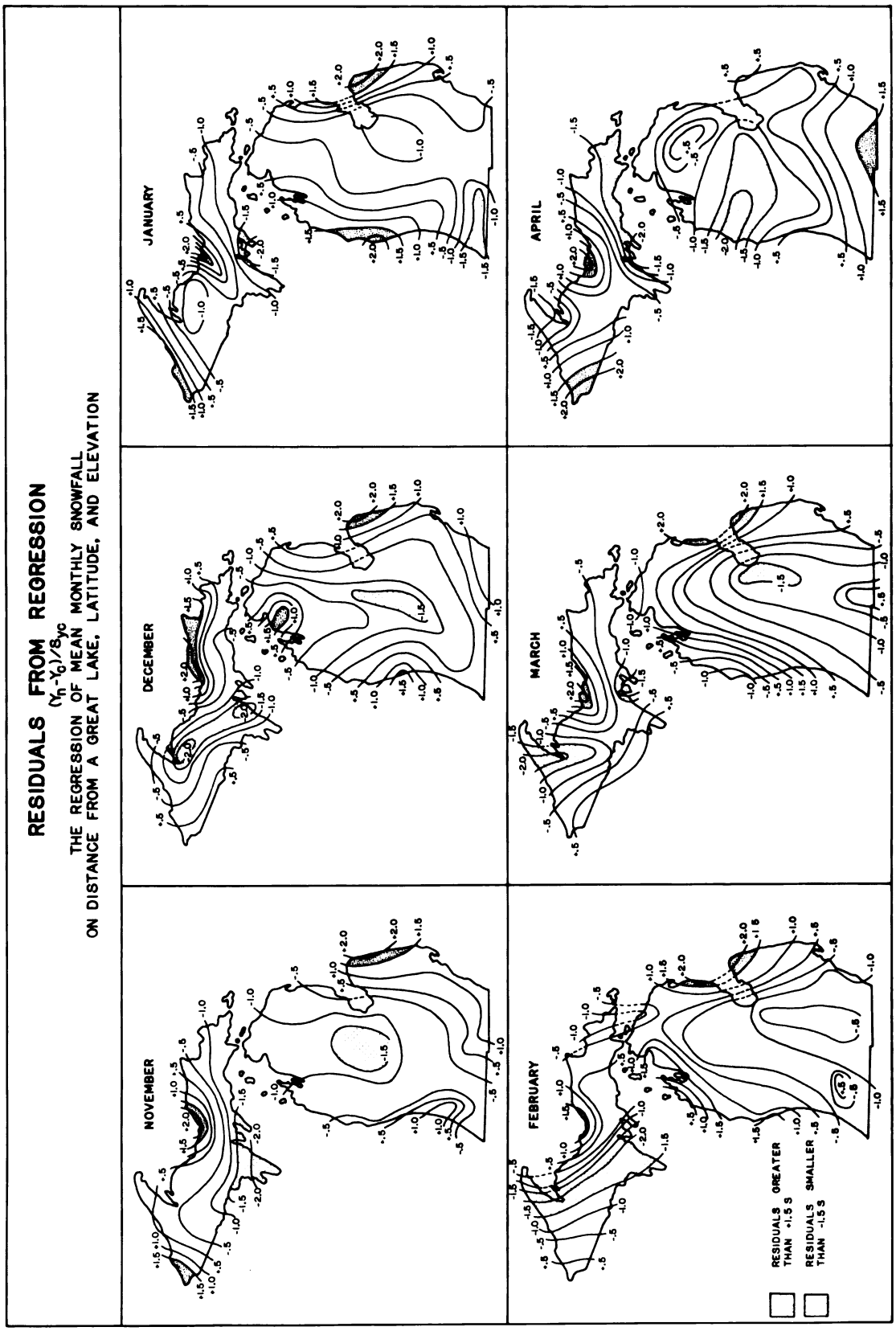

RESIDUALS FROM REGRESSION
$(Y_n-Y_c)/S_{yc}$
THE REGRESSION OF MEAN MONTHLY SNOWFALL
ON DISTANCE FROM A GREAT LAKE, LATITUDE, AND ELEVATION
NOVEMBER
DECEMBER
JANUARY
FEBRUARY
MARCH
APRIL
RESIDUALS GREATER THAN +1.5 S
RESIDUALS SMALLER THAN -1.5 S

Figure 25

negative residuals for winter precipitation). Its situation is to the lee-side of the Northern Highlands. Escanaba has the highest negative residuals of any station used in the snowfall analysis. The negative residuals extend eastward along the southern side of the Peninsula during several of the winter months. On the windward side of the Northern Highlands, however, high positive residuals are often encountered, as, for example, at Ironwood.

In the Lower Peninsula the most consistent pattern of high positive residuals is found along the southwestern shore of Lake Huron at Harrisville, Harbor Beach, and Port Huron. This pattern was also noted for precipitation during the winter months. Another area of positive residuals occurs along the Lake Michigan shore, or slightly inland, in most winter months. Although distance from Lake Michigan was used as an independent variable for the snowfall regression, it is apparent that snowfall is even greater near the Lake shore than was predicted by the regression equations. This indicates steeper than average gradients for snowfall near the Lakes.

The interior of the Lower Peninsula is enclosed by negative residuals with the isolines oriented meridionally in every month except April. Consequently, snowfall in this area is consistently overestimated, and sub-continentality can be related to below average snowfall. In April the well-defined meridional pattern changes to a zonal orientation. High positive residuals are now found in the southern Lower Peninsula while the northern two-thirds is dominated by negative residuals. The western Upper Peninsula becomes an area of high positive residuals, and the east a zone of negative residuals with the

notable exception of the highly positive Munising pocket. The residual pattern for April snowfall is markedly similar to the previously discussed late-spring precipitation pattern.

Because of high coefficients of multiple correlation relating snowfall to the three terrestrial factors, regionalization does not greatly increase the amount of variation that is explained. However, the possibility of random disturbances not directly related to distance, elevation, and latitude does not appear to be large. Therefore, the inclusion of snowfall regions based on the residual patterns should explain most of the variation not accounted for by the regression equations.

It is postulated that the residual snowfall-regions are largely the result of the following factors:

1. snowshadow effects that result in very steep gradients in amount of snow leeward from the snowbelts, as, for example, to the southeast of the Porcupine-Gogebic-Copper Range snowbelt;
2. sub-continentality in the interior of the Lower Peninsula where distance from both Lakes Michigan and Huron produces less snowfall than predicted by regression;
3. close proximity to southern Lake Huron where certain synoptic weather systems cause non-prevailing winds from the northeast with long fetch over the relatively warm water of Lake Huron before striking the shore transversely. Under these conditions the actual snowfall is greater than the estimated;
4. the Munising pocket is the result of the combined effects of

prevailing northerly winds, the great extent of Lake Superior to the north, and the shape of the shoreline, all combining to cause heavier snowfall than calculated.

Residuals from Regression for Mean Monthly Temperature

Isoline patterns for residuals from regression for mean monthly temperature are shown in Figures 26 and 27. Interpretation of these residuals should be based on the knowledge that regionalization adds little to the explanation of temperature variations in Michigan, because only 5 (November) to 20 (August) per cent of the variance is not accounted for by the relationship between temperature and the three terrestrial factors.

The patterns of residuals from regression for mean monthly temperature are as follows:

1. the western Upper Peninsula has negative residuals during the three winter months. However, in spring, summer, and fall this area is consistently and strongly positive (temperatures higher than predicted);
2. the eastern Upper Peninsula is negative in every month of the year without exception, and, thus, is consistently cooler than estimated by the terrestrial variables;
3. the Munising-Chatham pocket of high positive residuals, typical of snowfall patterns, is evident during the winter, and extends westward to include the Keweenaw Bay Lowlands and the littoral of the western Keweenaw Peninsula. However, the high positive residuals do not occur during the other seasons;

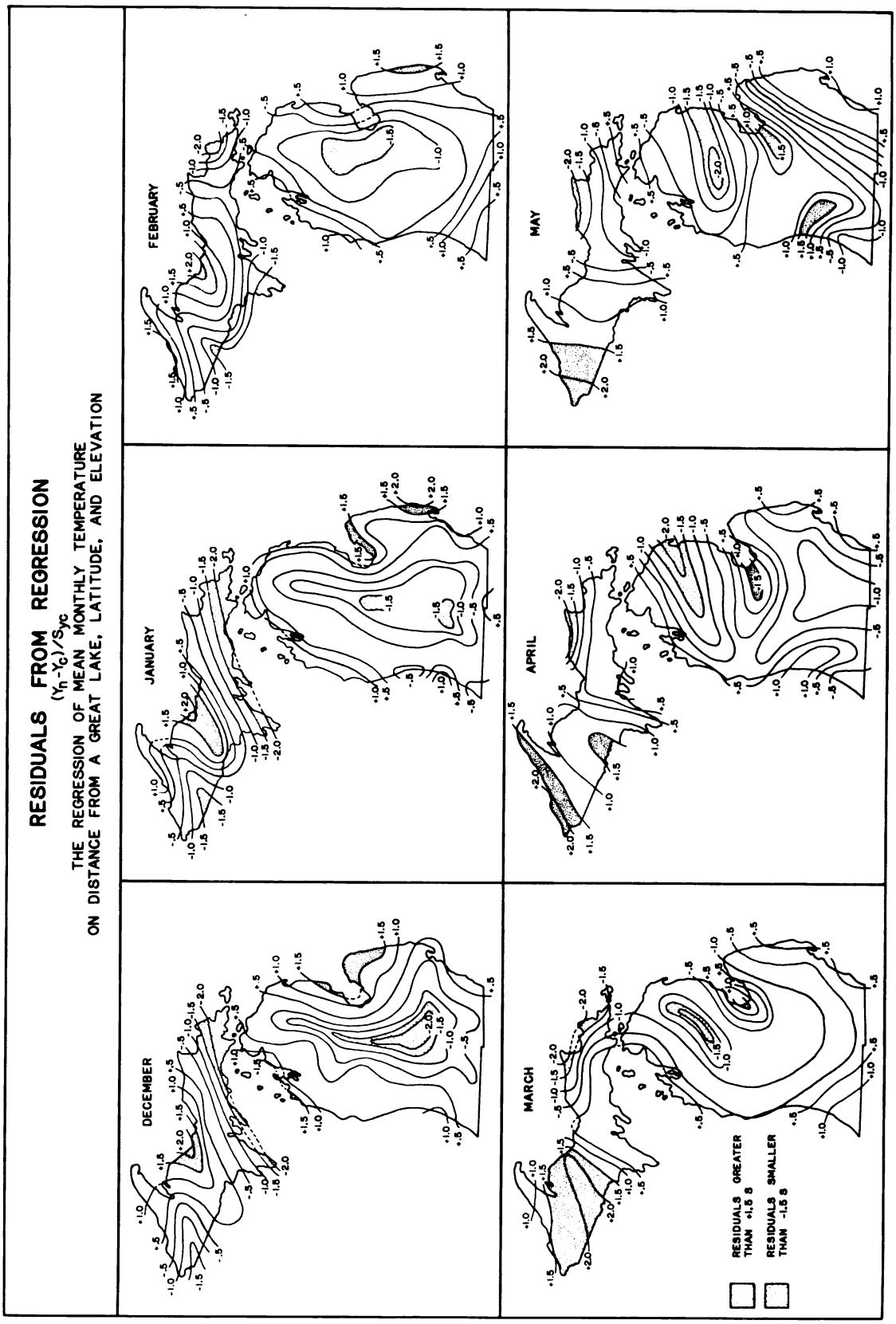

RESIDUALS FROM REGRESSION
$(Y_n-Y_c)/S_{yc}$
THE REGRESSION OF MEAN MONTHLY TEMPERATURE
ON DISTANCE FROM A GREAT LAKE, LATITUDE, AND ELEVATION
DECEMBER
JANUARY
FEBRUARY
MARCH
APRIL
MAY
RESIDUALS GREATER THAN +1.5 S
RESIDUALS SMALLER THAN -1.5 S

Figure 26

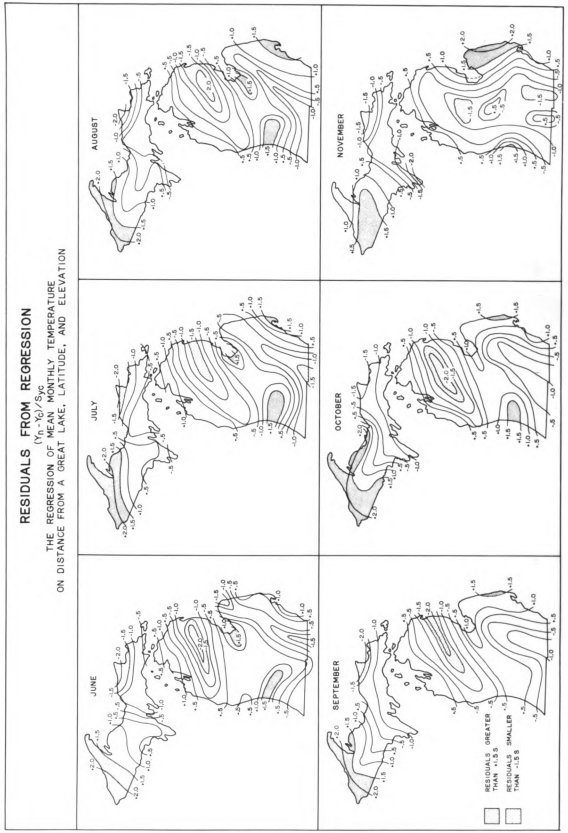

RESIDUALS FROM REGRESSION
$(Y_n - Y_0)/S_{YC}$
THE REGRESSION OF MEAN MONTHLY TEMPERATURE
ON DISTANCE FROM A GREAT LAKE, LATITUDE, AND ELEVATION
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
NOVEMBER
RESIDUALS GREATER THAN +0.5
RESIDUALS SMALLER THAN -0.5

Figure 27

4. from November to March there is a pronounced meridional orientation of the residuals in the Lower Peninsula, with positive values paralleling Lakes Michigan and Huron and negative values occupying the interior. The periphery of the Lower Peninsula has slightly higher temperatures than predicted while the interior has slightly lower temperatures than predicted for the winter;
5. in April the meridional pattern changes to a cellular pattern that continues through summer and into mid-fall (October). The principal cells composing this pattern are: (a) a cell of negative residuals roughly coincident with the Northern Upland in the northern Lower Peninsula; (b) two cells of high positive residuals, one centered along the Grand River Plain from Grand Haven to Grand Rapids, and the other in the Saginaw Bay area (Bay City and Saginaw); (c) a cell of moderately high negative residuals coincident with the Thumb Upland of the southeastern Lower Peninsula; and (d) the familiar southern Lake Huron positive cell which, however, is farther south for temperature than for precipitation or snowfall. The above patterns continue from April through October, but in November there is a return to the meridional pattern characteristic of winter.

In summary, the residuals from regression for temperature indicate a division of the Upper Peninsula into two major temperature regions and one subregion. The western Upper Peninsula has positive residuals, except for the interior during the winter; the eastern section has negatives throughout the year; and the Munising-Chatham pocket has high

positive values during the winter, but is predicted rather accurately the remainder of the year.

The Lower Peninsula has more complex temperature regions than the Upper Peninsula, but basically the regions are meridional during winter and cellular during summer. The meridional pattern consists of two bands of underestimated temperatures along the Great Lakes, and one wide band of overestimated temperatures in the interior of the Peninsula. The pattern of cells in the summer months corresponds closely to the outlines of the physiographic provinces with the areas of high elevation having negative values and the areas of low elevation having positive values.

Conclusions

On the basis of statistically significant results, the three hypotheses concerning the relationships between the terrestrial factors and the selected climatic elements are all accepted. The strongest relationships, as defined by the magnitude of the coefficients of multiple determination, exist between temperature and the terrestrial variables, the weakest between precipitation and the three controls, with snowfall being intermediate.

Nearly the entire areal variation in temperature is explained by its associations with latitude, elevation, and distance from a Great Lake. Therefore, regionalization on bases other than these terrestrial factors adds little to the interpretation of temperature differentiation within the study area. However, in the case of precipitation, only slightly less than half of the areal variation, on the average,

is explained by the regression analysis. Therefore, regionalization on bases other than the terrestrial factors must add substantially to the degree of explanation. It is concluded that the most important interpretative element in the observed regional patterns for precipitation is location with respect to isthmuses, and the consequent degree of land-control or Lake-control when air masses enter the study area from the south or southwest. Thus, the latter may be divided into predominantly land-controlled sections (i.e., the southern Lower Peninsula and western Upper Peninsula), and predominantly Lake-controlled sections (i.e., the northern Lower Peninsula and the eastern Upper Peninsula) on the basis of relative accessibility to unmodified air masses from the south or southwest.

Approximately two-thirds of the areal variation in snowfall is explained by the three terrestrial factors so that regionalization may not be expected to add greatly to the clarification of variance. Distance from a Great Lake is a more important factor in elucidating snowfall variations than in accounting for temperature and precipitation differentiations. It may be concluded that the Lake-effect influences snowfall proportionately more than it does mean monthly temperature or mean monthly precipitation.

CHAPTER V

THE CLIMATIC REGIONALIZATION OF MICHIGAN

The purpose of this chapter is to establish a system of climatic regions and subregions for the state of Michigan. Consideration is given to previous climatic regionalizations that pertain to the study area, to the genetic, elemental, and correlative analyses of the preceding chapters, and to certain cause-and-effect relationships existing between climatic phenomena and other elements of the physical environment.

The following climatic regionalization is organized hierarchically into four orders of magnitude, ranging from areal units with a high degree of generalization to units with limited generalization. The orders of magnitude, the criteria upon which they are based, and the geographic nomenclature used to describe them are given in Table 18.

The Climatic Zone

The territory of Michigan is situated within the climatic (or planetary) zone dominated by the circumpolar westerly upper-atmospheric circulation and its surface expression, the prevailing westerlies. Although the study area is but a very small part of this zone, it is subject to the same general atmospheric controls as all other locations encompassed by the Northern Hemisphere westerlies.

In addition to prevailing winds from the western quadrant, the

TABLE 18

ORDERS OF MAGNITUDE IN CLIMATIC CLASSIFICATION

	Criteria of Differentiation	Order of Climate	Geographic Nomenclature
I	Relationship to General Atmospheric Circulation	Zonal Climate	Climate Zone
II	Mean Values of Major Climatic Elements	Macroclimate	Climatic Region
III	Local Gradients of Individual Elements; Seasonality and Variability of the Major Elements	Mesoclimate	Climatic Province
IV	Topographic and other Locational Controls that Affect one or more Climatic Elements	Mesoclimate	Climatic Subprovince
V	Local Modification of Ground Layer of Troposphere	Microclimate*	Climatic Site*

* not considered in this study

most important features of the circumpolar westerly zone are: (1) control of surface weather phenomena by upper-atmospheric circulation types (zonal, meridional, and neutral); (2) interaction of tropical and polar air masses along polar and arctic fronts, with boundaries subject to constant fluctuations; and (3) a continuous succession of cyclones and anticyclones generally moving in an easterly direction.

The position of the study area within the climatic zone may be described as middle mid-latitude in the east-central section of North America. These locational attributes, combined with the distinctive physiography of North America (i.e. orientation and size of the Western Cordillera, the Gulf of Mexico, the open passageway between north and south in the mid-continent), and the dominant centers of action (principally the Bermuda High and the Canadian High) are responsible for the alternating control by continental Polar (cP) and maritime Tropical (mT) air masses.

The Macroclimatic Region

Within the circumpolar-westerly climatic zone many differences in controls and elements are manifest. These differences may be used as bases for the division of the zone into smaller areal units, or macroclimatic regions. The criteria adopted in this regionalization are the mean values of major climatic elements, specifically temperature and precipitation. Thus, the differentiation between climatic zone and macroclimatic region involves a move from genetic factors to elemental parameters. The boundaries between macroclimatic regions are best determined by critical isotherms and isohyets, with vegetational differences serving as corroborative evidence for the establishment of meaningful divisions.

The basic system of macroclimatic regions is the Koeppen classification and its numerous modifications.[1] According to this

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[1]See Wladimir Koeppen, "Versuch einer Klassifikation der Klimate, vorzugsweise nach Ihren Beziehungen zur Pflanzenwelt," Geographische Zeitschrift, Vol. 6, 1900, Pp. 593-611 and 657-679; also: "Klassifikation

classification Michigan is a part of the original "Snow and Forest" climatic region, designated as a D-type climate. The D climate is characterized by having at least four months averaging 50° F., or more, with the coldest month averaging 26.6° F., or less.[1] It is a humid regime; i.e. precipitation exceeds evaporation.

Although in terms of long period averages the Koeppen C climates ("warm temperate" or "humid mesothermal"[2]) do not extend far enough poleward to encompass the study area, the Cfa subtype ("humid subtropical," with the mean temperature of the coldest month less than 64.4° F. but greater than 26.6° F. and the mean of the warmest month exceeding 71.6° F.) lies immediately to the south of the study area, and, in individual years, within it. For example, in 1932, mean temperatures of the coldest month at many southern Michigan stations were well above 26.6° F., and would have had to be classified with the C-type. However, if long period averages are accepted, all stations

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der Klimate nach Temperatur, Niederschlag, and Jahreslauf," Petermanns Mitteilungen, Vol. 64, 1918, Pp. 193-203 and 243-248; the system most widely used today was published by Koeppen under the title Die Klimate der Erde: Grundriss der Klimakunde, (Berlin: deGruyter, 1923), and later in the Koeppen-Geiger Handbuch der Klimatologie, (Berlin: Gebroeder Borntraeger, 1936), Vol. I, Part C; also see Edward A. Ackerman, "The Koeppen Classification of Climates in North America," Geographical Review, Vol. 31, No. 1, Jan. 1941, Pp. 105-111.

[1]In North America the D climates comprise three subtypes, Dfa, Dfb, and Dfc. In the context of this study only the Dfa and Dfb areas are considered to be parts of the macroclimatic region, because Dfc is a higher mid-latitude, or subarctic, subtype rather than a middle mid-latitude subtype.

[2]The terms "microthermal" (for D) and "mesothermal" (for C) are widely used in the United States, but are not part of the original Koeppen system.

within the study area must be grouped with the D climate.[1]

The Koeppen differentiation of eastern North American climates is based principally on temperature parameters (i.e. the boundaries between the major types are strictly thermal). The boundaries between the Koeppen Dfa and Dfb subtypes are given in Figures 28 and 29, which show climatic regionalizations for eastern North America and the study area, respectively.

Borchert's[2] climatic regionalization of the same area is based primarily on precipitation characteristics. The main purpose of Borchert's study was to find relevant climatic factors to explain the distribution of grassland vegetation in central North America. In broad outline Borchert's regions resemble those of Koeppen, although established with a different set of criteria. The Borchert regionalization of eastern North America is shown in Figure 28.

Region I encompasses most of the study area. It is characterized by (1) heavy winter snowfall, (2) reliable, but not extraordinarily heavy summer precipitation, and (3) relatively low annual evapotranspiration. This region corresponds to the Koeppen D type, particularly

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[1]The frequency of Cfa climatic years for southern Michigan stations depends on the isotherm used to delimit the C from the D climates. In the Koeppen system the 26.6° F. isotherm is critical while in the Trewartha modification (see Glenn T. Trewartha, An Introduction to Climate, (New York: McGraw-Hill, 1954), 3rd Ed., Ch. 6) the 32° F. isotherm is used. Thus the former classification results in a greater number of C-years for southern Michigan. The Koeppen formula is used in this analysis because it is believed that it better emphasizes the transitional nature of the southern Lower Peninsula climate.

[2]See John R. Borchert, "The Climate of the Central North American Grassland," Annals of the Association of American Geographers, Vol. 40, 1950, Pp. 1-39.

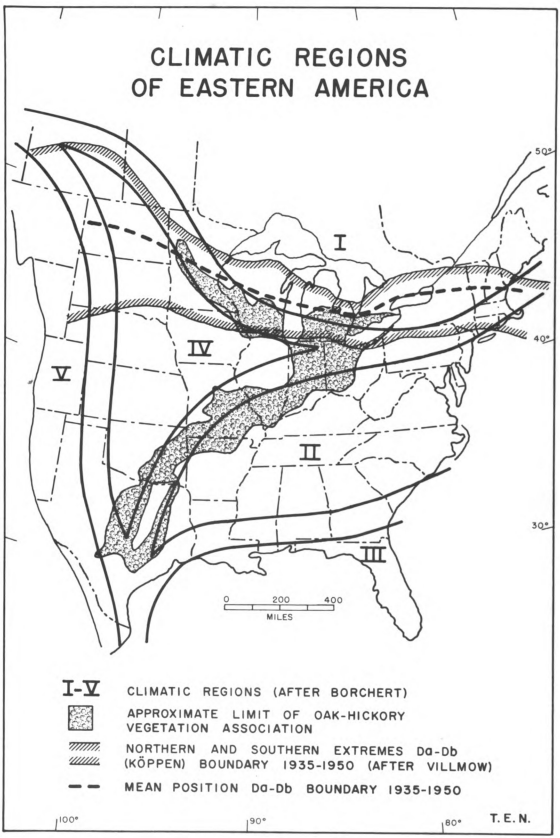

CLIMATIC REGIONS
OF EASTERN AMERICA
I
II
III
IV
V
50°
40°
30°
0 200 400
MILES
I-V CLIMATIC REGIONS (AFTER BORCHERT)
APPROXIMATE LIMIT OF OAK-HICKORY VEGETATION ASSOCIATION
NORTHERN AND SOUTHERN EXTREMES Dα-Db (KÖPPEN) BOUNDARY 1935-1950 (AFTER VILLMOW)
MEAN POSITION Dα-Db BOUNDARY 1935-1950
100°
90°
80°
T. E. N.

Figure 28

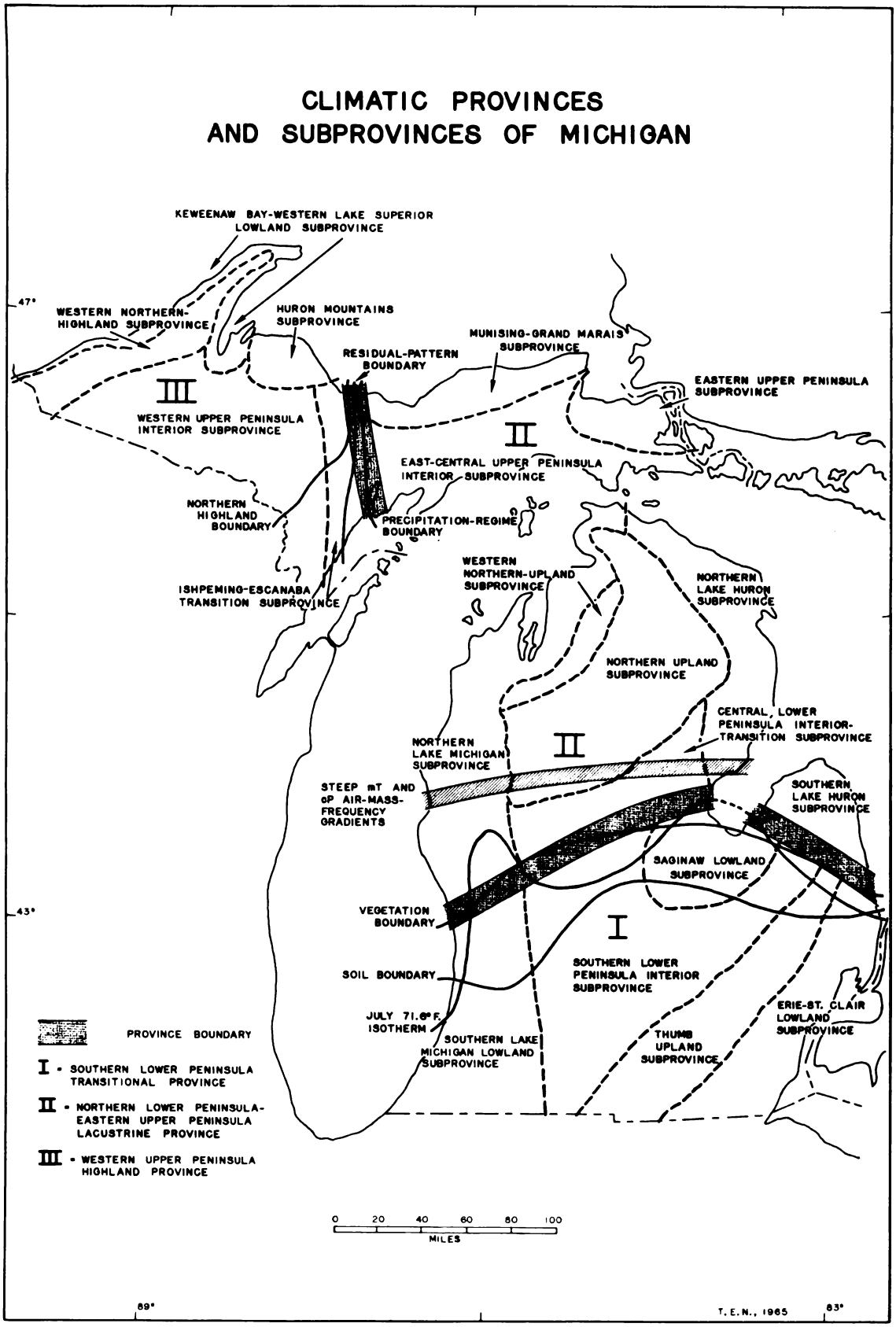

CLIMATIC PROVINCES
AND SUBPROVINCES OF MICHIGAN
KEWEENAW BAY-WESTERN LAKE SUPERIOR LOWLAND SUBPROVINCE
47°
WESTERN NORTHERN-HIGHLAND SUBPROVINCE
HURON MOUNTAINS SUBPROVINCE
MUNISING-GRAND MARAIS SUBPROVINCE
RESIDUAL-PATTERN BOUNDARY
EASTERN UPPER PENINSULA SUBPROVINCE
III
WESTERN UPPER PENINSULA INTERIOR SUBPROVINCE
II
EAST-CENTRAL UPPER PENINSULA INTERIOR SUBPROVINCE
NORTHERN HIGHLAND BOUNDARY
PRECIPITATION-REGIME BOUNDARY
WESTERN NORTHERN-UPLAND SUBPROVINCE
NORTHERN LAKE HURON SUBPROVINCE
ISHPEMING-ESCANABA TRANSITION SUBPROVINCE
NORTHERN UPLAND SUBPROVINCE
CENTRAL LOWER PENINSULA INTERIOR-TRANSITION SUBPROVINCE
NORTHERN LAKE MICHIGAN SUBPROVINCE
II
STEEP mT AND cP AIR-MASS-FREQUENCY GRADIENTS
SOUTHERN LAKE HURON SUBPROVINCE
SAGINAW LOWLAND SUBPROVINCE
43°
VEGETATION BOUNDARY
I
SOUTHERN LOWER PENINSULA INTERIOR SUBPROVINCE
SOIL BOUNDARY
ERIE-ST. CLAIR LOWLAND SUBPROVINCE
JULY 71.6°F. ISOTHERM
SOUTHERN LAKE MICHIGAN LOWLAND SUBPROVINCE
THUMB UPLAND SUBPROVINCE
PROVINCE BOUNDARY
I - SOUTHERN LOWER PENINSULA TRANSITIONAL PROVINCE
II - NORTHERN LOWER PENINSULA-EASTERN UPPER PENINSULA LACUSTRINE PROVINCE
III - WESTERN UPPER PENINSULA HIGHLAND PROVINCE
0 20 40 60 80 100
MILES
89°
T.E.N., 1965
83°

Figure 29

the Dfb subtype (see following section).

Region II receives heavy winter rainfall rather than the heavy snowfall of Region I. It also has more precipitation in the summer than the latter area, but, because of higher temperatures, evapotranspiration is greater. The large amount of winter rainfall is the distinctive climatic feature. Although the core of Region II is far to the south of the study area, its transition zone to Regions I and IV transects the southeastern section of the state. The area of heavy winter rainfall coincides approximately with the Koeppen Cfa (humid subtropical) region.

Region IV[1] is called the Prairie Wedge. It is characterized by (1) light winter rainfall and snowfall, (2) generally moderate-to-heavy summer rainfall, but occasional major droughts, (3) a strong importation of continental air from the base of the Rocky Mountains due to year-round mean westerly flow, and (4) natural vegetation of tall prairie grasses. The apex of the Prairie Wedge points toward the southern tip of Lake Michigan, but the region does not extend into the study area. However, the southwestern Lower Peninsula has a position transitional to Regions I, II, and IV. The remnants of prairie grass vegetation found in this section of the state may be related to a formerly expanded area of the Prairie Wedge.

In summary, the study area has a moderately continental, i.e., humid microthermal D-type macroclimate in the Koeppen system, and Borchert's "heavy winter snowfall-reliable summer rainfall" region is

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[1]Regions III and V are not discussed because they do not directly pertain to Michigan's climatic regionalization.

somewhat co-extensive. However, the transitional nature of the southern half of the Lower Peninsula in both thermal and moisture conditions is brought out in both classifications, and indicates that a major macroclimatic boundary must be recognized in the study area.

Mesoclimatic Provinces and Subprovinces

The third order of regional climatic differentiation is the mesoclimatic province. The provinces may be established on the basis of significant element gradients, and seasonality and variability characteristics of the major elements within the macroclimatic region. The principal mesoclimatic factors are:

1. differences in mean summer temperature, as indicated by the Da/Db boundary in the Lower Peninsula (see the 71.6° F. isotherm in Figure 29). The southern half of the Lower Peninsula is thus classified as Dfa (humid continental with warm summers) and the northern half of the Lower Peninsula and the Upper Peninsula are a part of the Dfb subtype (humid continental with cool summers). The fluctuations of this boundary from year to year are illustrated in Figure 28.[1] The temperature differences between northern and southern Michigan are primarily the result of steep gradients in frequencies of mT and cP air masses between Grand Rapids and Traverse City;
2. the various sections of the state are affected differently

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[1]See Jack Villmow, "The Position of the Koeppen Da/Db Boundary in the Eastern United States," Annals of the Association of American Geographers, Vol. 41, No. 1, 1952, Pp. 76-97.

by the Great Lakes because of relative location. In general the northern Lower Peninsula and eastern Upper Peninsula have a higher degree of Lake-control, while the southern Lower Peninsula and western Upper Peninsula have a higher degree of land-control;

3. precipitation regimes vary from area to area. The southern Lower Peninsula has a late spring-early summer maximum while the northern Lower Peninsula and eastern Upper Peninsula have late summer-early fall maxima. The western Upper Peninsula has precipitation maxima in early summer or mid-summer. The western Upper and southern Lower Peninsula also have somewhat greater mean annual precipitation than the lacustrine sections, but exhibit a greater interannual variability from year to year;
4. the higher elevations and greater local relief of the western Upper Peninsula are reflected in many of its mesoclimatic characteristics;
5. an important vegetational boundary is found in the study area, representing a change from broadleaf deciduous (oak-hickory association) forest in the south to mixed deciduous-coniferous (beech-birch-maple-hemlock) forest in the north. The boundary is shown in Figures 28 and 29;
6. the boundary between the gray-brown podzolic and podzol Great Soil Groups is located in close proximity to the aforementioned vegetational divide. Because of the strong relationships between climate, natural vegetation, and soils it may be

inferred that an important climatic change takes place in the vicinity of these lines;

7. patterns of residuals from regression (see Chapter IV) indicate significant regional variations with respect to the controls of temperature, precipitation, and snowfall, after the effects of latitude, elevation, and distance from a Great Lake have been removed.

On the basis of the above factors the study area has been divided into three mesoclimatic provinces (see Figure 29) which may be designated as follows:

I - Southern Lower Peninsula Transitional Province

II - The Northern Lower Peninsula-Eastern Upper Peninsula Lacustrine Province

III - The Western Upper Peninsula Highland Province.

Although each of the mesoclimatic provinces has a high degree of internal homogeneity, they all exhibit intraprovincial differentiations in greater or smaller measure. This is expressed in terms of significant variations in one or more climatic elements. The principal locational and terrestrial factors that cause contrasts within the provinces are: (1) relative proximity to a Great Lake with respect to prevailing winds; (2) differences in elevation; (3) a transitional position between two provinces; and (4) the local imposition of climatic factors centered outside the study area (e.g. climatic characteristics of the Prairie Wedge which are most evident in the southwestern Lower Peninsula). On the basis of these factors each province may be divided into a variable number of subprovinces as shown in Figure 29.

Description of Provinces and Subprovinces

Southern Lower Peninsula Transitional Province

The southern half of the Lower Peninsula has the greatest climatic variability of any part of the study area. In most years it has a Dfa regime, in some years it falls into the Dfb class, and occasionally it is grouped with the Cfa subtype. Borchert has shown that southern Michigan occupies a position intermediate to three different precipitation regions (see Figure 28). Figure 28 also illustrates that the characteristic vegetation of southern Michigan--oak-hickory--is coincident with the boundaries, or transition zones, of Regions I, II, and IV. Therefore, it seems appropriate to describe this area as a transitional province.

The Genetic Pattern

The more important climatic controls within this province are:

1. relatively close proximity to the polar front in winter, and strong weather activity during the front's northward migration in spring. However, the area lies well to the south of the polar front in summer;
2. a greater relative frequency of mT air masses during all seasons than in the more northerly sections of the state;
3. precipitation patterns are strongly influenced by the sL1 (southern Low through the Lakes) and n&eH (northern and eastern Highs with a stationary front through the study area) synoptic weather types;
4. with southerly flow of air there is a higher degree of

convectional activity than in the more lacustrine areas to the north; and

5. most of the province has low elevations and modest local relief so that contrasts in these terrestrial factors play only minor roles in the internal climatic differentiation.

The Elemental Pattern

The Southern Province has the highest mean annual temperatures of any part of the study area. Nearly all of the area has annual means in excess of 47° F., with some stations in the extreme southwest and southeast averaging temperatures above 50° F. In general, the province is milder in winter and warmer in summer than the other sections of the state, as may be ascertained from the thermal maps of Chapter II. Practically all of the transitional area has a frost-free period of at least 140 days, an indication of the more favorable thermal regime than most of the remainder of the state.

Mean annual precipitation within the province ranges from over 36 inches in the extreme southwest to less than 27 inches in the Saginaw Lowland. In general, it decreases eastward and northward. The southern Lower Peninsula has a greater extent of territory with over 34 inches of mean annual precipitation than the other provinces. The spring precipitation pattern is distinctive: the area clearly has much greater precipitation during this season than the other sections of the state. However, in the fall it is drier than the area to the north. In winter, precipitation varies from 4.5 inches to 6.5 inches, which is similar to the other provinces, but the area with over 6 inches is considerably larger than in the other sections. In summer, precipitation totals vary from approximately 8.0 inches to 11.0 inches; the area is wetter

than the lacustrine province to the north, but drier than the western Upper Peninsula. An important characteristic of the precipitation pattern is the high degree of variability which ranges from 14% to 22%, the highest in the state.

As far as solid precipitation is concerned, snowfall is relatively light compared to other sections of the study area, with annual values ranging from over 60 inches in the west to less than 30 inches in the east. However, the south has a greater frequency of hailstorms and freezing rains than the north. The transitional province also has more thunderstorms and more tornadoes, with the latter element-complex occurring much more frequently in the south than in the northern sections.

The Southern Lower Peninsula Transitional Province is divided into five subprovinces (see Figure 29), the most important characteristics of which are given in the following paragraphs.

Southern Lake Michigan-Lowland Subprovince.- The major characteristics of this subprovince are: (1) a strong effect from Lake Michigan, as indicated by the meridional orientation of isolines on many of the elemental maps of Chapter II; (2) very high precipitation variability in summer, with Benton Harbor having the highest coefficient of variation (75%) for July rainfall in the entire state; (3) much of the area has an annual snowfall of over 50 inches and a portion of it has over 60 inches, making this the snowiest part of Province I; (4) most of the subprovince has a mean annual temperature of over 49° F. It is one of the two warmest parts of the study area, the only other comparable section being the extreme southeast; (5) mean annual

precipitation of 31 to 36 inches is the greatest within its province, and is not exceeded elsewhere in the state. May precipitation exceeds 4.0 inches in the southern half of the area, but does not reach this total in any other part of the state; and (6) the frost-free season varies from over 170 days along the shore of Lake Michigan to slightly less than 150 days near the eastern boundary of the subprovince.

Southern Lower Peninsula Interior Subprovince.- The chief feature of the interior is its intermediate position between the outliers of two contrasting precipitation regions--the highly-variable summer rainfall type to the west and the winter-rainfall type to the east. Consequently, it receives more snowfall than the area to the east and slightly more winter rainfall than the area to the west. The southern part of this subprovince has the greatest mean February precipitation of any section of the study area except the Keweenaw Peninsula highlands (both have 2.0 to 2.2 inches). Its March and April precipitation are also among the highest in the state, being matched only in the Lake Michigan Lowland. In terms of mean spring precipitation the interior subprovince is the moistest part of the state with an extensive zone receiving from 9 to 10 inches. In the summer and, to a lesser extent, in the fall, precipitation patterns are marked by a decrease in amounts from southwest to northeast.

Thermal characteristics are indicative of the slightly higher degree of land-control in the interior. Absolute minimum temperatures of -22° F. are the lowest in the province. Mean minima of from 38-40° F. are also generally lower. For mean number of days with a minimum temperature of 0° F., or lower, the range is from about 5 to 10, or

nearly double that of most of the remainder of Province I. Land-control is best evidenced by the mean length of the frost-free season which varies from 145 days in the north to 155 days in the south, but nowhere approaches the 170 day period observed along the Great Lakes. Frequencies of thunderstorms, hailstorms, and tornadoes are not exceeded elsewhere in the study area.

Thumb Upland Subprovince.- The Thumb Upland is the most elevated part of southern Michigan and possesses the greatest average local relief. It is generally similar to the interior subprovince in its degree of continentality. The grain of the physiography is reflected in the southwestward bending isotherms of mean annual temperature. Most of the area has mean temperatures of less than 48° F. The upland is very clearly delineated on the temperature residual maps of Chapter IV.

With the exception of snowfall, precipitation follows no consistent pattern, and may be described as about average for the province. In the case of snowfall, however, the area stands out as a corridor of moderately heavier amounts. It is the only section of the southeastern quadrant of the state with snowfall means above 40 inches. In terms of variability of precipitation, as expressed by the coefficient of variation, its values of 16 to 18% are the lowest in the eastern half of the province.

Erie-St. Clair Lowland Subprovince.- Leeward position with respect to Lake Michigan, low elevations and local relief, occasional lacustrine effects with easterly winds, and a transitional location with respect to Borchert's "heavy winter rainfall" region to the south are the

principal terrestrial factors controlling the mesoclimate of this subprovince. Mean annual temperatures range from 48° F. to over 50° F., with the area thus being one of the two warmest in the state. In terms of mean length of frost-free season, most of the Erie-St. Clair Lowland has a period of at least 160 days, it being the only subprovince with a high percentage of its area having a frost-free season of this length.

As far as mean annual precipitation is concerned, amounts of 29 to 31 inches are average for the study area. During fall it is the driest part of the state with totals of less than 7.5 inches. In winter and summer it is near average, but the Lake St. Clair section is drier than the areas to the north and south in summer and is wetter in winter. In spring, like the remainder of southern Michigan, the area has amounts well above average for the state, with a steady decrease from south to north. Snowfall totals are generally lower than 35 inches, and the extreme southeast is the only part of the study area averaging less than 30 inches. The precipitation variability of 18 to 22% is very high.

Saginaw Lowland Subprovince.- The cellular pattern of climatic phenomena in the Saginaw Lowland stands out clearly on most of the analyses and maps presented earlier. The principal topoclimatic factors are the low, flat terrain in a basin setting, with the Saginaw Bay providing limited lacustrine influence. The area invariably has above average temperatures for its latitudinal position. Annual means of 48° F. are typical, while to the east and west temperatures as low as 46° F. occur. In terms of mean number of days with maximum temperature

of at least 90° F., frequencies in the lowland exceed 18, whereas stations on Lake Michigan have only 6 days and on Lake Huron only 10 days. The frost-free season is generally between 150-160 days while the surrounding area has less than 150 days.

The mean annual precipitation of 27-29 inches is below average for the study area. With the exception of the eastern Northern Upland, this is the only part of the state that has precipitation amounts below the state-wide average in every season. Coefficients of variation from 18 to 20% indicate a high degree of precipitation variability.

The Northern Lower Peninsula-Eastern Upper Peninsula Lacustrine Province

Province II is more nearly surrounded by the water of the Great Lakes than are the other sections of the state. Northward traveling mT or NcP air masses reach this area only after experiencing modifying effects due to passage over the Great Lakes. Quasi-maritime, or lacustrine, control of precipitation is stronger in this Province than in the remainder of the study area. The lacustrine control of climate is one of the primary factors responsible for the lesser degree of precipitation variability in this area. It also accounts for the delay in the period of maximum precipitation until late summer or early fall. It is rare that a station within the lacustrine province would not experience a D-climate regime of the Dfb subtype. Winters are more consistently long and snowy than they are in the southern transitional province.

The Genetic Pattern

The most important climatic controls within this area are:

1. the relative strength of the lacustrine effect due to Lake proximity, as discussed in the preceding paragraphs. Expecially on the periphery of the province, Lake control is pronounced throughout the year, as evidenced by the labilization of air masses during fall and winter and their stabilization during spring and summer;
2. the northward migration of the polar front in late spring, with the consequent increase in cyclonic activity, does not augment the precipitation of the area as greatly as it does that of the more continental (southern and western) parts of the state. However, the equatorward migration of the front in early fall has greater influence on it because of the labilizing effects of warm water;
3. precipitation patterns throughout the year are strongly influenced by the highly reliable mLl (Montana Low through the Lakes) synoptic weather type, the center of which tends to pass directly through the province, and which may be a major reason for its low precipitation variability. The relatively heavy fall precipitation is partially accounted for by the presence of the neH (New England High) system which yields more rainfall in this area than in the other parts of the state;
4. rather large intraprovincial variations of the climatic elements are the result of substantial differences in elevation and local relief. In particular, the Northern Upland stands out as an area with much more pronounced topographic

controls than the remainder of the province.

The Elemental Pattern

Most of the territory of the lacustrine province has mean annual temperatures between 40° F. and 47° F. In all months thermal patterns are definitely related to lacustrine and elevational controls, which, however, are best evidenced in winter and fall. Despite the high degree of lacustrine influence for the area as a whole, the highest absolute maximum and the lowest absolute minimum temperatures of the state were recorded in the province. That they occurred in the heart of the Northern Upland points to that area as an enclave of strong land-control of temperature. Temperature differences between the Northern Upland and the other sections are further emphasized by consideration of the frost-free season. The lowland (or Lake-periphery) areas have from 120 to 140 frost-free days per year on the average, while the uplands have only 120 to less than 80 days.

Precipitation values range from approximately 34 inches in the Munising area to 26 inches on the lee (eastern) side of the Northern Upland. In general, they are greatest in windward (northern and western) areas and least in leeward (eastern and southern) areas. In spring and summer this is the driest part of the study area, while, in the fall, it is the wettest. During winter the sections with a strong Lake-effect have above average precipitation for the study area while leeward areas have only average precipitation. Precipitation variability is the lowest in the study area as evidenced by the coefficients of variation ranging from 10 to 14%.

Snowfall is considerably heavier than in the area to the south

and only slightly less than that to the west. Totals range from over 120 inches in the Munising-Grand Marais area to less than 50 inches northwest of Saginaw Bay. Windward, elevated, and northern sites are favored while leeward, low, and southern locations record lesser amounts. Other forms of frozen precipitation--hail, freezing rain, and sleet--are relatively rare. Tornadoes occur occasionally (especially on the eastern side of the Northern Upland) but are less frequent than in the southern part of the study area.

Province II is divided into 9 subprovinces, indicative of its somewhat larger size, greater physiographic variations, and its separation into two disjunct segments, the Upper and Lower Peninsulas. The principal characteristics of the subprovinces are given in the following paragraphs.

Northern Lake Michigan Subprovince.- The principal genetic factor controlling the local climate in this area is close proximity to Lake Michigan. Thermal characteristics, in particular, show the effects of Lake modification. Mean annual temperatures vary from 47° F. adjacent to the water to 43° F. at the interior margins. In all months and for nearly all thermal parameters there is a steep gradient between Lakeshore and interior, although the direction of slope is reversed from summer to winter. For example, the mean length of the frost-free season changes from as much as 170 days along the Lake Michigan shore to as little as 120 days on the eastern periphery of the subprovince. Absolute maximum temperatures, however, are only 100° F. along the coast, but rise to 106° F. in the interior. Coefficients of continentality, which are as low as 35% adjacent to the shoreline, indicate the relative

strength of the lacustrine effect in this area.

The mean annual precipitation of 29-32 inches is slightly above average for the province and for the study area as a whole. In the fall much of the subprovince has more than 9.5 inches and a part exceeds 10.0 inches; it is one of the moistest sectors of the state at this time. In the spring and summer, however, it is relatively dry having generally less than 8.0 inches in the former period and less than 9.0 inches in the latter period. In the winter total precipitation as well as snowfall are average for most of the area and slightly above average in the extreme northwest. Coefficients of variation of precipitation ranging from 12-14% are the lowest in the Lower Peninsula.

Central Lower Peninsula Interior-Transition Subprovince.- The zone between Province I and the Northern Upland Subprovince is characterized by steep latitudinal temperature gradients. Mean annual temperature decreases from 47° F. in the south to less than 45° F. in the north within a latitudinal distance of about 25 miles. Relatively steep thermal gradients are also indicated in January, April, July, and October. The thermal gradient is further evidenced by the change from 155 days per year with a minimum temperature of 32° F., or lower, in the south to 175 days in the north. In terms of moisture patterns the subprovince lacks distinctiveness, for its total precipitation of 29-30 inches and its snowfall of 40-60 inches are average for this section of the state.

Northern Lake Huron Subprovince.- Because of the prevalence of westerly winds the Northern Lake Huron Subprovince is genetically on the leeward side of the state. The area does experience a lacustrine

effect, but of lesser magnitude than its counterpart, the Northern Lake Michigan Subprovince. Mean annual temperatures for most of the area are between 43-45° F. It is the coolest lacustrine area in the Lower Peninsula. As usual in an area adjacent to a Great Lake, thermal transition from shore to interior is rapid. For example, absolute minimum temperatures are as high as -22° F. near Lake Huron but decrease to as low as -38° F. at the western margins.

Precipitation is relatively light. Annual averages range from 27 to 29 inches, this being the driest Lake-shore region in the Lower Peninsula. In winter and spring, precipitation decreases slightly toward the interior, but, in summer, when the entire subprovince has less than 9.0 inches, rainfall increases toward the center of the Peninsula. In the month of June most stations within the subprovince receive less than 2.8 inches, and it is the driest section of the state. Precipitation variability is higher in the south (as great as 18%) than in the north (as little as 12%).

Southern Lake Huron Subprovince.- The tip of the Thumb is enclosed by Saginaw Bay on the west and Lake Huron on the east. Nevertheless, it is on the leeward side of the state with respect to prevailing winds, and its degree of lacustrine control is, therefore, less than might be expected. The principal characteristics of the area are: (1) a relatively high snowfall of 45-55 inches; and (2) low temperatures in terms of latitudinal position, as exemplified by mean annual values of less than 47° F. In April and July, temperature means decrease by more than 2° F. from the southern boundary to the tip of the Thumb. The coefficients of variation of 20 to 21% for mean annual precipitation are the

highest in Province II.

Northern Upland Subprovince.- Topographically, the Northern Upland is dominated by high elevations and a rim of hills with appreciable local relief. Its interior is the most significant enclave of land-controlled mesoclimate within the lacustrine province, as proven by its records for both absolute maximum (110° F. at Mio) and absolute minimum (-51° F. at Vanderbilt) temperatures. Therefore, here we have the largest absolute temperature range and the most continental climate in the state (in the traditional sense). On a large share of the elemental maps the isolines have cellular patterns which conform to physiographic features. Mean annual temperatures decrease centripetally from about 45° F. at the rim to 42° F. at the core. The steepest thermal gradients occur in January when temperatures average over 22° F. on the periphery and less than 18° F. near the center. The length of the frost-free season varies from 120 days at the edge to less than 80 days at the center.

Precipitation varies considerably within the subprovince. In general, the decrease is from west to east with extremely steep gradients in the south-central section. The occidental sections, with 30-32 inches, have average to slightly above average precipitation, whereas the east, with 26-30 inches, is one of the drier parts of the state. The eastern section is one of the two parts of the study area (the other being the Saginaw Lowland) having below average precipitation in every season. The western portion has fairly heavy rainfall in summer and fall, but is nearly as dry as the eastern during winter and spring. Coefficients of precipitation variation of 12-18% are the highest in

the northern Lower Peninsula, with the maximum values occurring in the Cadillac-Fife Lake-Lake City triangle.

Western Northern-Upland Subprovince.- In terms of physiography and the majority of climatic elements this area is similar to the previously discussed Northern Upland Subprovince. However, the combination of high hills and windward position with respect to Lake Michigan is responsible for the greatest amounts of snowfall in the Lower Peninsula, with means exceeding 100 inches. In November, December, and January total precipitation is significantly higher on the western rim than over the remainder of the Northern Upland.

Eastern Upper Peninsula Subprovince.- Terrestrial effects upon the climate of this area comprise a combination of strong land-control and marked lacustrine influences. To the northeast lies a large landmass, and to the northwest Lake Superior provides the longest fetch of water for any part of the state when winds are northwesterly. Easterly winds (off-shore flow) are characteristic in the winter and northwesterly winds (prevailing westerlies reinforced by on-shore flow) are common in the summer. The two wind systems combine to produce the lowest temperatures in any lowland section of the state. The mean annual temperatures of less than 40° F. are equalled only in the core of the Northern Highlands where elevations are 1000 feet higher. With prevailing northwesterly winds this is probably the most lacustrine part of the study area, as evidenced by the mean annual relative humidity, mean number of cloudy days, and frequency of days with dense fog, all of which reach maximum values in this area. Coefficients of continentality of only 35% are among the lowest in the study area. The strength of the lacustrine

effect is also indicated by coefficients of variation for precipitation of less than 10%, the lowest in the state.

With prevailing easterly winds mean winter temperatures are low. January means vary from 15° F. to 17° F. and are the lowest in the lacustrine province. The values of 29-31 inches for annual precipitation are average for the study area. However, in fall and winter the amounts are somewhat greater than the statewide normals while in spring and summer they are lower. The combination of low temperatures, high humidity, fogginess, and minimal precipitation variability is unique.

Munising-Grand Marais Subprovince.- The location of this area with respect to Lake Superior and the moderately high elevations and local relief are the chief terrestrial factors controlling the local climate. Elementally, the most important characteristics are heavy snowfall, steep snowfall gradients, and the greatest mean annual precipitation within the province. Snowfall totals reach their maximum values of 130 inches about 25 miles from Lake Superior, and decrease to 100 inches along the Lake and the southern margins. Mean annual precipitation is particularly high in the vicinity of Munising where it exceeds 34 inches. However, it decreases to 30 inches in the east. Fall (9-10 inches) and winter (6.0-6.5 inches) have above average precipitation for the study area, but spring (6.5-7.5 inches) and summer (8.0-9.5 inches) have below average rainfall.

In terms of thermal characteristics the subprovince has the lowest mean maxima (48-50° F.) for the entire state, and is one of the few areas where absolute maxima of less than 100° F. occur. In spring and summer it is the coolest part of the study area; April temperatures vary

from 36° F. to 38° F. and July means range from 62° F. to 65° F. In winter, however, it is a relatively warm section of the Upper Peninsula, as evidenced by the mean temperatures of 18-20° F. The frost-free season, which reaches maximum frequencies of 140 days adjacent to Lake Superior, is as long as that of the extreme southern-interior portion of the lacustrine province.

East-Central Upper Peninsula Interior Subprovince.- The remaining area of the eastern Upper Peninsula may be classified as an interior subprovince, although its southern boundary is marked by the water of Lakes Michigan and Huron. Despite proximity to the Great Lakes the modification due to the Lake-effect is moderate because of the relatively low prevalence of southerly winds in the northern part of the state.

The most important climatic characteristics are: (1) relatively low snowfall totals for the eastern Upper Peninsula, with amounts ranging from 60 to 100 inches; (2) average to below average mean annual precipitation (27-31 inches); (3) mean annual temperatures of 41-43° F., the highest in the Upper Peninsula; (4) fairly dry winters and springs, but average precipitation during summer and fall. The thermal characteristics are markedly similar to the Munising-Grand Marais Subprovince.

The Western Upper Peninsula Highland Province

Although in the same latitude as the northern half of Province II, in terms of location relative to land and water the western Upper Peninsula is similar to Province I, and consequently has a lesser degree of lacustrine control than the northern Upper Peninsula and eastern Lower Peninsula. Its higher elevations differentiate it from both Province I and Province II. Latitude and elevation assure that in

every year without exception the highland province is classified as a D climate, and in most years with the Dfb subtype.

The Genetic Pattern

As far as the terrestrial control of land and water is concerned, the western Upper Peninsula bears strong resemblance to the southern Lower Peninsula. Like the transitional province this area opens to the south with no intervening water to stabilize mT or NcP air masses moving northward in the late spring or early summer. With southerly or southwesterly air flow the degree of land control is thus higher than in the northern Lower Peninsula and eastern Upper Peninsula.

The polar front is normally too far equatorward to strongly affect the area during the winter. However, northern Lows traveling along the arctic front have greater influence here than in the more southerly sections of the state. In late spring or early summer the polar front migrates poleward through the province and causes heavy precipitation which is augmented by strong convectional activity. In the fall when the polar front migrates equatorward, the relative lack of lacustrine effects decreases the amount of precipitation received in comparison to the areas to the east.

Because of closer proximity to the source regions of cP and cA air masses, the province has a higher frequency of cold days than the areas to the south and east. If northern air masses approach the western Upper Peninsula from the north or northwest they are significantly modified by the water of Lake Superior. However, particularly with the nHs (Northern High to the South of the Great Lakes) synoptic situation, cA and cP may enter from the southwest with no lacustrine

modification, and, in winter, produce very cold and dry atmospheric conditions.

The Elemental Pattern

The high elevation and appreciable local relief of the western Upper Peninsula have a significant influence on temperature and precipitation. Orographic precipitation is greater than in other parts of the state, but is typical of winter only and normally occurs in conjunction with the Lake-effect. Rainshadow or snowshadow areas are better defined than in the remainder of the study area, and many of the elements exhibit steep gradients, as, for example, snowfall, length of frost-free season, and absolute minimum temperatures.

The mean annual temperatures of stations within Province III range from less than 40° F. to about 42° F. The relatively low temperatures of the interior areas during winter are somewhat compensated for by the higher temperatures of summer. The core of the province has January means of less than 14° F., the lowest in the study area. Along the shores of Lake Superior, however, temperatures rise to 19° F. By April mean temperatures in the western Upper Peninsula (40-42° F.) are slightly higher than in the eastern Upper Peninsula and about the same as in the northern Lower Peninsula. In July the west continues to be the warmest half of the Upper Peninsula, but in October the winter pattern becomes evident again and the eastern section is warmer.

Mean annual precipitation ranges from 30 to 36 inches. In terms of seasonal precipitation, summer is the dominant period. The total precipitation for June, July, and August is over 11.5 inches at about half the stations in the western Upper Peninsula, and several stations

in the southwestern interior receive over 13.0 inches, well above the amounts received elsewhere in the state during any season. In winter and fall the more elevated, windward areas have above average precipitation while the less elevated, leeward areas receive below average precipitation. In spring the pattern resembles that of summer except that the totals are considerably lower.

Snow is the dominant form of solid precipitation. The Province receives exceptionally large amounts but also has great intraprovincial variability. Means range from 160 inches in the Keweenaw Peninsula-Porcupine Mountain-Gogebic Range area to only 50 inches in the extreme southeast, for a very large difference of 110 inches. Other forms of solid precipitation are relatively rare, especially freezing rain and sleet because of the limited occurrence of occluded or warm fronts during the winter. Despite the lack of a strong lacustrine effect in the summer, tornadoes are rare (only 4 occurrences during the period 1953-1958).

The Western Upper Peninsula Highland Province is divided into five subprovinces which are discussed in the following paragraphs.

Ishpeming-Escanaba Transition Subprovince.- The narrow corridor extending north-south from Ishpeming to Escanaba is transitional with respect to the eastern and western Upper Peninsula climatic provinces. The chief characteristic that differentiates it from both of these areas is the precipitation regime. The area has the unique distinction of being the only section of the study area recording its maximum precipitation in mid-summer. In July and August it is marked by fairly steep precipitation gradients between the above average rainfall of

the west and the below average rainfall of the east. The transition zone has July and August averages of from 3.2 to 3.8 inches of precipitation, whereas to the west the maximum amounts exceed 4.0 inches and to the east the minimum amounts are less than 2.6 inches.

Keweenaw Bay-Western Lake Superior Lowland Subprovince.- The Keweenaw Peninsula is flanked by a narrow lowland which, because of its low elevations and proximity to Lake Superior, differs in several important climatic respects from the other western Upper Peninsula subprovinces. Although the snowfall of 90 to 110 inches is substantial it is less than occurs slightly farther inland at higher elevations. The mean annual precipitation of 30-32 inches is slightly above average for the state as a whole. Summer is the season of maximum precipitation, but with amounts of 10-11 inches it is slightly drier than most of the territory within its province. The winter precipitation is normal for the study area, but spring is a period of below average rainfall. In the fall the Keweenaw Bay area has average precipitation whereas the western littoral is relatively dry. The precipitation variability of 15-16% is higher than the typical values for the Upper Peninsula.

Thermal characteristics are also well marked. In general, summer temperatures are lower and winter temperatures are higher than elsewhere in the province. The mean annual temperature of approximately 42° F. is exceeded in the Upper Peninsula only by the extreme southern fringes along Lakes Michigan and Huron. In terms of mean number of days with a minimum temperature 0° F., or below, frequencies vary from 18 to 26, a lesser number than farther inland. For mean number of days with a maximum temperature of 90° F., or above, values range from 2 to 6,

whereas 4 to 8 "tropical" days are more common in the interior. The amelioration of extremes in comparison to inland areas is indicated by the range of mean maximum temperatures (49-51 F.°) and mean minimum temperatures (32-34 F.°). The frost-free season of 120 to 140 days is considerably longer than in the interior of the province.

Western Northern-Highland Subprovince.- The western periphery of the Northern Highlands (Keweenaw Peninsula-Porcupine Mountains-Gogebic Range area) is the largest, most clearly defined snowbelt in the state of Michigan. Total annual snowfall in this northeast-southwest trending area varies from 110 to 160 inches, the highest averages in the study area. On its lee, or southeastern, side snowfall gradients are the steepest in the state with a decrease of 100 inches occurring within 120 miles. It is the only part of Michigan that receives over 7 inches of precipitation in winter (December, January, and February). However, only 40 miles southeastward from the core of the subprovince, winter precipitation decreases to half that amount.

The mean annual precipitation of 31-36 inches is among the highest in the state. There is no season in which the entire area is dry relative to other parts of Province III, although in spring the southern third has 8.0-8.5 inches, which is greater than average, and the northern third has 6.5-7.0 inches, which is less than the statewide average. In summer and fall the subprovince is characterized by either above or near average precipitation in comparison to other sections of the study area.

Thermally, the area stands out as a transitional zone between the lacustrine sectors to the west and north and the land-controlled interior to the southeast. Consequently, isotherms and frequency isolines tend

to be closely spaced. Mean annual temperatures decrease from 42° F. to 40° F. The length of the frost-free season changes from 125 days in the west to 100 days in the east. Mean number of days with a minimum temperature of 0° F., or below, increases from 22 to 34, and mean number of days with a minimum temperature of 32° F., or below, increases from 180 to 190.

Huron Mountains Subprovince.- The Huron Mountains are a group of high hills situated between Keweenaw Bay and Marquette. The outstanding terrestrial control in the local climate is the possibility of orographic effects because of the elevation and proximity to Lake Superior, although its position within the rainshadow of the Keweenaw Peninsula highlands has to be considered. The principal climatic association is the existence of a minor (i.e., in terms of area and amounts) snowbelt, which receives moderate snow with northwesterly winds, but may experience heavy snowfalls with the occasional dominance of northeasterly air currents. Annual snowfall averages 100-120 inches. The mean annual precipitation is 30-33 inches, or slightly above normal for the study area. Thermally, the area is similar to the Western Northern-Highland Subprovince in that it is a transition zone between the lacustrine coast and the land-controlled interior. For example, the length of the frost-free season varies from 130 days along the Lake Superior shore to 110 days on the southern margins, and the mean number of days with maximum temperatures of 90° F., or above, increases from 2 to 7.

Western Upper Peninsula Interior Subprovince.- The interior of the western Upper Peninsula is characterized by a limited degree of lacustrine modification in comparison with other sections of Province

III. It is, therefore, more subject to extremes, as evidenced by its mean July temperatures of over 66° F. and its mean January temperatures of 12-16° F., the lowest in the state. The subprovince is in the rain-shadow of the Keweenaw Peninsula-Gogebic Range highland and the Huron Mountains, and tends to be somewhat drier than these areas. However, its precipitation patterns are complex. In winter its precipitation of 3.5-5.0 inches is the lowest in the state. In spring values range from 7 to 8 inches which is average for the study area. In summer the interior is very wet, with amounts of 11-13 inches being the greatest in the study area for any season. In fall precipitation totals 7.5-9.0 inches, and, again, it is a relatively dry area.

The outstanding climatic characteristic of the interior is the low snowfall totals in comparison to other sections of the province. Snowfall varies from over 100 inches to less than 50 inches with a steady decrease in a southeasterly direction. Thus a very small section in the southeast of the subprovince receives less snow in the average year than the Kalamazoo-Allegan-Bloomingdale area in the southwestern Lower Peninsula.

Mean annual temperatures vary from over 42° F. to less than 40° F., with the area enclosed by the latter isotherm being one of the two coldest sections of the state. Mean minimum temperatures of 28-32° F. are the lowest in the study area, but the mean maximum temperatures of from 52 to 54° F. are the highest in the Upper Peninsula. The frost-free season of 120 to 70 days is the shortest in the state with the exception of that in the Northern Upland Subprovince of Province II, and shows very rapid change from the periphery to the core. The extreme thermal

characteristics of this area are also indicated by the highest coefficients of continentality (47%) for the entire study area.

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APPENDIX A

List of Weather Stations Used

in Temperature Analyses

(1931-1960)

	Station	County	Years of Record (to 1960)
1.	Adrian	Lenawee	83
2.	Allegan	Allegan	72
3.	Alma	Gratiot	74
4.	Alpena AP	Alpena	43
5.	Ann Arbor	Washtenaw	81
6.	Bad Axe	Huron	36
7.	Battle Creek	Calhoun	77
8.	Bay City	Bay	65
9.	Bergland Dam*	Ontonagon	28
10.	Big Rapids	Mecosta	65
11.	Bloomingdale	Van Buren	57
12.	Cadillac	Wexford	52
13.	Caro	Tuscola	33
14.	Charlotte	Eaton	57
15.	Cheyboygan	Cheyboygan	71
16.	Chatham	Alger	56

*Missing records interpolated or estimated by U.S. Weather Bureau.

	Station	County	Years of Record (to 1960)
17.	Coldwater	Branch	54
18.	Detroit WBAP City	Wayne	90
19.	Detroit WBAP Wayne*	Wayne	4
20.	Dunbar*	Chippewa	18
21.	Eagle Harbor	Keweenaw	41
22.	East Jordan	Charlevoix	35
23.	East Tawas	Iosco	66
24.	Eau Claire	Berrien	37
25.	Elberta (Frankfort)	Benzie	58
26.	Escanaba	Delta	40
27.	Evart*	Osceola	9
28.	Fayette	Delta	40
29.	Fife Lake	Grand Traverse	42
30.	Flint	Genesee	72
31.	Germfask*	Schoolcraft	21
32.	Gladwin	Gladwin	56
33.	Grand Haven	Ottawa	90
34.	Grand Marais	Alger	61
35.	Grand Rapids	Kent	56
36.	Grayling	Crawford	71
37.	Greenville	Montcalm	48
38.	Gull Lake	Kalamazoo	32
39.	Hale Loud Dam	Iosco	48
40.	Harbor Beach 3NW	Huron	74
41.	Harrisville	Alcona	81

	Station	County	Years of Record (to 1960)
42.	Hart	Oceana	71
43.	Hastings	Barry	68
44.	Higgins Lake	Crawford	60
45.	Hillsdale	Hillsdale	64
46.	Holland	Ottawa	56
47.	Houghton FAA AP*	Houghton	8
48.	Houghton Lake	Roscommon	46
49.	Ionia	Ionia	30
50.	Iron Mountain	Dickinson	61
51.	Ironwood	Gogebic	59
52.	Ishpeming	Marquette	62
53.	Jackson	Jackson	64
54.	Kalamazoo St. Hosp.	Kalamazoo	85
55.	Kenton*	Houghton	20
56.	Lake City	Missaukee	43
57.	L'Anse*	Baraga	22
58.	Lansing*	Ingham	12
59.	Lapeer*	Lapeer	17
60.	Ludington 4 SE	Mason	64
61.	Mackinaw City	Cheyboygan	70
62.	Manistee	Manistee	66
63.	Manistique*	Schoolcraft	24
64.	Marquette	Marquette	89
65.	Midland	Midland	59
66.	Milford	Livingston	33

	Station	County	Years of Record (to 1960)
67.	Mio	Oscoda	57
68.	Monroe	Monroe	44
69.	Mount Clemens	Macomb	61
70.	Mount Pleasant	Isabella	60
71.	Munising	Alger	64
72.	Muskegon	Muskegon	65
73.	Newaygo	Newaygo	53
74.	Newberry	Luce	62
75.	Onaway	Presque Isle	32
76.	Ontonagon	Ontonagon	30
77.	Owosso	Shiawassee	65
78.	Paw Paw	Van Buren	40
79.	Pellston*	Emmet	19
80.	Pontiac	Oakland	73
81.	Port Huron	St. Clair	86
82.	Rexton*	Mackinac	27
83.	Saginaw FAA AP	Saginaw	64
84.	Sandusky	Sanilac	42
85.	Sault Ste. Marie	Chippewa	72
86.	South Haven	Van Buren	65
87.	Stambaugh	Iron	65
88.	Stephenson*	Menominee	21
89.	Three Rivers	St. Joseph	64
90.	Traverse City FAA AP	Grand Traverse	66
91.	Vanderbilt	Otsego	48

	Station	County	Years of Record (to 1960)
92.	Watersmeet*	Gogebic	22
93.	West Branch	Ogemaw	58
94.	Whitefish Point	Chippewa	51
95.	Willis	Washtenaw	31

List of Additional Stations Used

in Precipitation Analyses

(1931-1960)

	Station	County	Years of Record (to 1960)
1.	Albion	Calhoun	51
2.	Atlanta	Montmorency	34
3.	Baldwin	Lake	33
4.	Benton Harbor	Berrien	78
5.	Detour	Chippewa	30
6.	Harrison	Clare	54
7.	Kalkaska*	Kalkaska	21
8.	Kent City	Kent	41
9.	Kincheloe Air Force Base*	Chippewa	7
10.	Petosky*	Emmet	8
11.	Saint Ignace*	Mackinac	16
12.	Scottville	Mason	36
13.	Spaulding*	Menominee	7
14.	Suttons Bay*	Leelanau	21
15.	Wellston Tippey Dam	Manistee	40

List of Stations Used in Regression and Correlation Analyses of Chapter IV (1949-1961)

1. Adrian
2. Albion[a]
3. Allegan
4. Alma
5. Alpena[b]
6. Battle Creek
7. Bay City
8. Benton Harbor[b]
9. Big Rapids
10. Cadillac
11. Chatham
12. Coldwater
13. Detroit
14. Dunbar
15. Eagle Harbor[c]
16. East Jordan[b]
17. East Lansing
18. Escanaba
19. Flint
20. Gladwin
21. Grand Marais
22. Harbor Beach
23. Harrisville
24. Hart
25. Higgins Lake
26. Hillsdale
27. Holland
28. Ironwood
29. Ishpeming
30. Jackson
31. Kalamazoo
32. Kenton[b]
33. L'Anse[a]
34. Manistee
35. Marquette
36. Mio
37. Monroe
38. Mt. Clemens
39. Munising
40. Muskegon
41. Newberry
42. Onaway
43. Ontonagon
44. Owosso
45. Port Huron[b]
46. Saginaw
47. Sandusky
48. Sault Ste. Marie
49. South Haven
50. Stambaugh
51. Stephenson
52. Suttons Bay[a]
53. Three Rivers
54. Traverse City
55. Vanderbilt

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[a]not used in temperature analyses

[b]not used in snowfall analyses

[c]not used in temperature or snowfall analyses

TABLE I

DIFFERENCE OF MEANS TESTS[1] FOR NUMBER OF HIGHS AND LOWS PASSING THROUGH MICHIGAN (1951-1960)

High Pressure Systems

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Jan.	0											
Feb.	.40	0										
Mar.	.21	.58	0									
Apr.	.22	.16	.42	0								
May	2.76*	2.57*	2.50*	2.88*	0							
Jun.	2.79*	2.60*	2.58*	2.90*	.14	0						
Jul.	3.02*	2.69*	2.73*	3.15*	0	.15	0					
Aug.	2.81*	2.61*	2.59*	2.98*	0	.14	0	0				
Sep.	2.55*	2.35*	2.28*	2.68*	.30	.44	.32	.31	0			
Oct.	2.00*	1.91*	1.75*	2.14*	.76	.87	.80	.77	.47	0		
Nov.	1.28	.65	1.43	1.04	3.67*	3.65*	4.00*	3.80*	3.45*	2.98*	0	
Dec.	1.27	.73	1.38	1.05	3.43*	3.48*	3.65*	3.48*	3.28*	2.81*	.17	0

[1]For a description of difference of means tests and the use of the t-statistic, consult Wilfred J. Dixon and Frank J. Massey, Jr., Introduction to Statistical Analysis, (New York: McGraw-Hill, 1957), Pp. 112-124.

Note: * equals significant difference; level of significance equals .05.

TABLE I -- Continued

Low Pressure Systems

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Jan	0											
Feb.	1.30	0										
Mar.	1.41	0	0									
Apr.	2.29*	1.06	1.27	0								
May	1.93*	1.01	1.09	.40	0							
Jun.	3.30*	2.36*	2.74*	1.67	.57	0						
Jul.	4.73*	4.08*	4.70*	3.69*	1.87*	1.97*	0					
Aug.	3.47*	2.63*	2.96*	2.02*	.91	.53	1.27	0				
Sep.	3.76*	2.90*	3.45*	2.28*	.88	.48	1.62	.14	0			
Oct.	3.05*	2.10*	2.36*	1.59	.55	0	1.75*	.48	.41	0		
Nov.	2.17*	.91	1.09	.19	.50	1.86*	3.91*	2.17*	2.50*	1.57	0	
Dec.	1.56*	.26	.31	.79	.85	2.14*	3.92*	2.44*	2.69*	1.90*	.63	0

TABLE II

DIFFERENCE OF MEANS TEST FOR TEMPERATURES OF AIR MASSES (JANUARY)

Detroit

	cA	cP	NcP	mP	mT
cA	0				
cP	8.50*	0			
NcP	11.60*	2.11*	0		
mP	10.71*	2.25*	0.7	0	
mT	12.75*	2.55*	0.5	1.20	0

Sault Ste. Marie

	cA	cP	NcP	mP	mT
cA	0				
cP	8.93*	0			
NcP	9.72*	3.13*	0		
mP	11.09*	3.51*	0.71	0	
mT	10.12*	5.14*	0.65	4.16	0

Note:

* equals significant difference; level of significance equals .05.

TABLE III

DIFFERENCE OF MEANS TESTS FOR TEMPERATURES
OF WEATHER TYPES (JANUARY)

Detroit

	aLn	aL1	mL1	sL1	gLe	nHn	nHs	wH1	n&eH	nH1
aLn	0									
aL1	.8	0								
mL1	.9	.2	0							
sL1	.4	.4	.3	0						
gLe	.1	.8	1.1	.5	0					
nHn	4.3*	2.3*	3.6*	3.1*	4.6*	0				
nHs	13.1*	7.2*	12.2*	9.2*	14.5*	7.9*	0			
wH1	2.4*	.4	1.2	1.1	2.9*	3.3*	15.1*	0		
n&eH	.8	1.3	1.6	1.0	.8	4.5*	11.6*	2.8*	0	
nH1	9.0*	4.5*	8.1*	6.1*	10.2*	2.6*	5.3*	10.1*	8.2*	0

Sault Ste. Marie

	aLn	aL1	mL1	sL1	gLe	nHn	nHs	wH1	n&eH	nH1
aLn	0									
aL1	2.7*	0								
mL1	1.6	1.3	0							
sL1	1.1	1.6	.4	0						
gLe	1.4	1.1	.1	.5	0					
nHn	5.7*	1.8*	3.5*	3.9*	3.1*	0				
nHs	12.0*	3.8*	6.6*	7.1*	5.5*	1.8*	0			
wH1	2.2*	1.1	.3	.7	.1	3.4*	7.1*	0		
n&eH	1.4	.1	.8	.9	.7	1.0	1.9*	.6	0	
nH1	15.1*	3.4*	6.6*	7.3*	6.6*	1.3	1.1	6.9*	1.6	0

Note:

* equals significant difference; level of significance equals .05.

TABLE IV

CHI SQUARE[1] TESTS FOR RELATIVE FREQUENCY OF WEATHER TYPES DURING THE PERIODS 1953-1957 and 1958-1962

January

	fo	fe	fo-fe	$(fo-fe)^2$
aLn	12	10	2	4
aL1	16	20	-4	16
mL1	27	26	1	1
sL1	18	12	6	36
gLe	10	16	-6	36
nHn	18	32	-14	196
nHs	42	28	14	196
wH1	4	3	1	1
neH	0	2	-2	4
n&eH	4	4	0	0
nH1	2	0	2	4
	153	153		

X^2 equals 25.29 (95% level equals 14.1)

April

fo	fe	fo-fe	$(fo-fe)^2$
10	12	-2	4
1	3	-2	4
29	36	-7	49
34	34	0	0
2	1	1	1
9	7	2	4
26	20	6	36
14	8	6	36
0	0	0	0
14	16	-2	4
11	13	-2	4
150	150		

X^2 equals 11.49 (95% level equals 14.1)

July

	fo	fe	fo-fe	$(fo-fe)^2$
aLn	24	27	-3	9
aL1	2	2	0	0
mL1	32	29	3	9
sL1	1	0	1	1
gLe	0	0	0	0
nHn	5	9	-4	16
nHs	7	7	0	0
wH1	18	11	7	49
neH	0	0	0	0
n&eH	30	40	-10	100
nH1	36	30	6	36
	155	155		

X^2 equals 11.58 (95% level equals 12.6)

October

fo	fe	fo-fe	$(fo-fe)^2$
17	27	-10	100
3	7	-4	16
32	15	17	289
12	5	7	49
0	12	-12	144
12	15	-3	9
8	7	1	1
45	41	4	16
13	17	-4	16
9	8	-1	1
3	0	3	9
154	154		

X^2 equals 58.26 (95% level equals 14.1)

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[1]For a description of the chi-square statistic see Walker and Lev, op. cit., Pp. 81-108.

Note: X^2 equals $(fo-fe)^2/fe$; fo represents frequencies for the 1958-1962 period, and fe represents frequencies for the 1953-1957 period; level of significance equals 95%.

APPENDIX C

Explanation of the Multiple Regression and Correlation Analyses of Chapter IV

The multiple regression equations developed in Chapter IV express a functional relationship between a dependent variable (in this case a climatic element) and a set of three independent variables (the terrestrial factors). The equations are of the form:

$$Y_c = a_{y.123} + b_{y1.23}X_1 + b_{y2.13}X_2 + b_{y3.12}X_3$$

where, Y_c represents an estimated, or computed value of Y (the dependent variable) determined by the relationship between Y and the three independent variables;

$a_{y.123}$ represents a constant term that determines the height of the regression plane, and is referred to as the Y-intercept;

$b_{y1.23}$, etc., represent the partial regression coefficients;

X_1 represents distance from a Great Lake according to prevailing wind direction, in miles;

X_2 represents latitude, in degrees and tenths of degrees; and

X_3 represents elevation, in feet.

A regression equation for each climatic element for every month was solved by the Michigan State University Integral Computer (MISTIC) by the use of regression program Library Routine K 16-M. Equations were also solved for coefficients of multiple determination (R^2) and coefficients of multiple correlation (R). Formulae for these calculations are:

$$R^2 = \frac{SSR}{\Sigma Y^2 - N\bar{Y}^2}$$

where, SSR represents residual sum of squares;

N represents number of observations;

$\bar{Y}$ represents the mean of the dependent variable; and

$R = \sqrt{R^2}$.