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A Geographical Analysis of Selected Causes and Effects of Michigan Tornado Patterns, 1930-1969

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A GEOGRAPHICAL ANALYSIS OF SELECTED CAUSES AND EFFECTS OF MICHIGAN TORNADO PATTERNS, 1930-1969

by

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A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment
of the
Degree of Master of Arts

Western Michigan University
Kalamazoo, Michigan
April 1971

ACKNOWLEDGEMENTS

I am especially indebted to Mr. Strommen, State Climatologist, and his assistant Mrs. Oshel of the State Weather Bureau in Lansing, for providing most of the necessary tornado data. I also wish to express my thanks to the National Weather Records Center in Asheville for contributing additional sources. My thanks go also to Mr. Sadowski for kindly making his research results available. For the financial benefits of an assistantship and the intellectual training during my education at Western Michigan University, I am particularly thankful to the Geography Department and its members. I extend my sincere gratitude to Dr. Erhart who, as my advisor, has given many hours of guidance, constant encouragement, and limitless patience. The helpful advice and criticism rendered by my reader, Dr. Eichenlaub, are also gratefully acknowledged. For invaluable suggestions in methods of quantitative analysis I owe many thanks to Dr. Dickason of the Geography Department. My final thanks belong to Mrs. Constance Applegate for proof-reading and typing this thesis. The above acknowledgements, however, do not in any way divorce me from the sole responsibility for the validity of this study.

Hans J. Stolle

MASTER'S THESIS M-2765

STOLLE, Hans J., 1935-
A GEOGRAPHICAL ANALYSIS OF SELECTED CAUSES AND EFFECTS OF MICHIGAN TORNADO PATTERNS, 1930-1969.

Western Michigan University, M.A., 1971
Geography

University Microfilms, A XEROX Company, Ann Arbor, Michigan

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (continued)

LIST OF TABLES

CHAPTER I

INTRODUCTION

The tornado is a characteristic phenomenon of Michigan's spring and summer weather and its impact on man and his environment is particularly experienced in the form of severe storm disasters. The magnitude of tornado damage does not solely depend on the intensity and duration of the tornado, but also on the nature of the place that it strikes. Hence, an area of great population density and high property values is likely to suffer greater losses than wasteland areas and, since population and urbanization are rapidly increasing in Michigan, the probability of tornado damage in densely populated areas is also increasing. Forty years ago, climatologist P. C. Day[1] noticed this direct relationship when he wrote:

> Their [tornadoes'] destructive effects will continually be augmented, not by increased severity in storms, but as a result of the growing populations and the building of larger factories, schools, or other places where people congregate.

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[1] P. C. Day, "Weather Bureau Gets Data on Behavior and Effects of Tornadoes," Yearbook of Agriculture, 1930, U. S. Department of Agriculture (Washington, D. C.: Government Printing Office, 1930), p. 532.

His statement is especially appropriate when we consider that the urban population in Michigan has almost doubled since 1930.[2]

In view of this rapid population growth, it is particularly important to investigate the areal occurrences of tornadoes in order to discover the probabilities of damage to life and property for various parts of the state. Numerous studies have examined meteorological conditions that favor tornado developments. However, few works have investigated the potential effects of non-meteorological factors on tornado patterns. Equally scarce are investigations which consider the impact of tornado occurrences on populations. This lack of research directed toward the relationships between tornado patterns and the man-land environment led to the present study.

This investigation tests the hypothesis that the frequencies of tornado occurrences in Michigan are significantly influenced by geographic latitude and season of the year and that the individual tornado location is affected by relief configuration. In addition, the study will include an analysis of spatial and

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[2]Division of Research, Graduate School of Business Administration, Michigan State University, Michigan Statistical Abstract, 1970 (Lansing: Michigan State University, 1970), p. 6.

temporal variations of tornadoes in order to predict the probability of tornado recurrences and to relate these probabilities to potential effects on man. To initially test the hypothesis on a large region it was decided to look first at the national tornado pattern. A map showing tornado occurrences by one degree squares during a forty year period was obtained from the U. S. Department of Commerce Weather Bureau. This map served as a basis to compile a tornado isoline map rendering a general *tornado relief* which is shown on Figure 1. It is interesting to note from this cartographic analysis that ridges of high tornado occurrences, *the tornado alleys*, coincide with major surface depressions and, conversely, low occurrences of tornadoes correspond with highs of surface relief. A cursory check of Figure 1 shows also a general decrease of tornadoes with increase in latitude. Fawbush, Miller, and Starrett[3] found similar relief-tornado occurrence relationships when they constructed a cross section of mean tornado frequencies and mean terrain elevation per 50 mile squares.[4]

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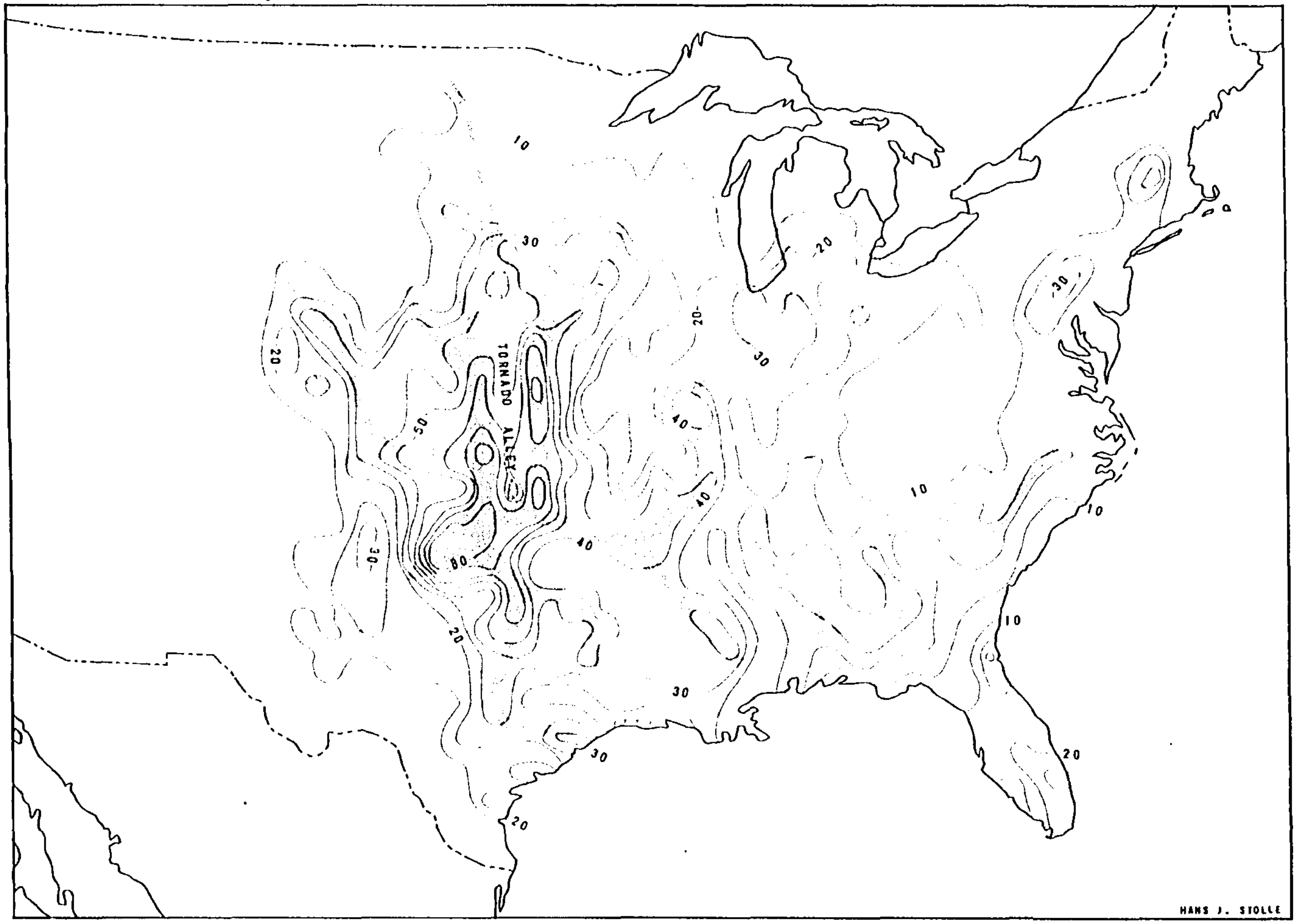
[3]E. J. Fawbush, R. C. Miller, and L. G. Starrett, "An Empirical Method of Forecasting Tornado Development," Bulletin of the American Meteorological Society, XXXII (January, 1951), p. 4.

[4]This study was carried out for the United States between latitudes of 34° and 43° north.

Figure 1--TORNADO FREQUENCY RELIEF OF THE UNITED STATES, 1930-1961



The findings of this preliminary probe proved sufficiently convincing to investigate in detail the distributions of tornadoes in the state of Michigan.

The study will be divided into four sections. The first section is primarily concerned with the evaluation of Michigan tornado data to find characteristic trends of tornado behavior. In the second section follows an analysis of tornado-relief relationships. The third section will apply inferential statistics to identify areas of various tornado recurrence probabilities. For these probability areas the fourth section will investigate tornado hazard impact on population.

CHAPTER II

REVIEW OF RELATED LITERATURE

The following collection of abstracts reviews several studies of tornado occurrences research. These articles were selected because each introduces a unique approach or methodology of tornado analysis which has been applied for the various areas of research for this thesis.

A *regional treatise* of tornadoes in Nebraska, 1916-1937, by Lemons,[1] investigated tornado trends for years, months, and hours. Tornado location, path lengths, widths, and direction are briefly reviewed. The conclusion touches on the subject and theory of probabilities of tornado occurrences and casualties. However, it does not go beyond elementary assessments.

Battan[2] examined *frequencies of tornado path lengths* in the United States during March through June, 1957 and 1958. He points out the inconsistencies in

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[1]Hoyt Lemons, "Some Aspects of Nebraska Tornadoes," Monthly Weather Review, LXVI (July, 1938), p. 207.

[2]Louis J. Battan, "Duration of Tornadoes," Bulletin of the American Meteorological Society, XL (July, 1959), p. 341.

tornado data records and suggests the use of a "reasonable guess" to select and discard the "unreliable" data. The modified data shows a frequency distribution with lower mean and median path lengths which Battan declares to be "closer to reality."

Thom[3] introduced statistical techniques for assessing *probabilities* of various trends of tornado movements in Iowa and Kansas. This work is based and enlarged on research initiated in 1945. Thom found that the Naperian logarithms of tornado path widths and lengths form a normal distribution. The logarithmic means of length and width are used to find a mean tornado path area which is then statistically adjusted for the path length and width correlation to give the expected (probable) mean path area. The expected mean path area is then used together with tornado observations of the past to find the probability of a tornado striking a given point.

The Palm Sunday tornado disasters of April 11, 1965, motivated Sadowski[4] to undertake this study of

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[3]H. C. S. Thom, "Tornado Probabilities," Monthly Weather Review, XCI (October, 1963), pp. 730-736.

[4]Alexander Sadowski, "Potential Casualties from Tornadoes" (paper presented at the 244th meeting of the American Meteorological Society; Cloud Physics and Severe Local Storms, Reno, Nevada, October 18-22, 1965), pp. 1-10.

potential casualties from tornadoes for the "tornado belt" areas of the United States. His numerical evaluation is based on the following parameters: (1) average area covered by one tornado, (2) number of observed tornadoes for each chosen statistical unit during 45 years, (3) area of each unit, and (4) their population densities. The results are expressed in potential tornado casualties for the period of 45 years per square mile within each unit.

Skaggs[5] applied *Thom's probability* techniques to examine probable tornado occurrences in the eastern United States. The results are mapped and their patterns briefly discussed. He particularly emphasizes the need for detailed investigations of effects of tornado hazards on human activities.

Safford[6] studied the *influence of terrain* on the frequency distributions of tornado and hail occurrence in the central Midwest. His analysis correlates hail and tornado occurrences with elevation, surface

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[5]Richard H. Skaggs, "On Tornado Probabilities," Proceedings of the A.A.G., II (1970), pp. 123-126.

[6]A. T. Safford, "The Influence of Terrain on Frequency Distribution of Tornado and Hail Occurrence in the Central Midwest." Unpublished Master's Thesis, St. Louis University, St. Louis, Missouri, April 1970, pp. vi + 82.

roughness, and slope parameters. The results indicate that surface roughness, which is the sum of magnitude of several mean elevations within each 30 minute square sample area, has highest negative correlations with tornado occurrences. Elevation and slopes show significant but lower correlations. The final evaluation reveals an inverse correlation of terrain with tornadoes and hail, with the former seeking the lower smoother areas and the latter perferring the higher and rougher portions of relief. Tornadoes were also found to favor positive slopes.

CHAPTER III

ANALYSIS OF TORNADO STATISTICS FOR MICHIGAN, 1930-1969

Data Sources and Reliability

The data of geographic locations, day and hour of occurrences, path lengths, widths, and directions for 246 tornadoes in Michigan during the 1930-1969 period were extracted from several sources. The pre-1949 information was compiled from the climatological tables of the _Monthly Weather Review_, 1930-1950, as well as the storm summaries on page one of the monthly _Climatological Data, Michigan Section_, 1930-1957. For the post-1949 period, data were found in the annual editions of the _Climatological Data, National Summary_, 1950-1958, and the monthly issues of _Storm Data_, 1959-1969. The _Climatological Data, Michigan Section_ was also used till 1957. The U. S. Department of Commerce Technical Papers Number 20[1] and 30[2]

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[1] Laura V. Wolford, _Tornado Occurrences in the United States_, U. S. Department of Commerce, Weather Bureau Technical Paper No. 20 (Washington, D. C.: Government Printing Office, 1960).

[2] Urban J. Linehan, _Tornado Deaths in the United States_, U. S. Department of Commerce, Weather Bureau Technical Paper No. 30 (Washington, D. C.: Government Printing Office, 1957).

as well as various articles from meteorological journals, provided additional sources.

During the mapping of all Michigan tornado touchdowns and their paths, it was often necessary to consult several sources to pinpoint exact locations. Different records covering identical time spans were found to provide most of the missing location descriptions. Some tornado positions, however, had to be mapped at the locale of their general description. The tornado data were also found to have incomplete path dimension and time of occurrence records. Data for path lengths and widths, for example, were found for about 60 per cent of all tornadoes, while times of occurrences were available for approximately 75 per cent of all tornadoes. It also became clear that a general increase of tornado awareness and progress in observation techniques rendered continuous improvements of tornado records over the years, particularly since 1949. Tepper[3] found evidence that the post-1949 records include tornado reports of lesser substantiation. Nevertheless, it was decided to accept all data as being equally reliable since it would defeat the purpose of this study to

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[3]Morris Tepper, "On the Evaluation of Tornado Reports and a Numerical Method for their Classification," Monthly Weather Review, LXXXV (May, 1957), p. 163.

reduce the data to the number of years for which complete data are available.

Tornado Occurrence Patterns

The frequencies of tornadoes for the 40 year period are shown on Figure 2. The distribution shows significant differences between the number of tornadoes which have occurred in the southern part of the Lower Peninsula, the northern part of the Lower Peninsula, and the Upper Peninsula. It is found, however, that the tornado distribution within these defined regions is not uniform; in fact, a patchwork of varying frequencies can be identified. Both observations suggest the existence of the postulated regional and local factors that are possibly responsible for these patterns. The regional decrease from south to north could be indicative of latitudinal influence, and the local variations might very well reflect terrain variations.

To provide a basis for testing these hypotheses, the actual tornado touch-downs and paths were transferred from the road map at 1 inch = 14 mile scale onto the smaller scale relief map (Figure 3). This map proves to be much more conclusive than the initially examined choropleth map (Figure 2), since it exhibits true tornado densities and the dynamic aspects of movement and

Figure 2-- MICHIGAN TORNADO FREQUENCIES BY COUNTIES, 1930-1969

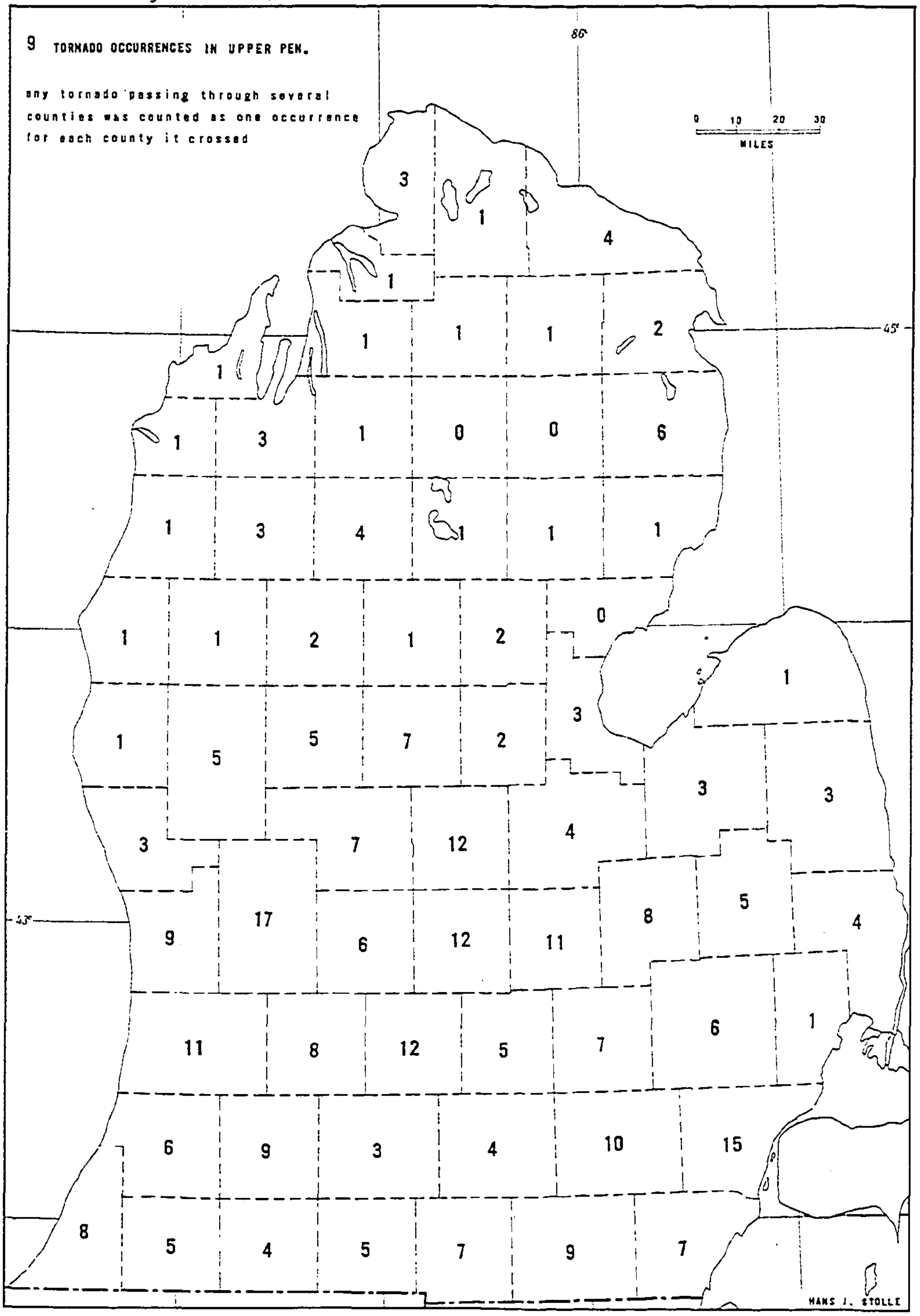
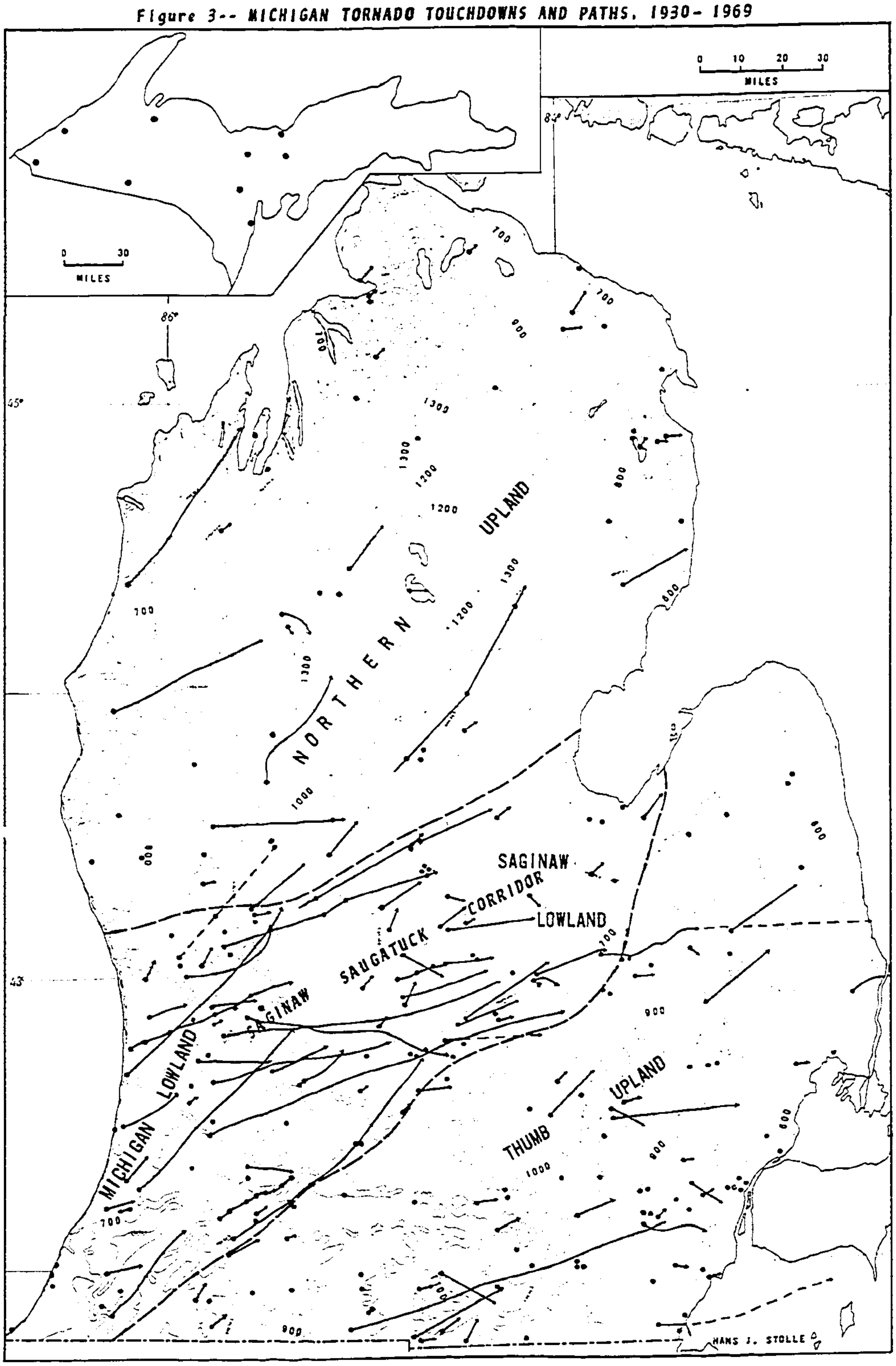


Figure 3-- MICHIGAN TORNADO TOUCHDOWNS AND PATHS, 1930- 1969



direction. The regional and local tornado variations previously recognized are here even more pronounced and the contour relief permits cartographical analysis of tornado-terrain relationships. The major relief of the Lower Peninsula shown in Figure 3 consists of the Northern Uplands in the north and the Thumb Uplands in the southeast. Nested between them are the Saginaw lowlands.[4] These lowlands form a 60 mile wide passage which for the purpose of this study is referred to as the Saginaw-Saugatuck corridor. It occupies about 24 per cent of the Lower Peninsula's land area and almost 45 per cent of all tornadoes in the Lower Peninsula during the study period occurred there. Tornadoes in the Upper Peninsula show a similar preference for natural depressions with five out of nine occurring in the Whitefish River passage which connects Little Bay de Noc with Au Train Bay. The remaining four tornadoes touched down at the four corners of the foothills of the Northern Highlands.

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[4] These terms of major physiographic divisions are adapted from: Bert Hudgins, Michigan: Geographic Backgrounds in the Development of the Commonwealth, 4th ed. (Detroit, Michigan: B. Hudgins, 1961), p. 21.

Direction of Tornado Movements

A windrose diagram with 20° sectors was employed to plot all tornado path termini for preferred (modal) direction analysis. Figure 4 presents the results and the diagram shows convincingly that the preferred direction of tornado movement is to the east-northeast. Ninety-one per cent of all path occurrences fall inside a 90° sector centered on the line of preferred direction. This indicates that most paths are clustered near the line of preferred direction and that this line represents a good approximation of tornado directions in Michigan. A comparison of tornado direction frequencies on a different windrose diagram for the United States and Michigan with 45° sectors shows similar results (Figure 5). A more critical evaluation, however, reveals that the percentage of eastward moving tornadoes in Michigan is twice as high as the national percentage. In addition, there are no south and northbound tornadoes and only one short westward tornado in Michigan. These differences are noteworthy deviations from the national pattern and support the hypothesis of terrain effects which are perpetrated by the accessibility of the east-northeast oriented corridor and the adjacent uplands of obstruction.

Figure 4-- PREFERRED DIRECTION OF MICHIGAN TORNADOES, 1930-1969

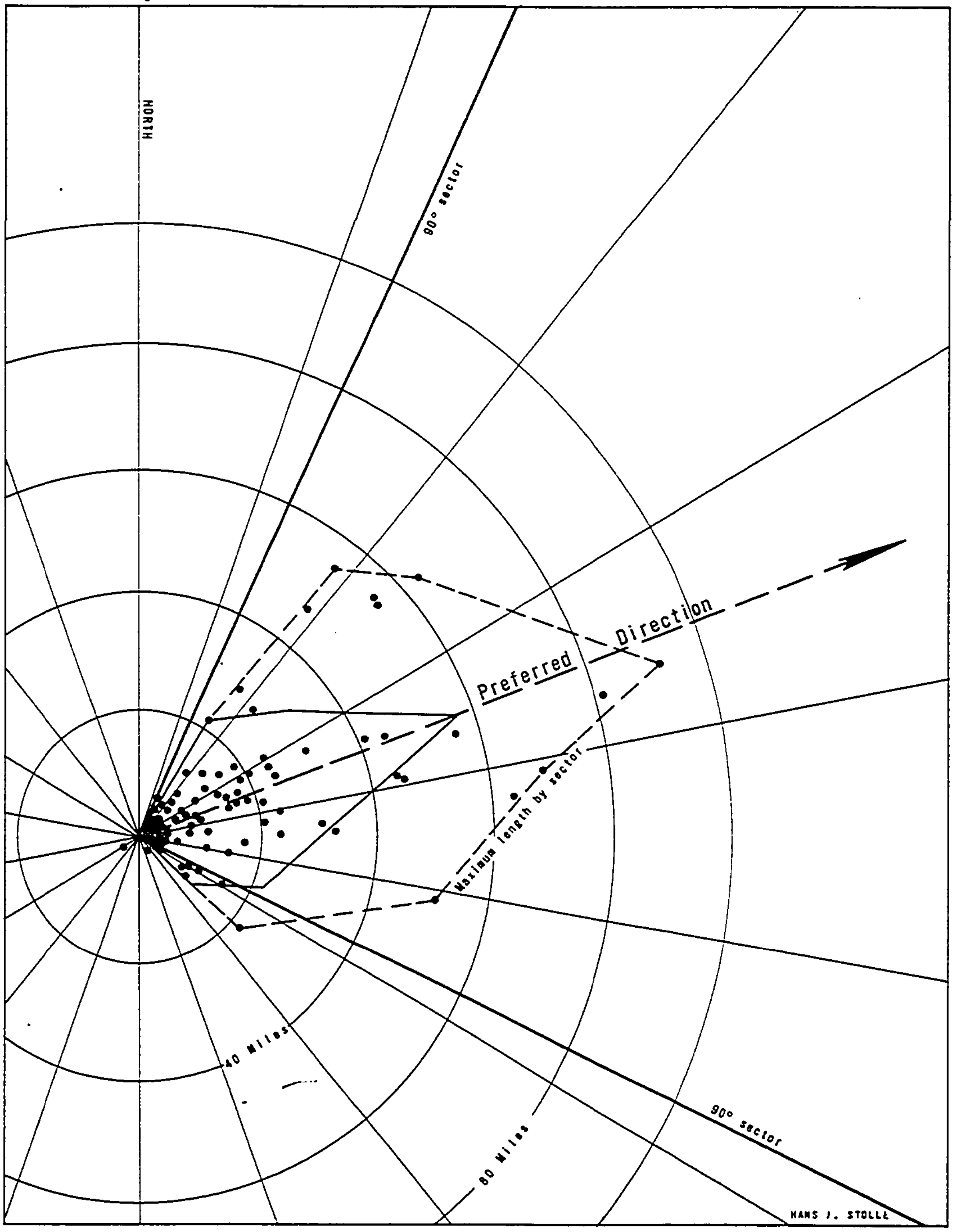
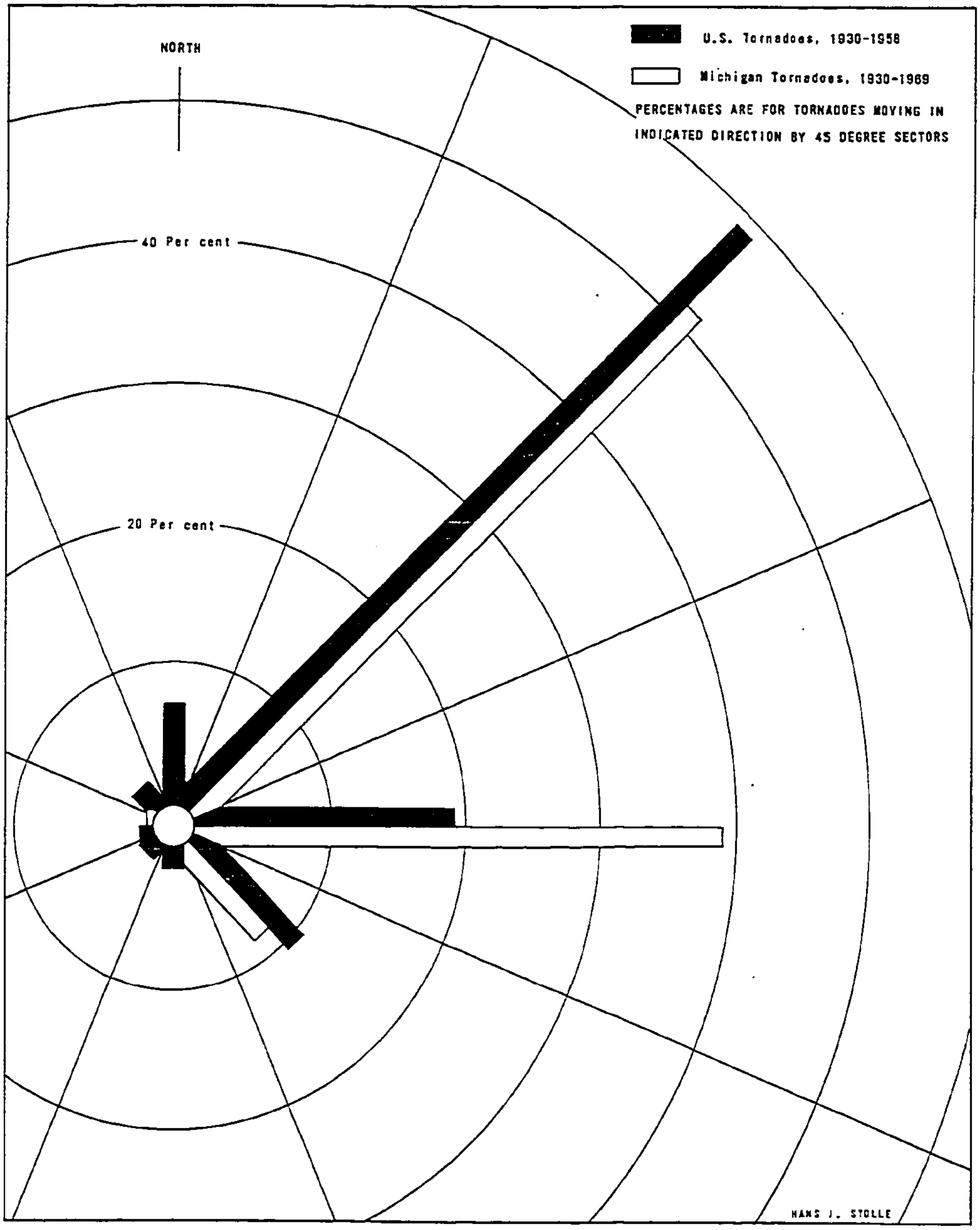


Figure 5-- TORNADO ROSE FOR MICHIGAN TORNADOES, 1930-1969 and TORNADOES IN THE UNITED STATES, 1930-1958



Tornado Path Lengths

The frequency distribution of 142 Michigan tornado path lengths in Figure 6 shows an inverse relationship of path length and frequency of occurrence. The most frequent paths are less than one mile in length. While the length of tornado paths range from less than one mile to more than 90 miles the calculated average length for all tornadoes was found to be 11 miles. The same average was found by Battan[5] for tornadoes in the United States. An evaluation of Figure 6 shows, however, that the 11 mile average is not a truly representative measure of the most probable length. The void of path occurrences between 35 and 45 miles offers a logical division between common and uncommon path lengths. If one considers separately the common path lengths which comprise 92 per cent of all recorded paths the new average path length is approximately seven miles.

The initial problem of path length estimates lies in the difficulty of agreement among several observers. Battan[6] notes that "it is doubtful that one can

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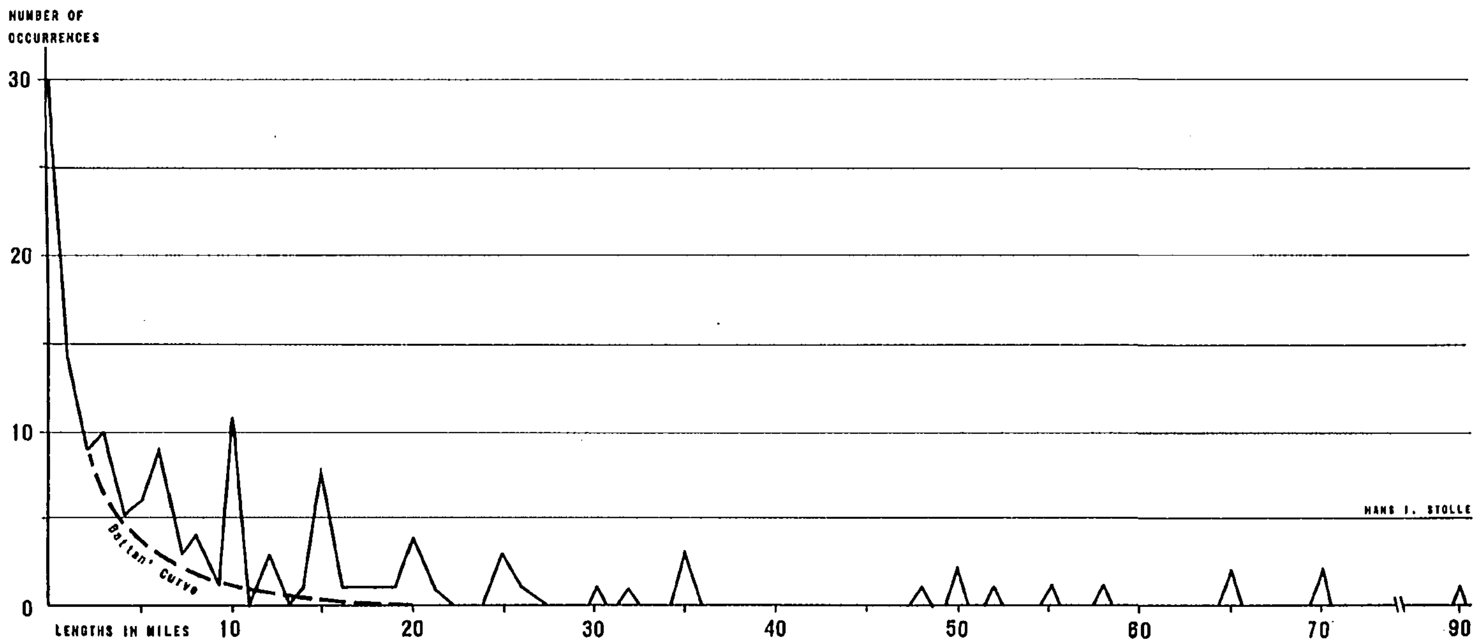
[5]Louis J. Battan, "Duration of Tornadoes," _Bulletin of the American Meteorological Society_, XL (July, 1959), p. 341.

[6]_Ibid._, pp. 341-342.

Figure 6-- FREQUENCY DISTRIBUTION OF MICHIGAN TORNADO PATH LENGTHS, 1930-1969



differentiate between two or more separate funnels and skipping of the same funnel, especially when various observers have combined their information." He continues by stating that "quite evidently the individual funnel cloud usually traverses a distance of less than three miles."

The application of Battan's arbitrary curve drawn through the lower envelope of the plotted points in Figure 6 intersects the axis of zero occurrence at 20 miles and the reduced average path length equals 2.7 miles. Assuming that the average tornado path vortex exists for less than three miles, conditions must be favorable to permit continuous formation of vortices to achieve unusual path lengths. A look at the tornado direction analysis (Figure 4) shows that the maximum path length of all Michigan tornadoes occurs in the sector of preferred direction with all other maxima decreasing with angular distance from the preferred sector. A comparison with Lemons'[7] study of Nebraska tornadoes concurs that the longest tornado path occurs in the sector of preferred direction. However, the theory of decrease of maximum lengths with angular distance

[7]Hoyt Lemons, "Some Aspects of Nebraska Tornadoes," Monthly Weather Review, LXVI (July, 1938), p. 207.

does not hold true. The Nebraska tornado length maxima shown on Table I have a distinct bimodal directional distribution.

TABLE I

MAXIMUM TORNADO PATH LENGTHS BY TWENTY DEGREE SECTORS FOR TORNADOES IN MICHIGAN AND NEBRASKA

	Sectors of Tornado Path Direction				
	0°	±20°	±40°	±60°	±80°
Michigan tornado maximum lengths in miles	90	+70 -64	+51 -56	+16 --	-- --
Nebraska tornado maximum lengths in miles	85	+22 -26	+ 8 -45	+57 -24	+ 8 --

0° represents the sector of preferred direction to the east-northeast for both groups.

\+ refers to sectors in clockwise direction from the preferred direction sector.

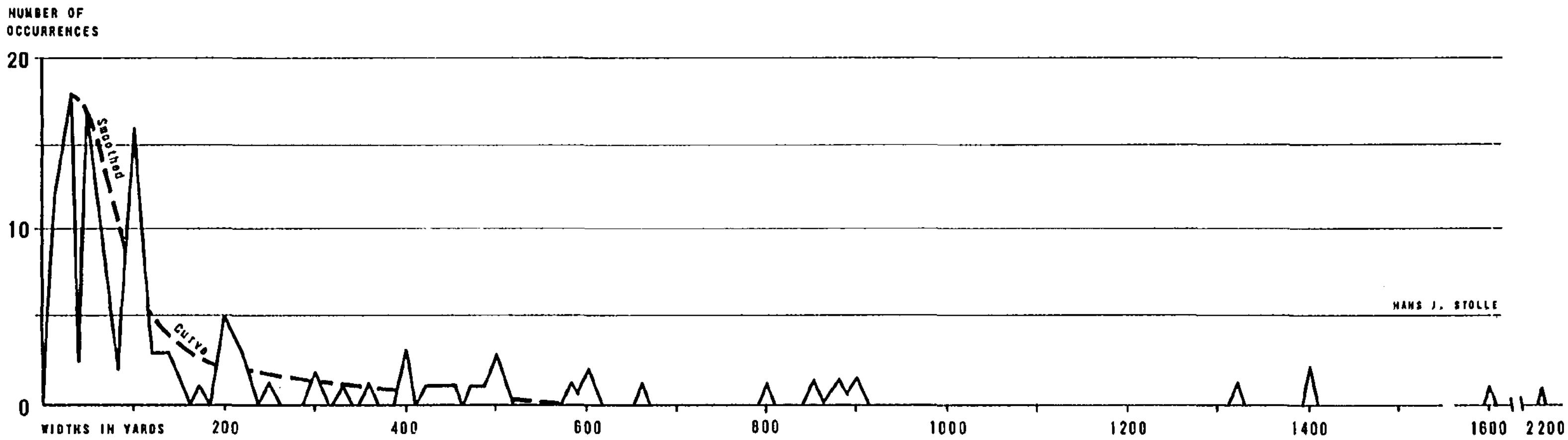
\- refers to sectors in counterclockwise direction from the preferred direction sector.

It is interesting to note that the relief of Nebraska is also oriented in two distinct directions, one to the northeast and the other to the east-southeast. As already pointed out earlier, the Saginaw-Saugatuck corridor shown on Figure 3 coincides with the preferred direction. As many as 58 per cent of all tornadoes of 10 mile paths and longer occur within this area. The same percentage of Michigan tornadoes of 30 miles and longer are found there. Tornadoes with 50 mile paths and longer found in the lowland account for 70 per cent of all 50 mile path occurrences. Most tornadoes of considerable length, found outside the corridor, follow also along natural passages as the relief map Figure 3 indicates. This seems to suggest that especially long tornado paths generally follow surfaces of low relief containing few obstructions.

Tornado Path Widths

The frequency distribution of 115 tornado path widths in Michigan is shown on Figure 7. The distribution curve is positively skewed with the highest frequencies occurring at 25, 50, and 100 yards. Sharp drops in frequencies between these high path occurrences reflect probable tendencies to round out numbers when tornado paths are estimated by individual observers. The path width for all 115 tornadoes ranges from less than 10 yards to 2,200 yards, and averages about 200 yards. If the few path widths above 700 yards (which amount to 7 per cent of all path widths) are disregarded, a reduced average of 125 yards results. The smoothed

Figure 7-- FREQUENCY DISTRIBUTION OF MICHIGAN TORNADO PATH WIDTHS, 1930-1969



curve which is similar to Battan's path lengths curve[8] portrays perhaps an even more realistic path width distribution, and its average is 105 yards.

Tornado Path Lengths and Widths Relationships

The previously discussed characteristics of tornado path length and width illustrated that paths with short lengths and narrow widths occur most frequently. The peak of the curve representing the modal path length of less than one mile is found closer to zero length and slightly more skewed than the width curve with a modal path width of 30 yards. Nevertheless, both distributions show similarities in their positively skewed curves and tail angles.

Since the frequency distribution of path lengths and widths were found to show a certain direct relationship, it is reasonably safe to compare their means and arrive at mean length-width ratios.

Table II shows the means of the total, the common, and the smoothed path lengths and widths occurrences. The approximate ratio of 1:100 is found twice and the much lower third ratio of 1:45 reflects a reduction that is much greater for the smoothed path length than it is

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[8] Battan, op. cit., pp. 341-342.

for the smoothed path width. Hence, the ratio of one width unit to approximately 100 length units seems most representative of the average Michigan tornado. Inasmuch as these assumptions seem plausible they must be considered hypothetical and speculative until sound research provides the correct answers.

TABLE II

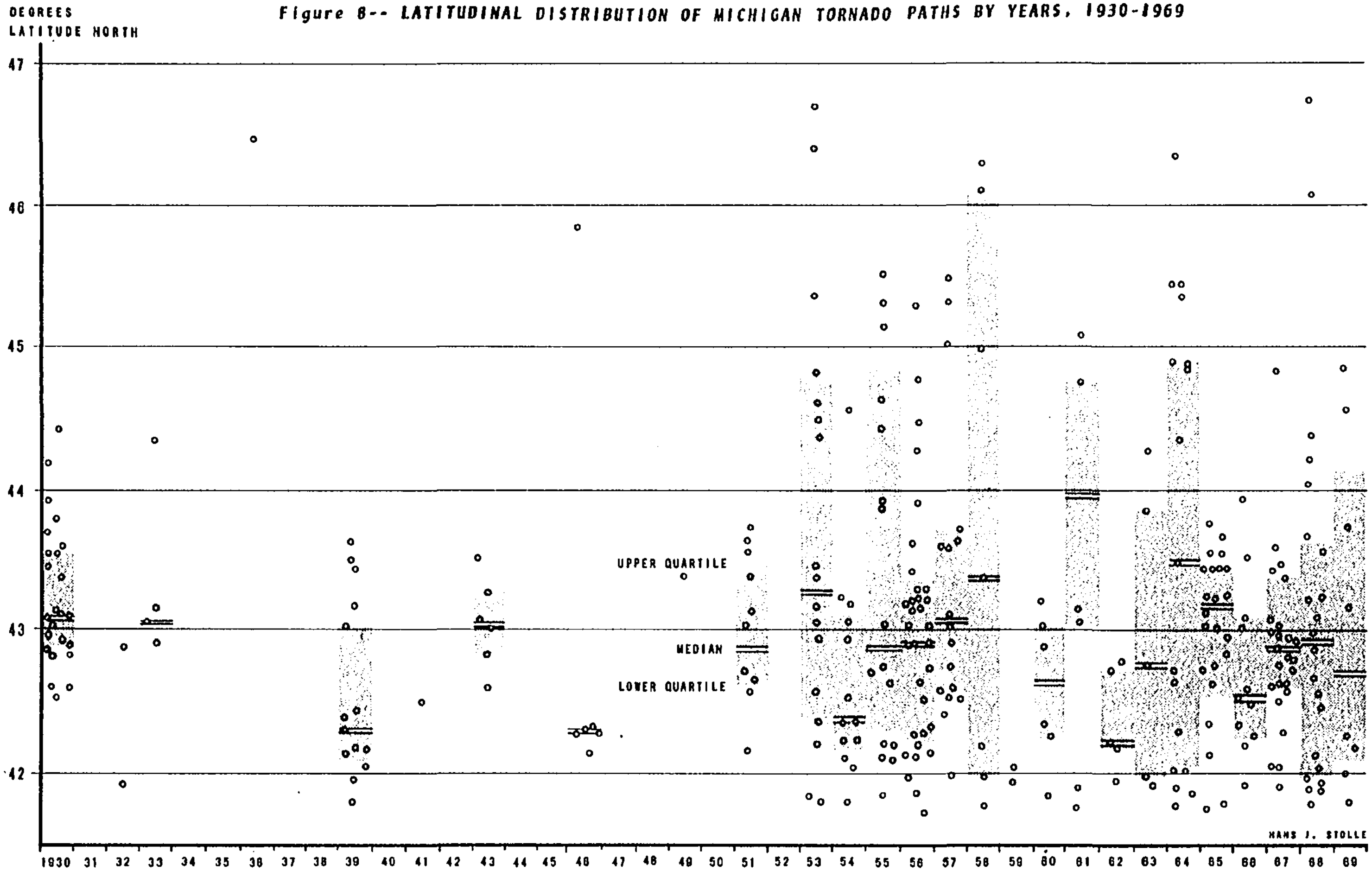
MEAN TORNADO PATH LENGTHS AND WIDTHS RATIOS

	Length		Width		
	Miles	Yards	Miles	Yards	Ratio
Means of total occurrences	11	19,360	.114	200	1:96.8
Means of common occurrences	7	12,320	.07	125	1:98.6
Means of smoothed occurrences	2.7	4,754	.06	105	1:45.3

Latitudinal Tornado Distribution by Years

All tornado touch-downs and paths are plotted by their year and latitude of occurrence on Figure 8. The individual annual columns of tornadoes by latitude are subdivided by median and quartiles to identify significant concentrations by latitudes. A perusal of the 40 columns finds a noteworthy increase in occurrences since 1950 which had been previously explained by improved

Figure 8-- LATITUDINAL DISTRIBUTION OF MICHIGAN TORNADO PATHS BY YEARS, 1930-1969



recording practices. The overall pattern does not show any significant regularities or rythms. Instead, the path medians and quartiles fluctuate between the state's low and high latitudes. Nonetheless, it is interesting to find that all but one median (1961) does not exceed the northern limit of 43° 30' north and most upper quartiles are found south of 45° north. There is no evidence of a significant latitudinal shift of the state's tornado pattern during the past 40 years.

Latitudinal Tornado Distribution by Months

Each of the 12 columns on Figure 9 shows the monthly tornado occurrences for 40 years by latitudes. Again the columns have been subdivided into medians and quartiles to ascertain significant latitudinal patterns. The result shows a bell-shaped distribution. Only one out of 246 tornadoes (a November occurrence) falls outside this seasonal curve. It can be seen that the northern limits of tornado occurrences migrate with the sun to reach their peak during June, July, and August. Not a single tornado in March during the 40 years has occurred north of 43°N. and no April tornado has touched down north of 45°N. All September tornadoes struck in the Lower Peninsula only, and all October tornadoes occurred in the southern part of the Lower Peninsula. All monthly path

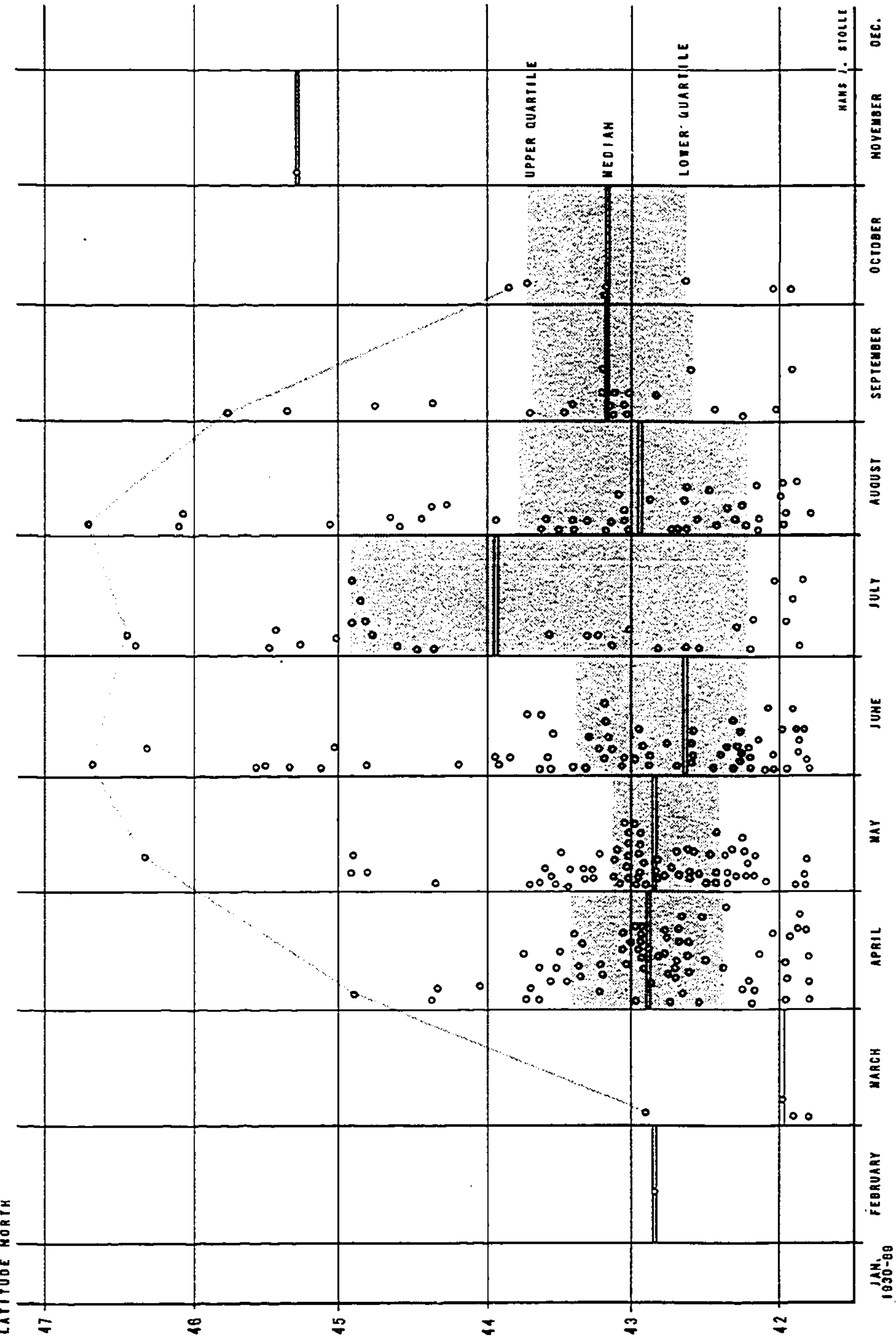


Figure 9-- LATITUDINAL DISTRIBUTION OF MICHIGAN TORNADO PATHS BY MONTHS, 1930-1969

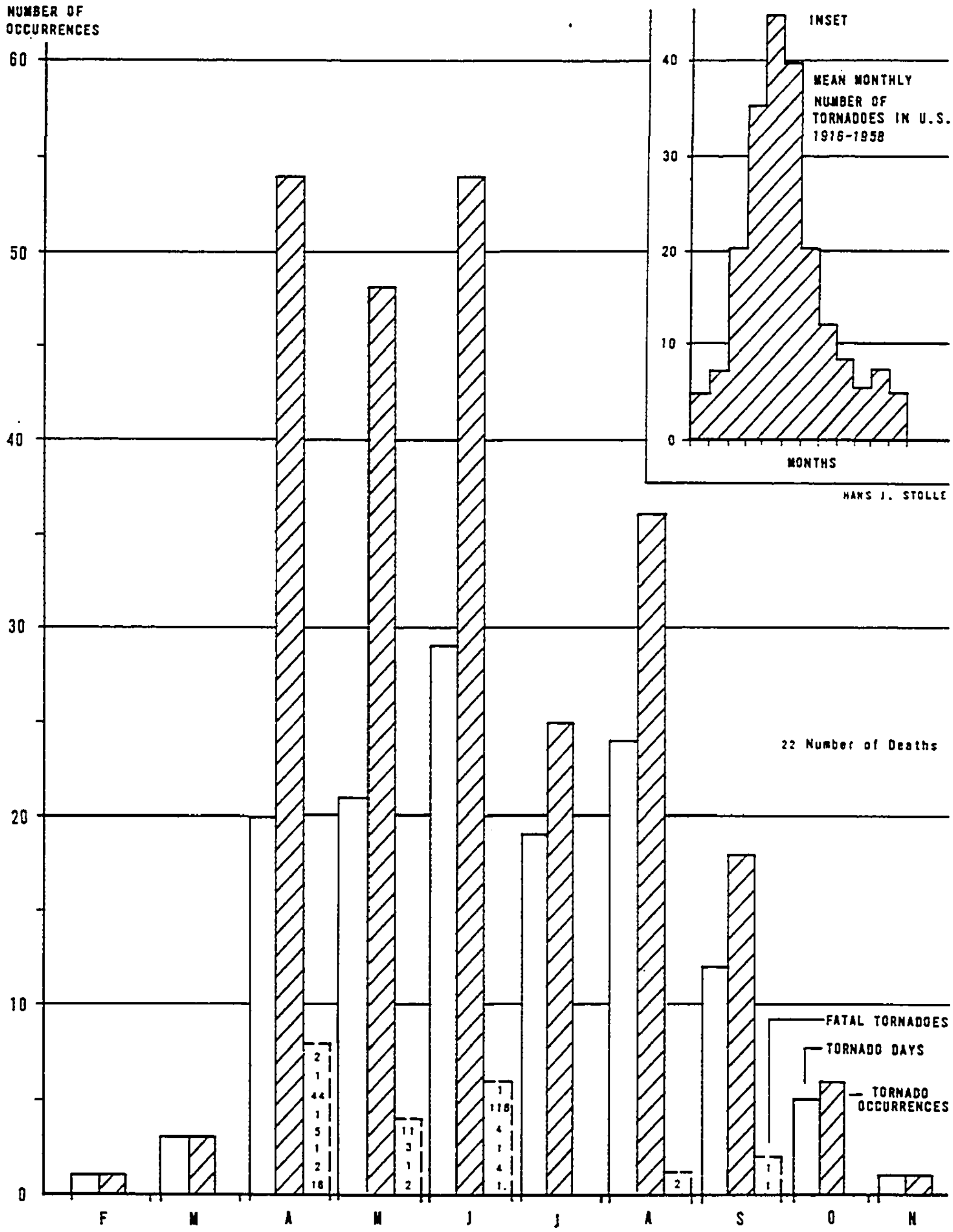
medians with the exception of July are close to the 43°N. parallel.

The latitudinal distance of the quartile ranges was used to measure tornado concentrations since it shows at what latitudinal zone 50 per cent of all monthly tornadoes occur. For example, the spring and fall months have approximately one degree quartile ranges with their medians at the 43°N. parallel. Only the July quartiles have a range of three degrees from 42°N. to 45°N. This clearly indicates that the section of Michigan between latitudes of 42°N. and 44°N. receives at least 50 per cent of all monthly tornadoes occurring during April, May, June, August, September, and October. In fact, during March and October it receives all, and in April, May, June, August, and September more than 75 per cent of monthly tornado occurrences. This latitudinal zone coincides with the location of the Saginaw-Saugatuck corridor. Areas north of this zone experience fewer tornadoes and the parallels of 44°N. and 45°N. form distinct divisions between areas with tornado seasons of 8 months, 6 months, and 5 months. The frequencies of tornadoes are seen to decrease in similar proportions with increase in latitude.

Tornado Frequency Distribution by Months

The histogram on Figure 10 shows the frequencies of Michigan's tornado occurrences, tornado days, and fatal tornadoes by months for the 1930-1969 period. The curve of tornado occurrences illustrates a great leap from very few tornadoes in March to 54 tornadoes in April. This high frequency is seen to continue on through May and June and drops off considerably in July. There is a second increase in August, followed by rapid descend in September and October. Both November and February have recorded only one tornado each, while December and January show no recorded tornadoes over the 40 year period. The frequency distribution of tornado days is found to be more symmetrical than the tornado occurrence distribution. The modal frequency of tornado days in June, however, coincides with the modal frequency of tornado occurrences. April, May, and June show great differences in tornado and tornado day frequencies, which is indicative of the violent spring and early summer storms which usually cause several tornadoes per day. Most other months display constant ratios of tornadoes and tornado days. The number of fatal tornadoes represents only a small portion of all Michigan tornadoes, yet their monthly distribution is

Figure 10-- FREQUENCY DISTRIBUTIONS OF TOTAL NUMBER OF MICHIGAN TORNADOES, TORNADO DAYS, AND FATAL TORNADOES BY MONTHS, 1930-1969



very similar to the tornado occurrence and tornado day distributions. The small figures represent the number of tornado fatalities for each fatal tornado. There is a noteworthy low in all three frequencies during July which probably reflects the unfavorable tornado conditions of the atmosphere during that month. For tornado death activities in the United States during the 1916-1953 period Linehan found also a "precipitous drop soon after arrival of summer, probably reaching a minimum in July."[9] The inset on Figure 10 provides a comparison of the monthly tornado frequencies in Michigan with those of the United States. The major difference of both distributions lies in the rapid tornado increase in April for Michigan which does not exist for the United States as a whole. This difference is probably due to Michigan's climatological conditions during the spring which permit rapid warming of the land area as well as occasional invasions of northern cold air masses.

Tornado Frequency Distribution by Hours

Time records for 198 tornadoes were available and their frequency distribution is shown on Figure 11. The symmetric curve reaches its high between 6:30 p.m. and

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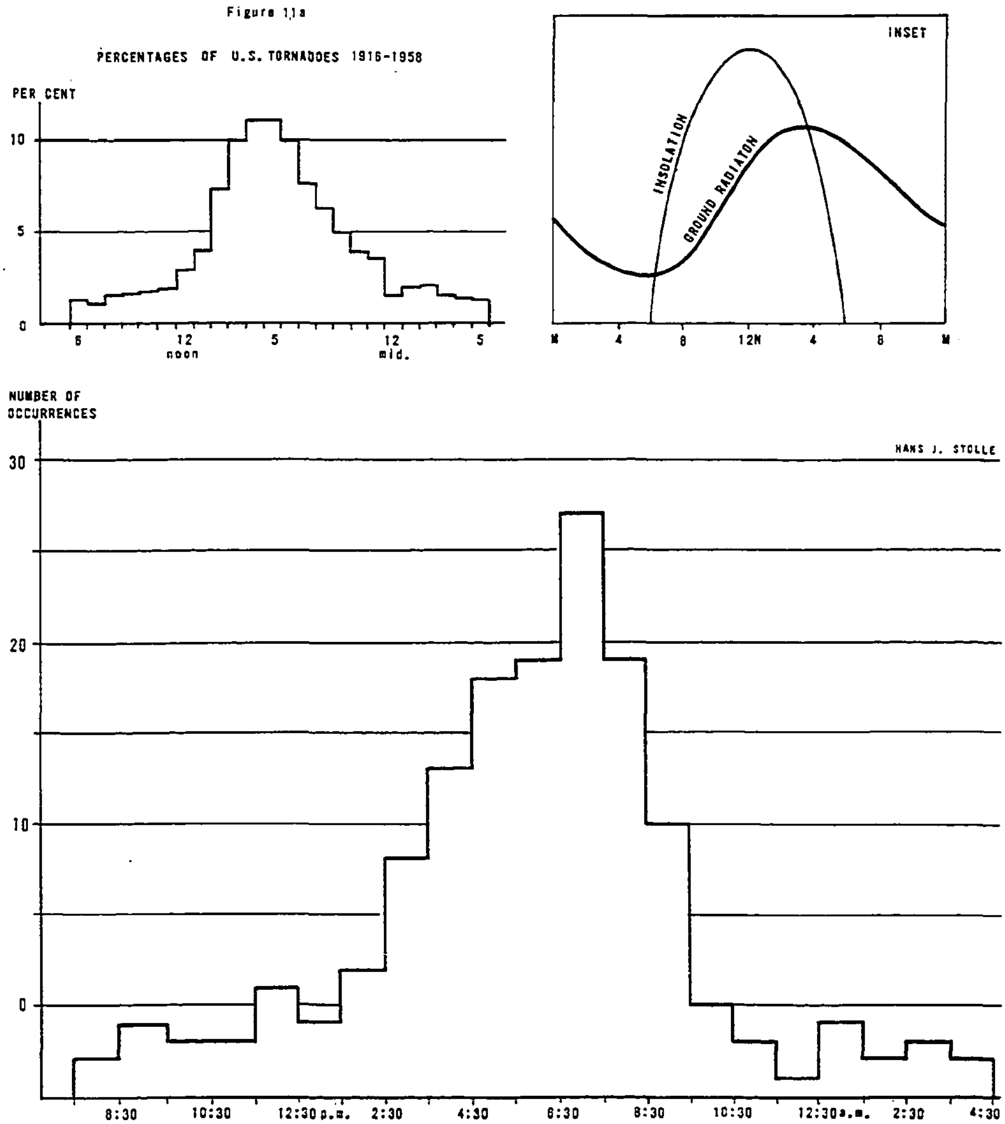
[9] Linehan, _op. cit_.

Figure II-- FREQUENCY DISTRIBUTION OF MICHIGAN TORNADO OCCURRENCES BY HOURS, 1930-1969



7:30 p.m. in the evening. About 7 out of 10 tornadoes occur between 2:30 p.m. in the afternoon and 9:30 p.m. at night. This 7 hour concentration marks this part of the day as distinct tornado hours. It is noteworthy to point out that the very gradual increase from 8 a.m. in the morning and a similar decrease after the peak hour resembles the standard curve of ground radiation shown as inset on Figure 11.

A comparison of hourly tornado occurrences in Michigan with those of the United States (Figure 11a) does not produce any significant differences. The somewhat smoother curve for the United States is probably due to the much larger sample, and its peak hour shift to 5:30 p.m. results in an even better fit with the standard curve of ground radiation. If one considers Michigan's location at the extreme western portion of the Eastern Standard Time Zone, it becomes apparent why the peak hours of Michigan tornadoes occur one hour later than tornado peak hours for the entire United States.

Summary

This chapter has analyzed several spatial and temporal relationships of tornadoes in Michigan. It was found that tornado occurrence frequencies decrease with increase in latitude. Further investigations of latitudinal tornado distributions of monthly occurrences discovered a significant pattern of seasonal migration. This shows that not only tornado frequencies but also lengths of tornado season decrease with latitude. An examination of monthly tornado frequencies identified the early summer months as the severe tornado season for southern Michigan. A comparison with the number of monthly tornado days found that the monthly tornado frequencies are highest for April, May, and June and that these tornadoes occur at a higher occurrence per day rate than at any other months. The frequencies of fatal tornadoes in Michigan were found to be low; however, their monthly distribution emphasizes the violence of storms during April, May, and June. The preferred hours of tornado events are found between 2:30 p.m. in the afternoon and 9:30 p.m. at night.

Almost half of all Michigan tornadoes are located in the Saginaw-Saugatuck corridor and most tornadoes with considerable path length are found there.

A synthesis of the conclusions found for the Michigan tornado statistics analysis renders proof that the regional factors of geographic latitude, time of the year, and time of the day each have significant effects on tornado frequencies. The investigation touched also on substantial evidence that major local relief configurations have controlling influence on individual tornado locations.

CHAPTER IV

CORRELATION ANALYSIS OF SELECTED TERRAIN PARAMETERS AND TORNADO OCCURRENCES

During the 1930-1969 period a total of 246 tornadoes occurred in the State of Michigan. Only nine of them, or four per cent, were recorded in the Upper Peninsula. Because of the small number of tornado occurrences in the Upper Peninsula they were excluded from the quantitative investigations which follow.

Data Preparation

This chapter is testing the hypothesis that relief is one of the factors which affect the locations of tornadoes. To test the hypothesis a multiple correlation analysis is applied. The data for the multiple correlation analysis were gathered from a suitable base map (Figure 3), which allowed sampling of the tornado occurrences and the relief parameters of elevation, terrain roughness value, and slope category. A grid composed of 6 x 6 mile units was superimposed at random location with the fixed orientation in preferred tornado path direction. Such a grid created reasonably large sampling units of 36 square miles. The number of tornado occurrences and the values for the individual relief parameters could now be found and tabulated for each square. Any tornado passing through several squares was counted several times since it actually occurred in several squares. This count resulted in a total of 511 squares with tornado occurrences ranging in frequencies from 1 to 5. The mean elevations for each unit were then calculated from the contours.

Next followed the sampling of the terrain roughness. This term was adopted from Safford[1] and was redefined for this study as the measure of relative relief expressed in number of 100 foot contour occurrences per 36 square mile unit. For expedient sampling of slope angles a modification of the base-map relief which would show slopes graphically was needed. It was decided to apply the Kitiro Tanaka method[2] of orthogonally viewed traces of inclined planes which shows relief as a series of inclined profiles. The present writer is exploring the utility of Tanaka's technique to show relief and

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[1] A. T. Safford, "The Influence of Terrain on Frequency Distribution of Tornado and Hail Occurrence in the Central Midwest." Unpublished Master's Thesis, St. Louis University, St. Louis, Missouri, April 1970, p. 42.

[2] Kitiro Tanaka, "The Orthographical Relief Method of Representing Hill Features on a Topographical Map," Geographical Journal, LXXIX (March, 1932), pp. 212-219.

indicate slope angles. No evidence was found that this possibility of slope evaluation has been applied previously although Robinson and Thrower acknowledged it briefly.[3]

The Tanaka relief of traces of inclined planes is shown on Figure 12. The traces are spaced at a distance of 1.3333 miles which is approximately 70 times the contour interval. Since the contour interval measures 100 feet and the traces of inclined planes are spaced at a distance of 1.3333 miles, or 7,038 feet, the angle of inclined planes can be calculated.

$$\tan \theta = \frac{h}{D} = \frac{100}{7.038.2} = .0142 \qquad \theta = 0°49' \qquad (1)$$

Viewing traces of inclined planes at such small angle results in trace line angles that are many times larger than the true slope angles which they are trying to portray. Nevertheless, if a slope scale provides the true angle values for the exaggerated trace line angles the observer can relate the exaggerated terrain to nature. Most map users have had some experience with such visual assimilations when applying the scale of changing latitudes on a Mercator projection map. Categories of four

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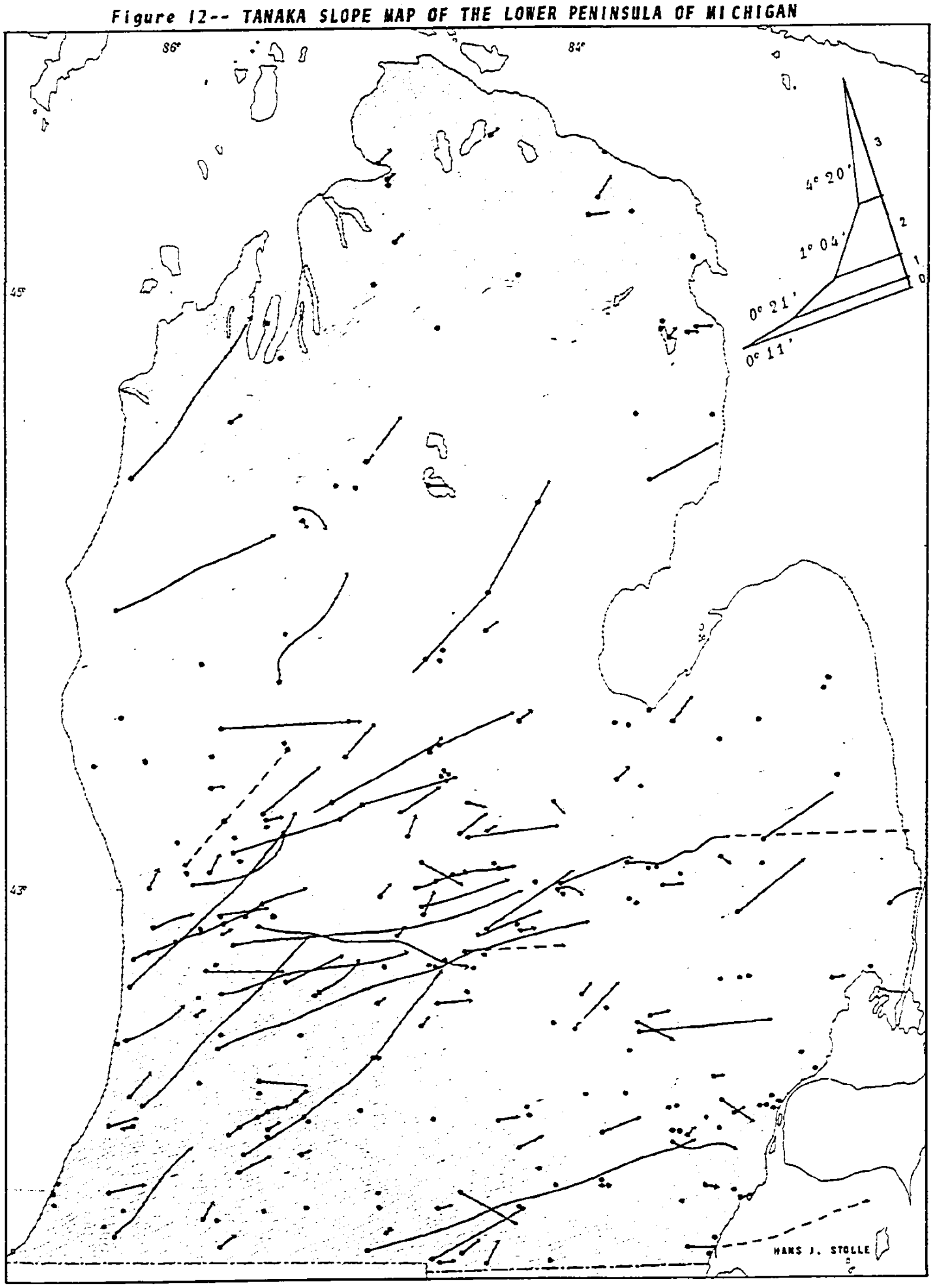
[3]Arthur H. Robinson and Norman J. W. Thrower, "A Method of Terrain Representation," Geographical Review, XLII (October, 1957), p. 517.

Figure 12-- TANAKA SLOPE MAP OF THE LOWER PENINSULA OF MICHIGAN



distinctly different gradients of 100 foot elevation changes at 1/4 mile, 1 mile, 3 miles, and 6 miles were identified as representative slopes of the inclined plane profile relief (Figure 12). Their true slope angles were calculated and the four gradients, their true slopes and exaggerated counterparts for each category are compared on Table III.

TABLE III

TRUE AND EXAGGERATED SLOPE ANGLES BY CATEGORY

True Gradient	True Slope	Exaggerated Slope	Category
100' = 1/4 mile	4°20'	79°20'	3
100' = 1 mile	1°04'	52°59'	2
100' = 3 miles	0°21'	23°50'	1
100' = 6 miles	0°11'	12°28'	0

The slope scale on Figure 12 shows for each defined category the exaggerated slopes graphically and the true slopes numerically. The scale is oriented in the direction of the inclined planes. The direction of the inclined planes coincides with the preferred tornado path direction so that the individual inclined plane trace portrays a profile which most mapped tornadoes traverse. This permits not only visual evaluation but also allows for each sample unit the determination of a mean positive, mean negative, or neutral slope category in relationship to its principal tornado direction.

Data Analysis

The complete data of tornado frequencies, and the three terrain parameters of elevation, slope, and roughness were then punched on tape and subjected to a computer multiple correlation analysis. The correlation coefficients for significantly related variable pairs are shown on Table IV.

TABLE IV

SIGNIFICANT TORNADO-TERRAIN CORRELATION COEFFICIENTS

Variables	Correlation Coefficient	Z-score
x(1) vs x (3)	R = -0.184323	Z = -4.20246
x(1) vs x (4)	R = -0.077531	Z = -1.75098
x(3) vs x (4)	R = 0.322922	Z = 7.54841

x(1) tornado frequencies (dependent variable)
x(3) values of terrain roughness
x(4) elevation of terrain

The highest correlation coefficient is found for the variable pair x(3), x(4), which indicates that terrain roughness increases with elevation and its significance is attested by a very high z-score. The second highest correlation of R = -0.184323 points out a decrease of tornado frequencies with increase in surface roughness. Although the coefficient of correlation is low the z-score of 4.20246 denotes significance. The third pair of tornado frequencies and elevation shows the lowest correlation and the least significant z-score. The computed multiple correlation coefficient of .18579 and its coefficient of multiple determination of .03452 explains only three and one-half per cent of all tornado frequencies.

Though the initial cartographic evaluations had given rise to very encouraging conclusions, the correlation coefficients do not offer equally encouraging support. However, when considering that correlation analysis renders one measure of correlation for each variable pair and only one value for all variables it becomes clear that significant trends within the compared data are not shown. It is also known that frequency distributions of different linear configurations will not correlate too well. Furthermore, it must be remembered that one terrain parameter was measured by an ordinal scale and the two others were measured at grouped interval scales. The correlation analysis technique, however, works best for interval scale variables. Hence, the validity of the discussed multiple correlation analysis results is questionable. Therefore, it was decided to test the relationships of tornado frequencies and each terrain parameter with a more effective statistical technique, the Goodman and Kruskal Tau test. This test can measure associations for variables at ordinal and interval scales. Tau test values of 1 indicate a perfect association, and 0 shows that there is none. The data of the two variables under test must be arrayed in a contingency table which also permits visual evaluation of distribution and relationships. The significant findings of the results of the Tau test are then compared with the results of Safford's work[4] which to the knowledge of this author is the only other existing research report on terrain-tornado occurrence relationships.

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[4]Safford, <u>op. cit.</u>, pp. vi + 82.

Tornado Occurrences by Slope Categories

The previously found correlation coefficient for tornado frequencies and slopes measures a modest .015148. When, however, the 511 tornadoes are arranged in the 7 x 5 matrix, Table V, a significant bell-shaped distribution becomes apparent.

TABLE V

SLOPE CATEGORY AND TORNADO FREQUENCY MATRIX

Slope Categories	Tornado Frequencies by Sampling Units					Total
	1	2	3	4	5	
+3	2	--	--	--	--	2
+2	11	5	1	--	--	17
+1	86	22	10	3	2	123
0	149	63	16	2	2	232
-1	83	28	6	1	--	118
-2	11	3	1	--	--	15
-3	4	--	--	--	--	4
Total:	346	121	34	6	4	511

Almost 50 per cent of all tornado occurrences are found at the modal group of 0 slope category. Over 90 per cent occur at +1, 0, and -1 slope categories. The number of tornado occurrences is seen to decrease rapidly with increase in slope categories. Most tornado frequency scores on positive slopes are slightly higher than those on negative slopes. Safford[5] concurs that tornadoes have some preference for positive slopes. The matrix demonstrates further a correlation of slope categories and tornado frequencies per sampling unit. The one frequency per unit scores which have the highest possibility to occur at any place by chance are found at all slope categories. Nevertheless, 90 per cent of all occurrences cluster between the +1 and -1 slope categories. The number of all 2-tornadoes-per-unit occurrences is less than one-third of the number of 1-tornado-per-unit scores and none of them occur at the extreme slope categories. As one looks at the higher tornado frequencies of 3, 4, and 5 occurrences per sampling unit it becomes apparent that each successively larger frequency shows a successively smaller number of occurrences. The range of slope categories on which these tornadoes touch down or move along becomes also successively smaller. Since these high tornado frequencies rule out the possibility of having all occurred in the same unit per chance, one can conclude that most tornado touch-downs and paths are influenced by slopes. This conclusion is confirmed by the high Tau test value of .55. The majority of tornadoes are,

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[5] _Ibid._, p. 64.

therefore, expected to touch down and move along shallow slopes with a slight preference for positive slopes.

Tornado Occurrences by Terrain Roughness

The correlation coefficient of -0.184323 for tornado frequencies and terrain roughness is shown on Table IV. The high negative z-score indicates a significant inverse relationship for both variables. The 6 x 5 matrix, Table VI, displays this inverse relationship very well.

TABLE VI

TERRAIN ROUGHNESS AND TORNADO FREQUENCY MATRIX

Terrain Roughness Values	Tornado Frequencies by Sampling Units					Total
	1	2	3	4	5	
0	59	30	11	2	1	103
1	156	65	17	4	3	245
2	96	22	6	--	--	124
3	22	4	--	--	--	26
4	10	--	--	--	--	10
5	3	--	--	--	--	3
6	--	--	--	--	--	--
Total:	346	121	34	6	4	511

With the exception of tornado frequencies at roughness value 1, a perfect linear distribution exists. This irregularity can, however, be explained since one 100 foot contour per sampling unit could have its second contour at a distance of 6 miles or more. This, according to the definition on Table III, would classify them as a 0 slope category. Since the slope categories and terrain roughness values are closely related the number of tornado occurrences at slope category 0 on Table V should indicate how many of the 245 tornado occurrences at terrain roughness value 1 on Table VI actually belong to the 0 roughness frequencies. Table V shows that there are 232 tornadoes at 0 slope category and, therefore, it can be assumed that about 50 per cent of all tornado frequencies at terrain roughness values 1 on Table VI occur at terrain of 0 roughness. This would result in a perfect linear distribution which indicates that the higher the tornado frequency per sample unit the lower the roughness values at which they occur. Since the occurring of high frequencies by chance is minimal, it can be concluded that tornadoes generally prefer surfaces of low roughness values. The Tau test shows a .56 measure of high association which supports the same conclusion. Safford concurs with the following statement:

> The smooth portion of 72 per cent of the [study] area contains 82 per cent of the tornadoes, while the remainder occurred in the rough 28 per cent of the area. Over the entire geographical area

> considered, this is a clear indication that tornadoes avoid the rougher terrain areas on the 30-mile scale.[6]

The geographic distribution of the various roughness values in Michigan are mapped on Figure 13, and the preference for smooth terrain which most tornadoes exhibit becomes apparent. The high correlation of terrain roughness and elevation pointed out by the correlation analysis coefficients on Table IV is also readily perceived. Safford compared the roughness and north-south slope distributions and found the following elevation-roughness relationships: "For the best visual fit of this skewed distribution 30 minute squares with values above 3,500 feet were considered smooth."[7] For the Michigan study roughness values of 3, 4, 5, and 6 are considered rough.

Tornado Occurrences by Elevation

The correlation coefficient of -0.0775 for tornado frequencies and elevation shown on Table IV is not very significant, and yet the 10 x 5 matrix Table VII shows a skewed distribution with most tornadoes occurring at 700 foot elevations. The number of tornadoes decreases

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[6] *Ibid.*, p. 67.

[7] *Ibid.*, p. 45.

Figure 13-- TERRAIN ROUGHNESS OF THE LOWER PENINSULA OF MICHIGAN

for higher and lower elevations. Planimeter measurements of the areas of the various elevation zones bounded by the 100 foot contours for the Lower Peninsula show a distribution which is very similar to the tornado frequency distribution by elevation.

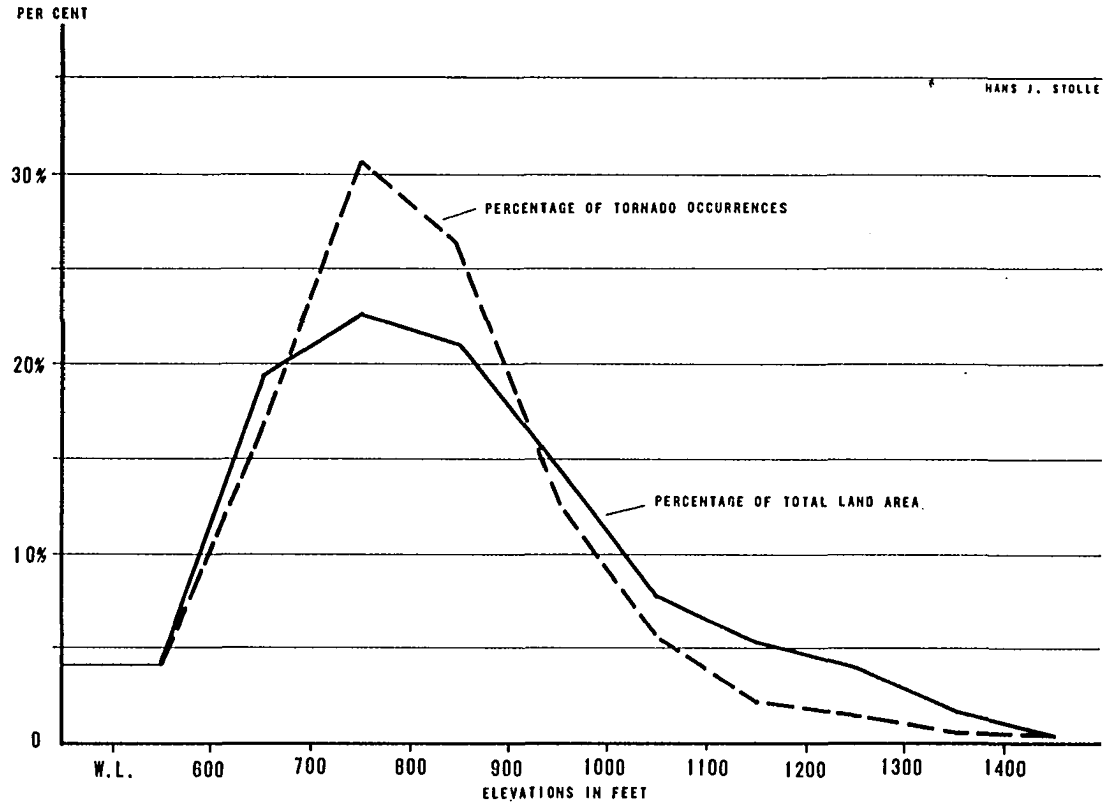
TABLE VII

ELEVATION AND TORNADO FREQUENCY MATRIX

Terrain Elevations in feet	Tornado Frequencies by Sampling Units					
	1	2	3	4	5	Total
1,400	1	--	--	--	--	1
1,300	3	--	--	--	--	3
1,200	8	1	--	--	--	9
1,100	9	2	1	--	--	12
1,000	22	7	1	--	--	30
900	53	15	3	--	--	71
800	89	29	8	3	2	131
700	89	38	17	2	1	147
600	63	20	4	--	1	88
500	9	9	--	1	--	19
Total:	346	121	34	6	4	511

Both distributions are compared on Figure 14. There is no doubt that the percentages of tornadoes occurring at the various elevation zones are similar to the percentages of land areas of these zones. However, not all

Figure 14-- DISTRIBUTION OF TORNADO OCCURRENCES AND LAND AREA AT SELECTED ELEVATIONS, 1930- 1969



parts of the Lower Peninsula are affected by tornadoes and, therefore, the similitude of both distributions is not as significant as it appears to be. Still, it could be argued that this finding negates the significance of the correlation coefficient. However, as it is seen on Table VII there is a decrease in elevation range with each increase in tornado frequency. Again, the high frequencies of tornadoes per sampling unit can be used to test the distribution's validity. The very high frequencies of 4 and 5 tornadoes per unit occur at elevations below 900 feet only. The less pronounced decrease of tornado occurrences with increase of frequencies at elevations below 700 feet reflects, probably, the smaller land areas for these elevations. Therefore, the frequency distribution is most likely an inverse linear distribution which shows a decrease of tornado occurrences with increase in elevation. Safford[8] found similar trends in his study. Figure 15 shows all Lower Peninsula land areas of 900 feet elevations and above, and most of these areas coincide with roughness values 3, 4, 5, and 6. A comparison with Figure 3 shows that the 900 foot elevation contours coincide almost with the Saginaw-Saugatuck corridor's lateral boundaries.

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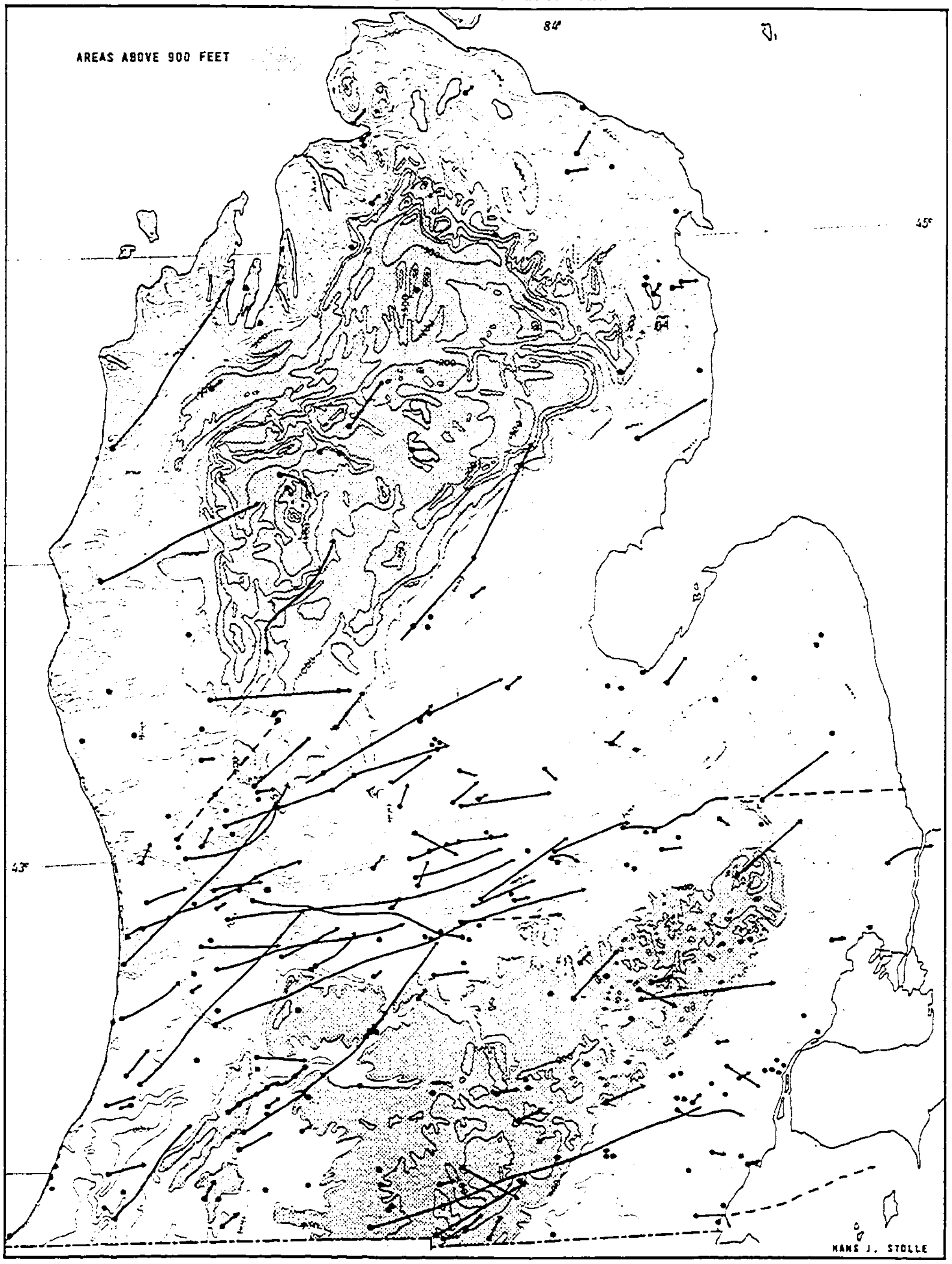
[8] *Ibid.*, p. 65.

Figure 15-- LAND AREAS 'WITH ELEVATUIONS OVER 900 FEET IN THE LOWER PENINSULA OF MICHIGAN



Summary

This chapter has applied several statistical techniques to test the significance of the relationship between relief and tornado occurrences. A multiple correlation analysis identified satisfactory correlations , but the very nature of the data limited this technique's strength considerably. The Goodman and Kruskal Tau test proved to be more suitable since it measures associations of one independent and its dependent variable at ordinal and interval scales. The Tau test contingency tables provided graphical distributions and relationships also. The results of the test confirmed that most tornadoes prefer gentle slopes over steep slopes. Consequently, most tornadoes avoid areas of undulating or rough topography. Thirdly, tornadoes occur most frequently at elevations below 900 feet. These findings concur generally with Safford's conclusions and verify the speculative assumptions of Chapter III which identified the Saginaw-Saugatuck corridor and other major depressions as main tornado areas. The study of tornado habits and the recognition of some of their causal factors discussed in Chapters III and IV yield evidence that tornado patterns have a non-random distribution, and that perhaps knowledge of the pattern of the past represents a predictive tool for the future.

CHAPTER V

TORNADO PROBABILITIES FOR THE LOWER PENINSULA OF MICHIGAN

The investigations of the first half of this study were primarily concerned with the compilation and analysis of tornado occurrences in the past. This next portion will employ statistical inference to explore probabilities of tornado recurrence.

Data Preparation

The study applies Thom's methodology of tornado probability evaluation. The statistical methods and their validities are described in detail by Thom[1] and only the portions used for this study are here reviewed briefly. First, it must be remembered that all tornado paths are different in length and width and that, therefore, all path areas differ too. The investigation of path length and width was discussed in Chapter III and representative mean measurements were found. Thom bases his probability of a tornado striking a point on a

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[1] H. C. S. Thom, "Tornado Probabilities," Monthly Weather Review, XCI (October, 1963), pp. 730-736.

representative mean path area which he develops and defines. At the outset he demonstrates that the distribution of tornado path length and width are normally distributed when their dimensions are transformed to lognormal values. The relationship of both normalized path dimension distributions are then tested by a correlation analysis. Next, the logarithmic mean path area is found simply by adding the logarithmic path length and width means.

$$\ln(\bar{a}) = \ln(\bar{l}) + \ln(\bar{w}) \qquad (2)$$

where ln are the Naperian logarithms of $\bar{a}$ the mean area, $\bar{l}$ the mean path length, and $\bar{w}$ the mean path width. Since the Naperian logarithms of the path lengths and the path widths are distributed normally, their sums (areas) are also normally distributed. However, an adjustment for the correlation of path length and width must be made to find the expected mean path area. First, the path area variance $\sigma^2(a)$ is calculated from widths and lengths variances, standard deviations, and correlation coefficient,

$$\sigma^2(a) = \sigma^2(l) + \sigma^2(w) + 2\rho(l,w)\ \sigma(l)\ \sigma(w) \qquad (3)$$

of which half is then added to the mean path area $\ln(\bar{a})$ to adjust for the correlation of path length and width. This finds the expected mean path area ln Ea.

$$\ln\ (Ea) = \ln\ \bar{a}\ + 1/2\rho(a) \qquad (4)$$

The antilog value Ea is thus Thom's mean path area expressed in mile yards which is then divided by 1,760 to give square miles. "By the principles of geometric probability," Thom states that, "the probability of a tornado striking a point is the ratio of the mean area covered by tornadoes per year to the area over which the tornadoes may occur."[2] This provides the necessary probability formula

$$P = \frac{Ea\ \bar{t}}{A} \tag{5}$$

where P is the mean probability of a tornado striking a point in any year for a given geographic area A in square miles. Ea represents the mean path area obtained from formula (4) and $\bar{t}$ stands for the area's mean annual tornado occurrences.

Records for 112 tornado path length and width pairs were found in the data of the 246 tornado occurrences for the 40 year period in Michigan. These sample pair values were transformed to Naperian logarithms and punched on tape for computer correlation analysis. Table VIII shows the necessary parameters for the probability calculation which were obtained from the correlation analysis.

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[2] Ibid., p. 736.

TABLE VIII

STATISTICAL PARAMETERS OF TORNADO PATH LENGTH AND WIDTH

Statistical Parameters	Path Length l	Path Width w
mean	1.4300	4.3690
s	1.3559	1.1524
s^2	1.8385	1.3280

correlation coefficient $\rho(l,w) = +.488701$

The expected mean Michigan tornado path area (Ea) is found by inserting the various statistical paramenters in Table VIII into Thom's formulae.

$$\ln(\bar{a}) = 1.4300 + 4.3690$$
$$\ln(\bar{a}) = 5.7990. \qquad (2)$$

To adjust this mean path area for the mean path length and width correlation the mean path area variance is calculated

$$s^2(a) = 1.8385 + 1.3280 + .9774\ (1.3559 \times 1.1524)$$
$$s^2(a) = 4.6938 \qquad (3)$$

and the expected mean path area is found by adding one-half of the area variance to the mean path area

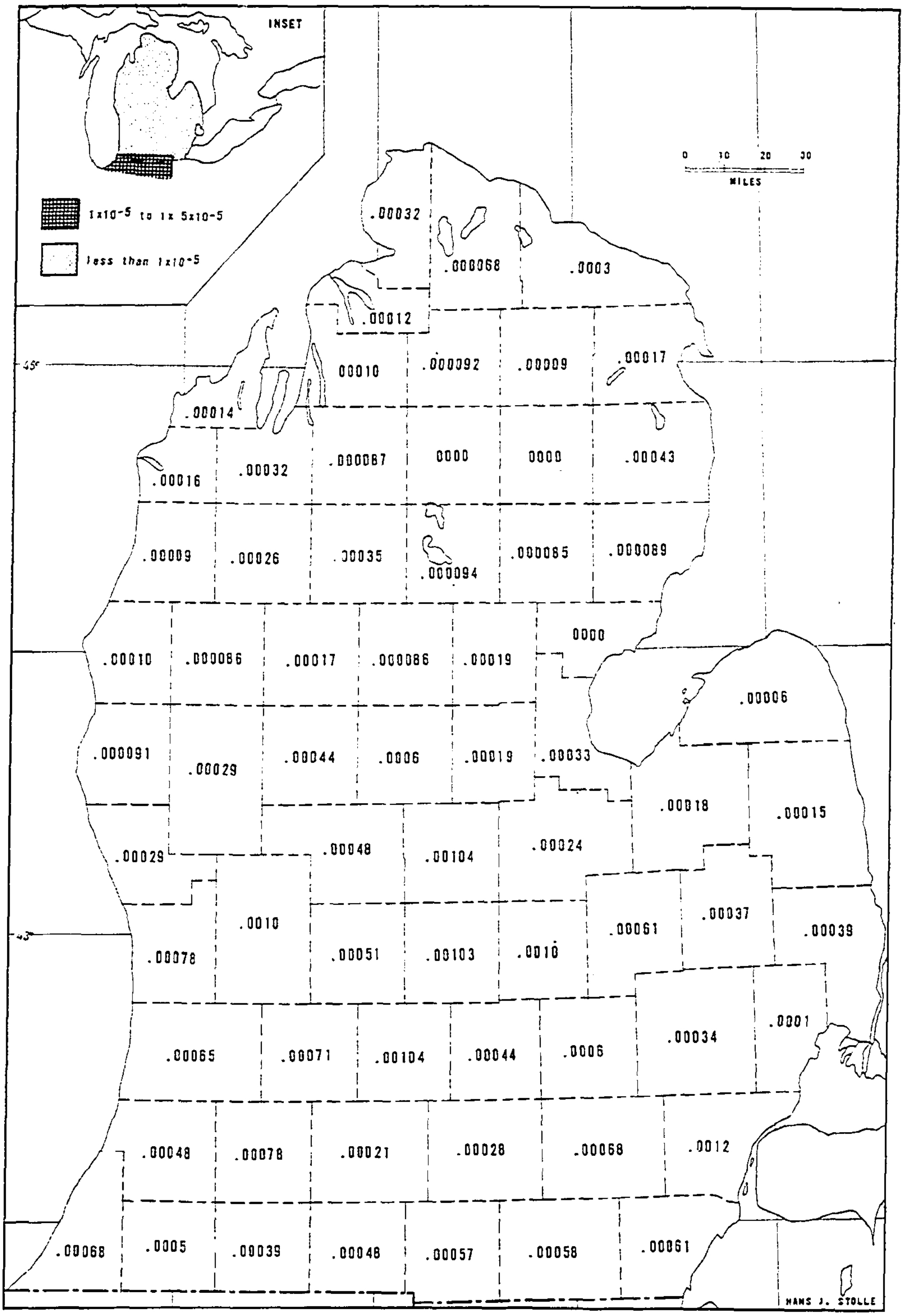
$$\ln\ (Ea) = 5.7990 + 2.3469$$
$$\ln\ (Ea) = 8.1459. \qquad (4)$$

The antilog Ea equals 3449.208 mile yards which represent an area that is 3449.208 yards wide and one mile long. The mile yard area is then divided by 1,760 which results in Ea = 1.9597 square miles.

Data Analysis

The calculated mean path area (Ea) is then used with formula (5) to compute tornado probabilities for the counties in the Lower Peninsula. Since the mean number of tornadoes per year $\bar{t}$ and the geographic area A vary for each county, the calculations differ for each of the 68 counties and are, therefore, not given here. The results of tornado probabilities by counties are shown on Figure 16. These probability values are seen to range from less than 1×10^{-5} to more than 1×10^{-4}. This indicates that the former has a recurrence interval, for a tornado striking any point in the county, of R = 1/P or 10,000 years. Counties with the latter probability values have a recurrence interval of 1,000 years. Tornado probability values are closely related to number of occurrences shown on Figure 2 and hence, probability patterns are similar to occurrence patterns. However, since the area of each county has an effect on its probability value some shifts of magnitude are evident. Kent County, for instance, records the highest number of

Figure 16-- PROBABILITIES OF TORNADO RECURRENCE FOR COUNTIES IN THE LOWER PENINSULA OF MICHIGAN



tornado occurrences on Figure 2 but ranks only sixth in tornado probability on Figure 16. Other shifts become apparent when both maps are carefully compared. The Saginaw-Saugatuck corridor contains the highest probabilities with a second area of high probabilities at Wayne County and its adjacent counties in the west and south. The inset on Figure 16 shows the Michigan portion of Skaggs'[3] study of tornado probabilities for the United States east of the 104th meridian. His work is also based on Thom's methodology and hence, his results are compatible with the findings of this study. The increase in probability detail with decrease of sample area size becomes apparent since Skaggs' study shows an almost uniform probability pattern for the entire Lower Peninsula. The very thin border zone of higher probabilities in the southern parts is mainly due to spillover from Indiana. The increase in detail on Figure 16 does not only point out higher probabilities for certain areas but also shows that some areas in the Lower Peninsula have zero tornado probabilities.

The achieved increase in detail through decreasing the sample area size from 100 x 100 miles (Skaggs' study)

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[3]Richard H. Skaggs, "On Tornado Probabilities," Proceedings of the A.A.G., II (1970), pp. 123-126.

to 25 x 25 miles (approximate average county size) is remarkable. It was therefore decided to go one step further and compute probabilities for the 6 x 6 miles sample areas that were used for the tornado-relief analysis in Chapter IV. The calculations involved very little extra data manipulation since the tornado frequencies for 40 years were previously found to range from 1 to 5, and because the uniform sample area and mean path area (Ea) remain a constant 36 square miles and 1.96 square miles respectively for all calculations. Table IX shows the 5 tornado probability values by 6 x 6 mile areas.

TABLE IX

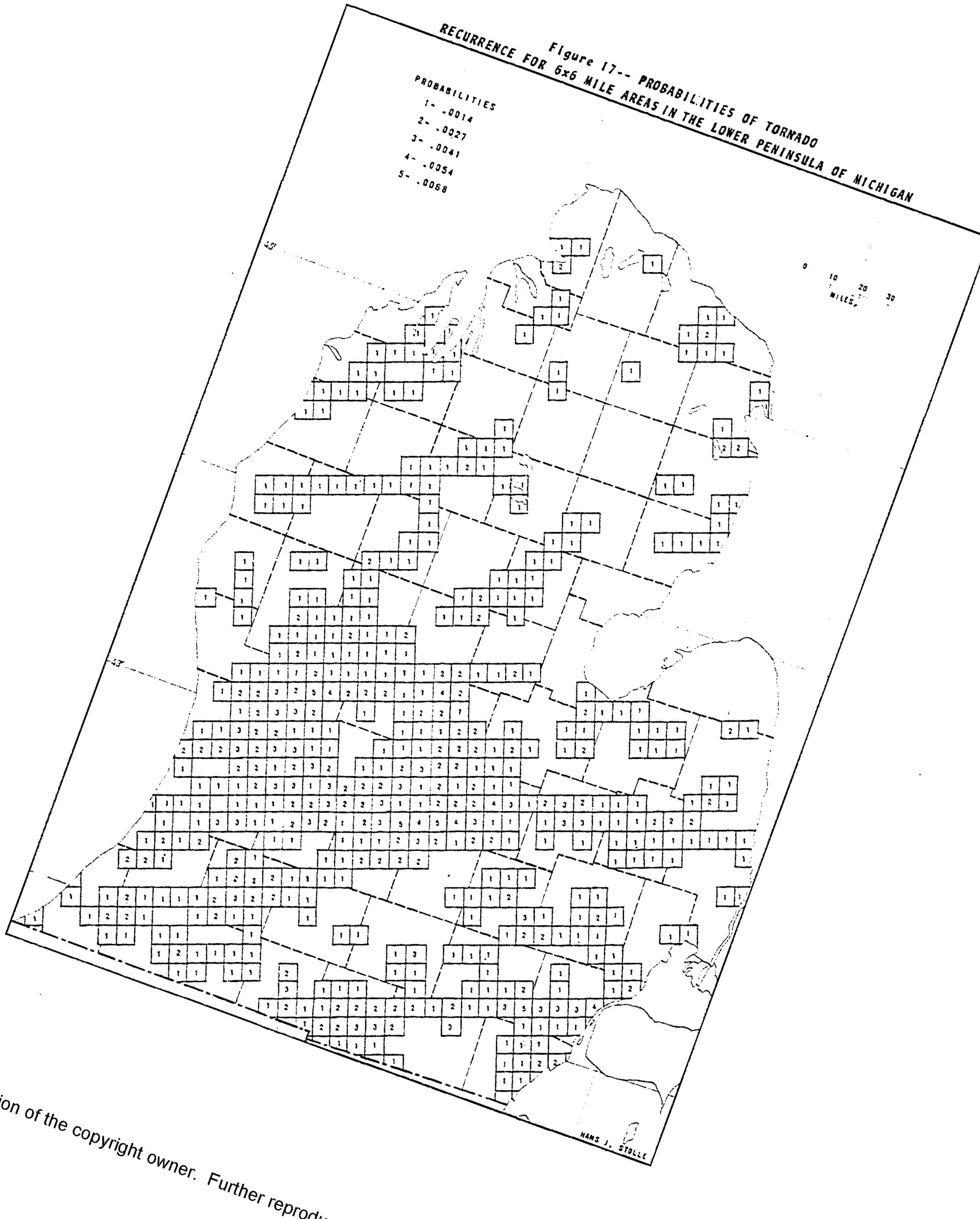
TORNADO PROBABILITIES FOR THIRTY-SIX SQUARE MILE AREAS

Occurrences for 40 Years t	Mean Annual Occurrence $\bar{t} = t/40$	Probabilities P		Recurrence Ratio 1/P
1	.025	.0014	$1.4\text{x}10^{-4}$	714 years
2	.050	.0027	$2.7\text{x}10^{-4}$	370 years
3	.075	.0041	$4.1\text{x}10^{-4}$	244 years
4	.100	.0054	$5.4\text{x}10^{-4}$	185 years
5	.125	.0068	$6.8\text{x}10^{-4}$	147 years

The spatial occurrences of the five probabilities are mapped on Figure 17. The patterns differ considerable from the patterns on Figure 16. Significant increases are noticed at the extreme ends of the probability range. For instance, we find a great increase in areas of no occurrence as well as a noteworthy addition of areas of higher probabilities. The mapped probabilities range now from 1.4×10^{-4} to 6.8×10^{-4} which shows mean recurrence interval ranges from 714 years to 147 years for a tornado striking a given point in the 36 square mile areas. These probabilities are much higher than those shown on Figure 16 and speak much for the usefulness of Figure 17. The areas of highest recurrence probabilities are primarily located in the Saginaw-Saugatuck corridor. More specifically, they are found near Cedar Springs, Kent County; just northwest of Alma, Gratiot County; and in a strip extending from Grand Ledge, Eaton County touching northern Lansing, and East Lansing in Clinton and Ingham Counties to Owosso in Shiawassee County. An additional area of high probabilities is found south of Ypsilanti, Washtenaw County, which stretches in northeasterly direction to Grosse Pointe, Wayne County.

Areas of secondary probability importance are found near most primary probability areas. Other secondary

Figure 17-- PROBABILITIES OF TORNADO RECURRENCE FOR 6x6 MILE AREAS IN THE LOWER PENINSULA OF MICHIGAN



areas are at Grand Rapids, Kent County, and its neighboring areas to the north, south, and west. Further small areas of secondary probabilities are found near Allegan, Allegan County; Hastings, Barry County; and Portage in Kalamazoo County. In the central portion of southern Michigan secondary probability areas are located in the western parts of Clinton County; Corunna in Shiawassee County; and Flint in Genesee County. The remaining secondary areas are scattered throughout southern Michigan and are found near Brighton, Livingston County; east of Jackson, Jackson County; in the vicinity of Coldwater, Branch County; and the southeastern part of Hillsdale County. While areas of lowest probability are found all over the Lower Peninsula, most areas with the higher probability values of 2.7×10^{-4} are primarily located in the Saginaw-Saugatuck corridor.

Summary

This chapter demonstrated the utility of statistical inference for tornado probability determinations for the Lower Peninsula of Michigan. Tornado probabilities for sample areas of 10,000 square miles, 625 square miles, and 36 square miles were calculated, mapped, and compared. It was found that each decrease in sample area size produced an increase in probability range and precision of spatial delineation. This tempts one to believe that repetition of this process could produce even more accurate probability results. However, at first it must be cautioned that some tornado touch down and path locations are not known within several miles. Secondly, it must be realized that the mapping scale imposes limitations on measurement accuracy. Thirdly, it is known that spatial relationships can become insignificant when they are assessed for extremely small areas. Therefore, the 6 x 6 miles sample area which equals the area of a township can be considered effective and efficient. The derived areas of primary and secondary tornado probabilities represent, therefore, locations of great interest. Next, it seems logical to focus on these areas to learn more about the impact of such tornado probabilities. Since most areas of high probabilities appear to coincide with densely populated areas, a study of tornado impact on man seems appropriate.

CHAPTER VI

POTENTIAL TORNADO CASUALTIES FOR THE LOWER PENINSULA OF MICHIGAN

The literature on tornado occurrences cites frequently high findings of correlations of population densities and tornado occurrences. In many cases the findings were, however, rejected for reasons of probable bias or over-zealous reportings. Should one, however, question the validity of such high correlations or should we simply recognize that we often find high tornado frequencies in densely settled areas? Surely, the latter fact in itself is worth investigating since the impact of a given tornado on population in densely settled areas tends to be much higher than in sparsely populated areas.

The study of Michigan tornadoes described in the previous chapters found high tornado concentrations in the Saginaw-Saugatuck corridor and in the Hillsdale and Wayne County areas. A comparison with Stilgenbauer and Honzatka's population map,[1] Figure 18, reveals similar high concentration of population in most of these tornado

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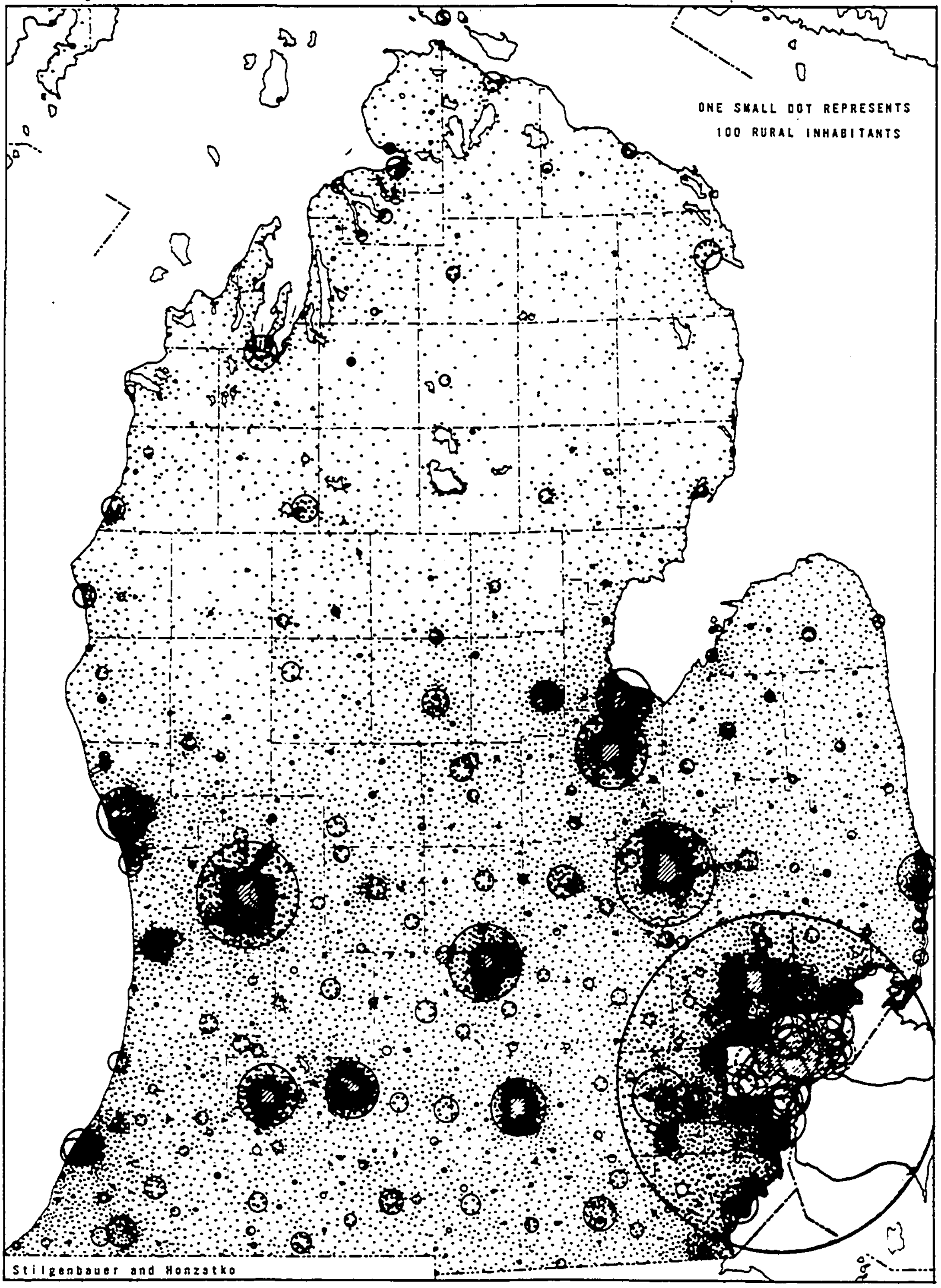
[1]Bert Hudgins, Michigan: Geographic Backgrounds in the Development of the Commonwealth (Detroit, Michigan: B. Hudgins, 1961), p. 109.

Figure 18-- POPULATION DISTRIBUTION OF THE LOWER PENINSULA OF MICHIGAN, 1950



areas. To test the impact of tornadoes on populations of the 68 counties of the Lower Peninsula, the records of 222 tornado deaths for the 1930-1969 period were mapped in Figure 19. It can be observed that the locations of the disaster areas correspond closely to population density patterns. Considering, however, that almost 90 per cent of all deaths occurred at four disaster locations, it becomes clear that tornado fatalities are not necessarily indicative of the total tornado impact on population. Number of injuries, value of property damages, and death rates combined would probably lead to a more accurate evaluation of tornado impact.

An effective index of tornado impact on population was devised by Sadowski.[2] His index calculates potential casualties from tornadoes. This should not be interpreted as probable death rates but rather should be viewed as a measure of possible casualties including deaths and injuries. If we take the mean tornado path area Ea = 1.96 square miles (given in Chapter V) we can find PC, the potential tornado casualties per square

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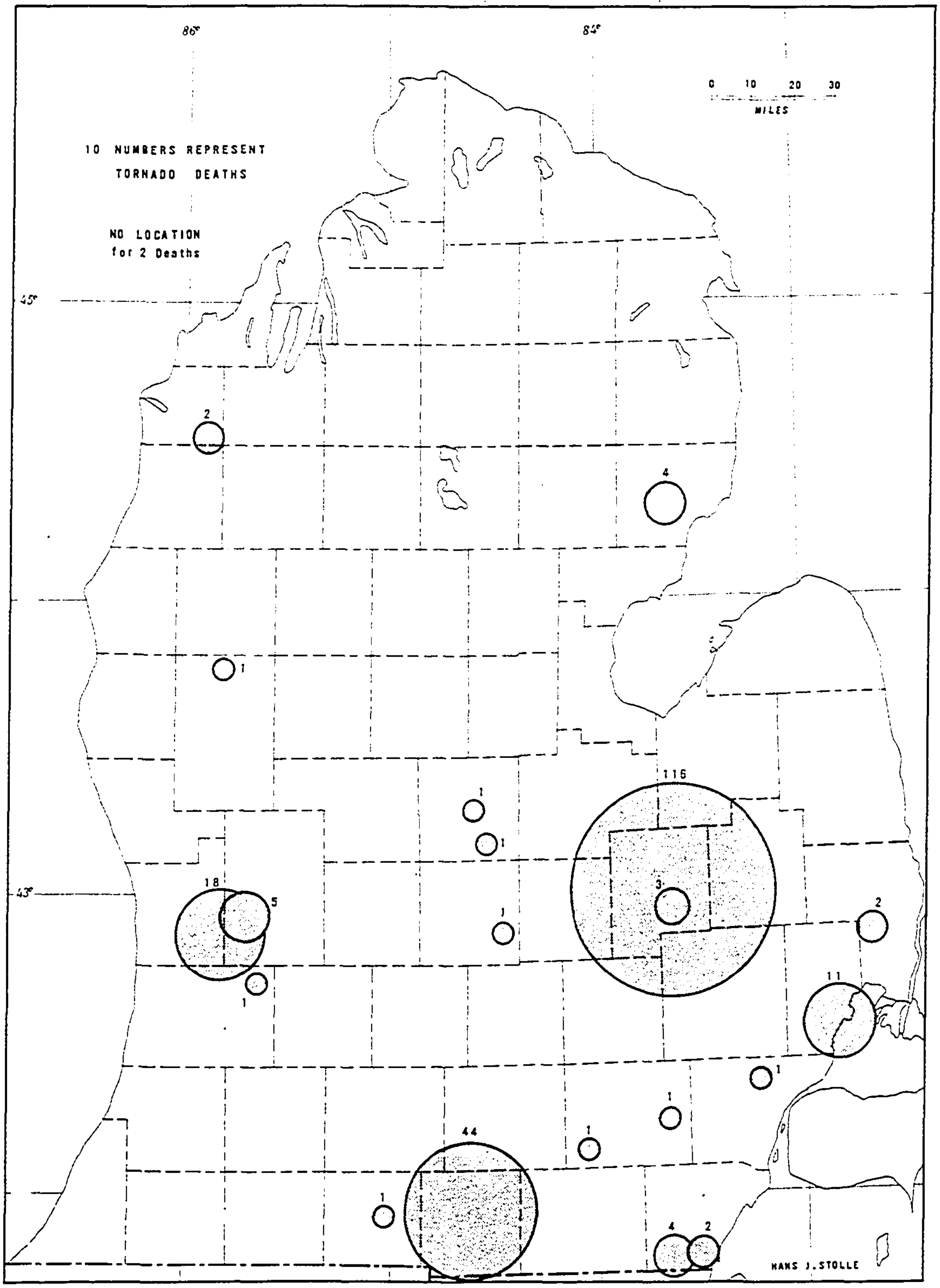
[2]Alexander Sadowski, "Potential Casualties from Tornadoes" (paper presented at the 244th meeting of the American Meteorological Society; Cloud Physics and Severe Local Storms, Reno, Nevada, October 18-22, 1965), pp. 1-10.

Figure 19-- LOCATION OF TORNADO DEATHS IN THE LOWER PENINSULA OF MICHIGAN, 1930-1969



mile for a given period of years with

$$PC = \frac{Ea\ t}{A} \times D \qquad (6)$$

where t is the number of tornadoes per sample area A in square miles, during a given period of years, and D is the number of persons per square mile ratio for the sample area A.

The potential casualties for the 68 counties in the Lower Peninsula were calculated from the county figures of 40 year tornado occurrences (Figure 2) and square mile and population density values.[3] The mapped potential casualty values by counties (Figure 20) show the combined effects of tornado occurrences and population densities. Therefore, areas with high population densities and high tornado occurrences show extremely high potential casualty values, while counties with low population density and high tornado occurrence and vice versa show potential casualty rates between medium and high values. However, when interpreting these patterns, one must be aware of the possible shortcomings of this method. Firstly, since the calculated values represent potential casualties from tornadoes for the past 40 years, one has

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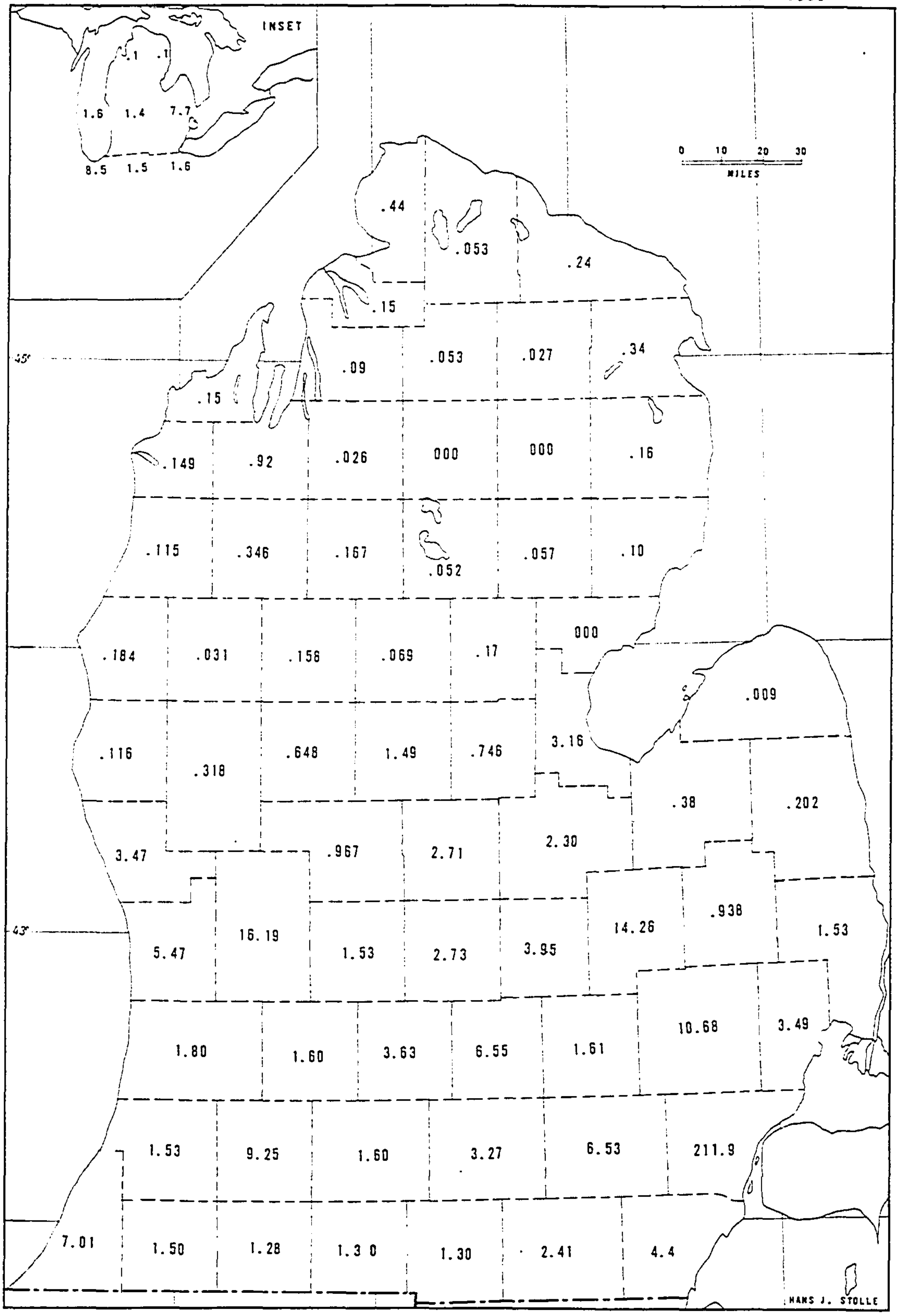
[3]Division of Research, Graduate School of Business Administration, Michigan State University, <u>Michigan Statistical Abstract, 1970</u> (Lansing: Michigan State University, 1970), pp. 19, 90.

Figure 20-- POTENTIAL CASUALTIES FROM TORNADOES FOR COUNTIES IN THE LOWER PENINSULA OF MICHIGAN, 1930 -1969



to divide the potential casualties by 40 to arrive at a mean annual potential casualty figure. Secondly, the population figures for each county were taken from the 1960 census counts and thus do not represent the population that was actually affected during the 40 years. The average population per county for the 1930-1969 period would have been more appropriate. Hence, the county indices of potential casualties from tornadoes should be considered only as relative values which identify counties of high, medium, and low potential casualty occurrences per square mile. Nevertheless, the method provided a useful map index with a minimum requirement of data information which emphasizes the method's usefulness for tornado impact assessment.

The inset on Figure 20 shows the Michigan coverage of Sadowski's work[4] which investigated the potential casualties from tornadoes for the "tornado belt" areas of the United States. A significant increase in detail and accuracy with decrease in sample size area is seen when Sadowski's map is compared with Figure 20. Not only does Figure 20 show a more variegated potential casualty pattern but also a considerable increase in potential casualty range is seen. The main

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[4]Sadowski, op. cit., p. 10.

concentrations of potential casualties are found in the southeast of the state with a secondary area in the southwest.

Table X shows the counties with the ten highest tornado frequencies, probabilities, and potential casualties.

TABLE X

COUNTIES WITH THE TEN HIGHEST TORNADO OCCURRENCES, PROBABILITIES, AND POTENTIAL CASUALTIES

Tornado Occurrences		Tornado Probabilities		Tornado Potential Casualties	
Kent	17	Wayne	00120	Wayne	211.00
Wayne	15	Gratiot	00104	Kent	16.19
Gratiot	12	Eaton	00104	Genesee	14.26
Clinton	12	Clinton	00103	Oakland	10.68
Eaton	12	Shiawassee	00101	Kalamazoo	9.25
Shiawassee	11	Kent	00100	Berrien	7.01
Allegan	11	Kalamazoo	00078	Ingham	6.55
Washtenaw	10	Ottawa	00078	Washtenaw	6.53
Kalamazoo	9	Barry	00071	Ottawa	5.47
Lenawee	9	Washtenaw	00068	Monroe	4.40

It is seen that some counties maintain their high position in all three categories, which indicates that they have high tornado occurrences and high population densities. These counties are Kent, Wayne, Kalamazoo, and Washtenaw. Others belong to the ten highest *tornado occurrence* counties but they do not appear in column 3 due to their low population density. A third group of counties has *tornado occurrences* below 9 and yet they rank high in *potential casualties* because of their high populations.

Since a further reduction in sample area size to 6 x 6 mile units had proven successful for the tornado probability investigation (Chapter V), it was decided to calculate Sadowski's potential casualties from tornadoes for the same 511 sampling units. This, however, posed the problem of finding the populations for each of these 511 sample areas. A population dot and graduated circle map was found to offer one feasible solution because such a map shows population distributions by dots which can be counted for each sample area. The sample area assessment of urban population shown by graduated circles is also possible. For instance, values of graduated circles representing urban areas that fall inside one sample area are simply counted for that sample area. Values of graduated circles for urban areas that occupy several sample units can be divided among these units proportionately. It should be recognized, however, that these values do not represent the exact populations per unit area, but that they are at best a reasonable approximation which suffices for the purpose of this study. The Michigan population map (Figure 18) was found to meet the requirements. Though the 20 year old map raised some doubts at first as to its suitability, it was discovered that it represents, by sheer coincidence, the approximate mean population for the 1930-1969 period. Hence, this map was used to find the populations for each of the 511 units and, together with their tornado frequencies, Sadowski's potential casualties were calculated. The results are mapped on Figure 21. The potential casualties from tornadoes are seen to range now from .2 to 449, which is twice the range shown on Figure 20. All units with potential casualty values of 10 and more were outlined as significant impact areas. Areas with values of 120 and more, or 3 persons and more per year, were classified as primary potential casualty areas. These areas are found in the vicinities of Detroit, Flint, Grand Rapids, Lansing, Kalamazoo, and Saginaw. Areas of secondary importance were based on values of 40-119 or 1-3 persons per year, and they are mainly located at the outskirts of the primary areas, with additional towns of Port Huron, Bay City, Alma, Owosso, Pontiac, Ypsilanty, Jackson, Coldwater, Battle Creek, and Hastings.

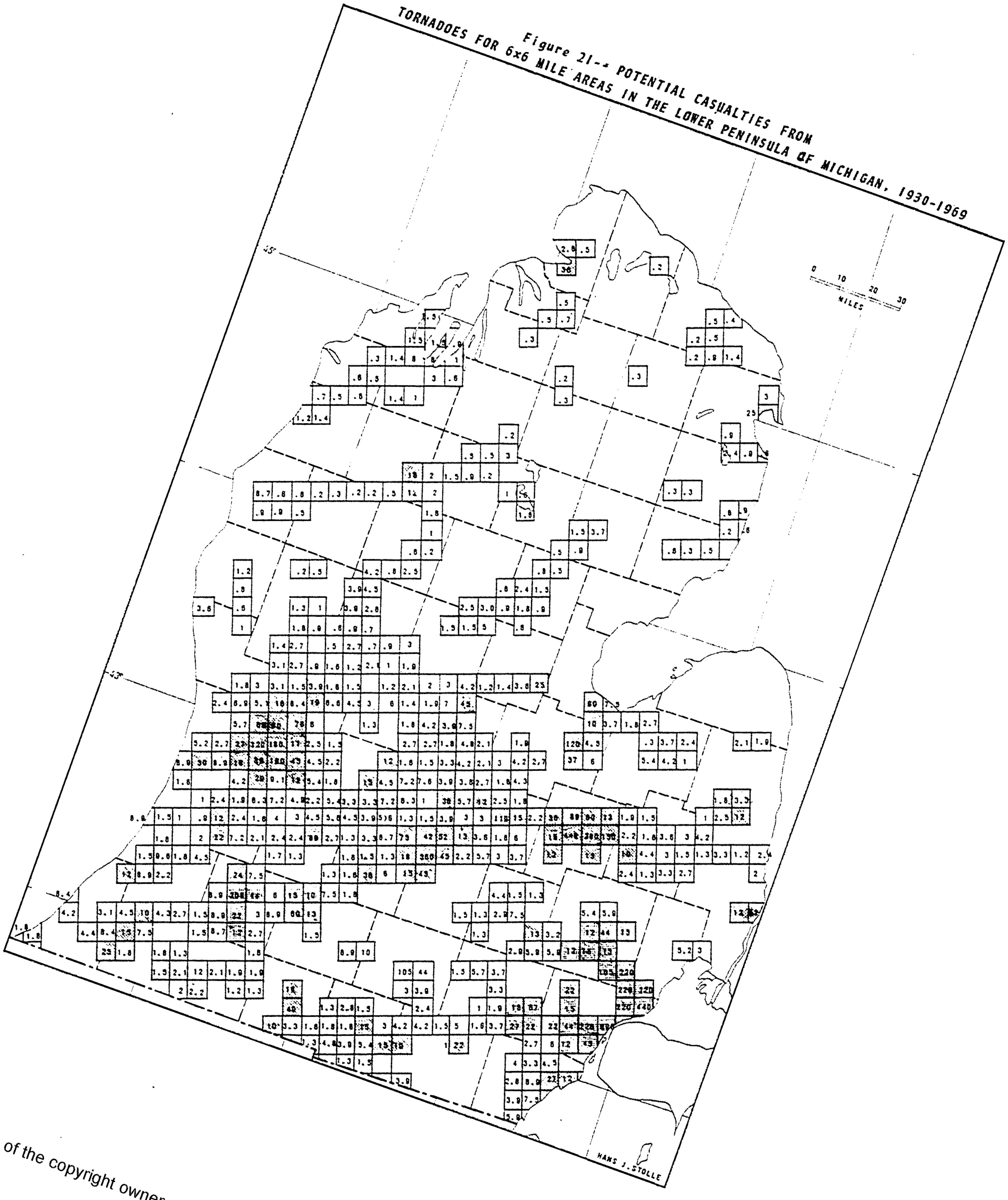

Figure 21.- POTENTIAL CASUALTIES FROM TORNADOES FOR 6x6 MILE AREAS IN THE LOWER PENINSULA OF MICHIGAN, 1930-1969

Summary

This chapter has examined the potential tornado impact on populations in the Lower Peninsula of Michigan. The investigations were implemented at three levels of sample areas with 10,000, 625, and 36 square miles. Similar to the probability study in Chapter V, the details and areal definitions improved with each decrease in sample area. Analogous to the variations of contour configurations with change in contour interval, the potential casualty pattern shifted with each change in sample area. The combined effects of tornado occurrences and population densities were found to become more pronounced with each reduction in sample size. A comparison of Michigan potential casualties from tornadoes for 40 years with the actual Michigan tornado deaths for that same period shows some verification of Sadowski's potential casualty theory. It is believed that combining actual injuries with deaths would lead to an even closer agreement of potential and actual casualty areas. This would prove the usefulness of Sadowski's index for planning and implementing precautionary and protective measures in areas of high potential casualties from tornadoes.

CHAPTER VII

CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

The results of this study have provided sufficient evidence to support the initially proposed research hypothesis that tornado frequencies in Michigan are significantly influenced by geographic latitude, season, and relief configuration. First, it was found that due to Michigan's extent in latitude there are several latitudinal zones of tornado occurrences which decrease in frequency with increase in latitude. A separate analysis of monthly tornado distribution by latitude provided proof that there is also a migration of the northern tornado limit which coincides with the annual migration of the sun. Secondly, it was found that most individual tornado paths favored specific relief configurations and that frequency of occurrence was reduced with increasing elevation, slope, and surface irregularity.

When considering the effects of all controlling factors in context of their geographic locations, we can recognize several regions of distinctly different tornado concentrations. We find 80 per cent of all Michigan tornadoes to the south of a line between Standish, Arenac

County and Ludington, Mason County. This dividing line coincides with the 44°N. parallel which also divides the 8 months tornado season areas in southern Michigan from areas with a 6 months season to the north. Within this southern region the relief effect on tornado locations is quite evident in the Thumb Uplands where only few occurrences are found. On the other hand, there are high tornado concentrations in the Saginaw and Michigan Lowlands which, with their broad and flat surface characteristics, make them particularly favorable tornado passages. The Erie-St. Clair Plain shows a secondary cluster of tornado occurrences. North of this primary region we find that the effect of latitude on tornado frequencies becomes greater, which places the second regional division between Alpena, Alpena County and Traverse City, Grand Traverse County. This division corresponds closely to the line of 45°N. latitude which also marks the decrease in tornado season by one additional month. About 11 per cent of all Michigan tornadoes are found in this second region, and the effects of relief on tornado locations are well exemplified by several tornado path-valley concurrences. The remaining northern part of the Lower Peninsula and the area of the Upper Peninsula represent a third and fourth tornado region. Both, however, show extremely low percentages of Michigan's tornado occurrences and there are many large areas in the Upper Peninsula that show no tornadoes for the 40 year period.

The discussed patterns of tornado frequencies and locations within the outlined regional division of the State of Michigan were found to be similar to patterns of calculated probabilities of tornado recurrence. Therefore, most areas inside the extreme southern region show high probabilities of tornado recurrence. A more detailed study, however, effectively isolated small areas of very high, high, midum, and low tornado probabilities. Further investigations tested the impact of the various tornado probabilities on population. The results identify small areas of primary, secondary, tertiary, and negligible potential casualties from tornadoes. Most primary areas of potential casualties from tornadoes were found to be located at the major urban areas of the southern part of the state with many secondary areas clustered at their perimeters. In addition, some small towns qualify as secondary potential areas due to their high tornado probabilities. In summarizing all findings it is evident that the core area of Michigan tornado activities is in southern Michigan and more specifically in the areas defined by the detailed studies of tornado occurrences, recurrence probabilities, and potential casualties.

In retrospect, it seems proper to explain why all areas without tornado occurrences were omitted from the various analyses. The reasons for that decision were twofold. Firstly, it was felt that a 40 year period of observations should identify tornado areas of considerable statistical significance and, secondly, it was statistically not feasible to calculate recurrence probability and potential casualties for areas without tornado occurrence. In any event, the results and conclusions of this study should not be viewed as indisputable and final. Instead, it is rather hoped that this investigation will stimulate different approaches to similar regional studies based on more observations, using more sophisticated evaluations and, perhaps, successfully combining meteorological and non-meteorological factors of tornado formations for the final analysis.

Suggestions for further research include the updating of this study which, because of its open-ended structure, permits periodical revision and reevaluation. Encouraging results are also promised by further investigations of tornado area-population relationships which perhaps together with highway density analysis could test the validity of tornado-population correlations. The established hierarchy of areas with probable tornado recurrence and potential tornado casualties and their spatial distribution lends itself as base for a hazard perception study. This work could also quite easily branch out to study housing standards in primary tornado areas. Cottages and house trailers, for instance, are more frequently damaged than sturdier structures. Mapping these house types could perhaps produce sufficient evidence to suggest certain building codes and location recommendations. Certain of the study's findings also offer guidelines for persons involved in planning and maintaining safety and insurance for the public. For example, many potential earthquake regions enforce already rigid building standards and, if similar precautions should ever be enforced in parts of Michigan, the areas identified as primary and secondary tornado hazard areas could provide a useful base for zoning building standards. Considering that Thom's study of tornado probabilities for Iowa and Kansas was initiated on request of an insurance company speaks for the potential utility of the present study in that field.

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