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A COMPUTER SIMULATION OF THE EFFECTS OF POSSIBLE TORNADO MODIFICATION ON THE EXTENT OF THE TORNADO HAZARD

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A COMPUTER SIMULATION OF THE EFFECTS OF POSSIBLE

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

A COMPUTER SIMULATION OF THE EFFECTS OF POSSIBLE TORNADO MODIFICATION ON THE EXTENT OF THE TORNADO HAZARD

CHAPTER 1

INTRODUCTION

Tornadoes have caused approximately 225 million dollars damage and have killed 60 persons each year for the past five years. Tornado deaths account for 60% of the natural hazard deaths resulting from hurricanes, floods, earthquakes, and tornadoes in the United States (Mitchell, 1974, 316). The death and destruction totals are increasing because of the ever increasing population and property-at-risk.

One adjustment by which man can decrease the loss of life and property is to decrease the hazard producing mechanism. To date, man has been partially successful in decreasing some severe local storm losses, in particular hail losses (Battan, 1969). Meteorological research is continuing in the study of tornado mechanics and dynamics (Kessler, 1972). Because of the increasing population and property-at-risk, and the advances made in basic meteorological tornado research, it is likely that attempts will be made in the near future to modify the hazard producing properties of tornadoes.

Every natural hazard has three parameters controlling the extent of that hazard: frequency, magnitude, and intensity. Tornado modification could be aimed at decreasing any one or a number of these tornado parameters based on the expense involved and the level of technological ability. It therefore, becomes imperative to have theoretical information concerning the effects these tornado parameter adjustments would have on the extent of the tornado hazard. Such information would indicate the tornado parameter or combination of parameter adjustments that would decrease the tornado hazard to the greatest extent. Also it would enable researchers to predict, given the ability to decrease one or more of these parameters by a certain quantity, the expected decrease in the extent of the tornado hazard. This research examines the theoretical effects that adjustments of frequency, magnitude and intensity of tornadoes would have on the extent of the tornado hazard.

Natural hazard research, a truly interdisciplinary field, involves the study of the characteristics of natural hazard events and their interaction with the human use systems of the affected areas (Kates, 1971). Hazard researchers have, in general, limited themselves to five areas of investigation. These include (1) assessing the extent of human occupance of hazard zones, (2) identifying the full range of possible human adjustments to hazard, (3) studying human perception and estimation of hazard, (4) describing the process of adopting hazard adjustments, and (5) estimating the optimal set of adjustments and its social consequences (Mitchell, 1974, 312). Since this man-environment theme has long been a major focus in geography, geographers have contributed significantly to natural hazard research particularly in studying the variations in the pattern of extreme events (Mitchell, 1974, 313).

The need for accurate and complete assessment of the regional patterns of natural hazard damage potential is great. Such an assessment would enable man to translate these risk levels into economically feasible programs which are effective in disaster mitigation. H. C. S. Thom (Thom, 1963) has studied the variations of tornado frequency in the United States and has developed a method by which the probability of a point being struck by a tornado can be determined. By using Thom's data, the areal probability of a tornado striking a point within the region of highest frequency, Central Oklahoma, is approximately .0036 per year. The probability, for instance, of a tornado striking in a medium frequency area, Northern Indiana, is .0016 per year and in an area of low frequency, Central New York State, equals .00016 per year. These probabilities result in mean recurrence intervals for a tornado striking a point ($RI = \frac{1}{p}$) to vary from 277 years for high frequency areas to 6250 years in low frequency areas.

Mitigation of natural hazard damage losses can be accomplished by (1) compensating the losers through federal or private funds, (2) land use controls in areas of high risk, (3) building code supplements which require structures that can withstand the maximum credible event, and (4) decreasing the hazard producing mechanism. Since tornado probabilities and recurrence intervals are small and tornado winds have been estimated as high as 400 miles per hour, it is unlikely that the strengthening of building codes, analogous to flood proofing in flood prone areas, would be economically feasible. Tornado frequency varies continuously over the United States and no well defined area separates high and low risk areas as is present in flood prone areas. Also, the total area of land use controls would need to be extremely large and the structural investment in these areas is already enormous. Hazard mitigation through compensation to losers is a strategy that will become more undesirable as population and property-at-risk increases temporally. It, therefore, can be argued that the only truly acceptable method of tornado damage mitigation is the modification of the hazard producing mechanism. If this can be done more cheaply than compensating property owners, then modification is economically justifiable.

Because mitigation of tornado losses is likely to take the form of actual physical modification of tornadoes, the anticipated effects of this future modification must be known before tornado modification techniques are developed and attempted. Tornado modifiers must be aware of the overall anticipated benefit that changes in tornado frequency, magnitude and intensity have on decreasing the extent of the tornado hazard. This information would enable researchers to estimate, given the ability to decrease one or more tornado parameters, the anticipated decrease in tornado path area and an approximate decrease in damage losses. It is the goal of this research to provide this information which hopefully will be used by future tornado modifiers to estimate the effects their modification should have on decreasing tornado path area and enable them to determine a cost-benefit ratio.

Investigation of the theoretical effects of tornado parameter modification presents numerous methodological problems. The first involves the general type of model to be used in investigating these effects. Deterministic models are deductively derived and allow for no variance in the relationship among the phenomena under study (King, 1969, 3). Deductively derived models are inherently based on the initial assumptions and considering the absence of any empirical evidence concerning the relationship among frequency, magnitude and intensity of tornadoes, the deterministic model approach must be discarded. Indeterministic or stochastic models allow for variance in relationships among the phenomena under study, and are thus capable of more accurate representation of the process and form present in most "real world" relationships. L. J. King (King, 1969, 227) quotes L. Curry (Curry, 1966) as indicating that the stochastic approach has the advantage that "it allows a problem to be approached with the explicit admission of considerable ignorance." Because of the lack of knowledge concerning the exact relationships among the tornado parameters and the expected ability to stochastic models to more accurately represent the "real world," a stochastic model was used to investigate the relationship among the tornado parameters.

Solutions to stochastic models present other difficult problems. In situations where the model is complex, solutions are so complicated and distant from reality that the solutions, when applied to the original problem, may be difficult or impossible to interpret (Naylor, 1966, 6). In geography (King, 1969, 228) and other disciplines computer simulation has proved to be an efficient and preferred technique of numerical analysis for solving complicated stochastic models and a variety of other mathematical problems (Naylor, 1966, 7).

Computer simulation is a numerical technique for conducting experiments on a digital computer which involves certain types of mathematical and logical models that describe the behavior of a system over extended periods of time (Naylor, 1966, 3). As in the development of any model of some real system, computer simulation models involve a "trade off" between "pure" reality and simplicity. On one hand the model should serve as a reasonably close approximation to the real system and incorporate most of the important aspects of the system.

On the other hand the model must not be so complex that it is impossible to understand and manipulate. In most cases realistic models are not simple, and simple models are not realistic. Therefore philosophical decisions must be made by the model builder concerning the complexity of the model based on the problem under consideration (Naylor, 1966, 10).

Stochastic computer simulation, or Monte Carlo simulation, involves random sampling from one or more theoretical or empirical probability distribution functions. This probability distribution function or operating characteristic is used to generate the behavior of the system being simulated. Obviously, the accuracy of the results of any Monte Carlo simulation depend to a great extent on the ability of these functions to estimate the real system parameters (King, 1969, 229).

Computer simulation allows researchers to study the dynamics of the object system. Once a simulation is validated as representing an abstraction of the "real world" system, changes in the operating characteristics can be made to investigate the sensitivity of the system to the changes by examining the resulting output (Barton, 1970, 22). Sensitivity analysis was used to investigate the effect that changes in tornado frequency, magnitude and intensity have on the extent of the tornado hazard.

Operationalizing the research problem in a simulation context requires a number of steps that are very similar to standard scientific methodological procedures (Naylor, 1966, 23). These steps include the following: (1) Problem Formulation; (2) Collection and Processing of Real World Data; (3) Estimation of Parameters of Operating Characteristics from the Real World Data; (4) Evaluation of the Model and Parameter estimates; (5) Formulation of the Computer Program;

(6) Validation of the Computer Model; (7) Design of the Simulation Experiments; (8) Analysis of the Simulated Data.

The following is a brief description of each of the steps. A more detailed discussion of these steps including the actual procedures and techniques used in each step is found in Chapter 3--Simulation Model Development.

1. Problem Formulation

As stated previously, this research is aimed at evaluating the effects that various tornado parameter changes might have on the extent of the tornado hazard. The extent of the tornado hazard can be defined in two quite contrasting forms. One would involve solely the area that would be expected to be affected by tornadoes during a given time period. A second would involve consideration of tornado area in conjunction with the population and/or property-at-risk.

The primary research problem can be most efficiently investigated by measuring the extent of the tornado hazard using the area affected by tornadoes during a given time period. The major interest is in the operation and sensitivity of the physical system under consideration without including population and/or property-at-risk which is independent of the operation of the physical system. The area affected by a tornado is defined as the area within the tornado path.

A useful unitless measure directly related to the area of tornado paths is areal probability. Areal probability is defined as the probability of a tornado striking a point within a specified areal unit. Mathematically it is expressed

$$P = \frac{TA}{A} \tag{1}$$

where TA equals tornado path area, and A equals the area of the areal unit (Thom, 1963, 737).

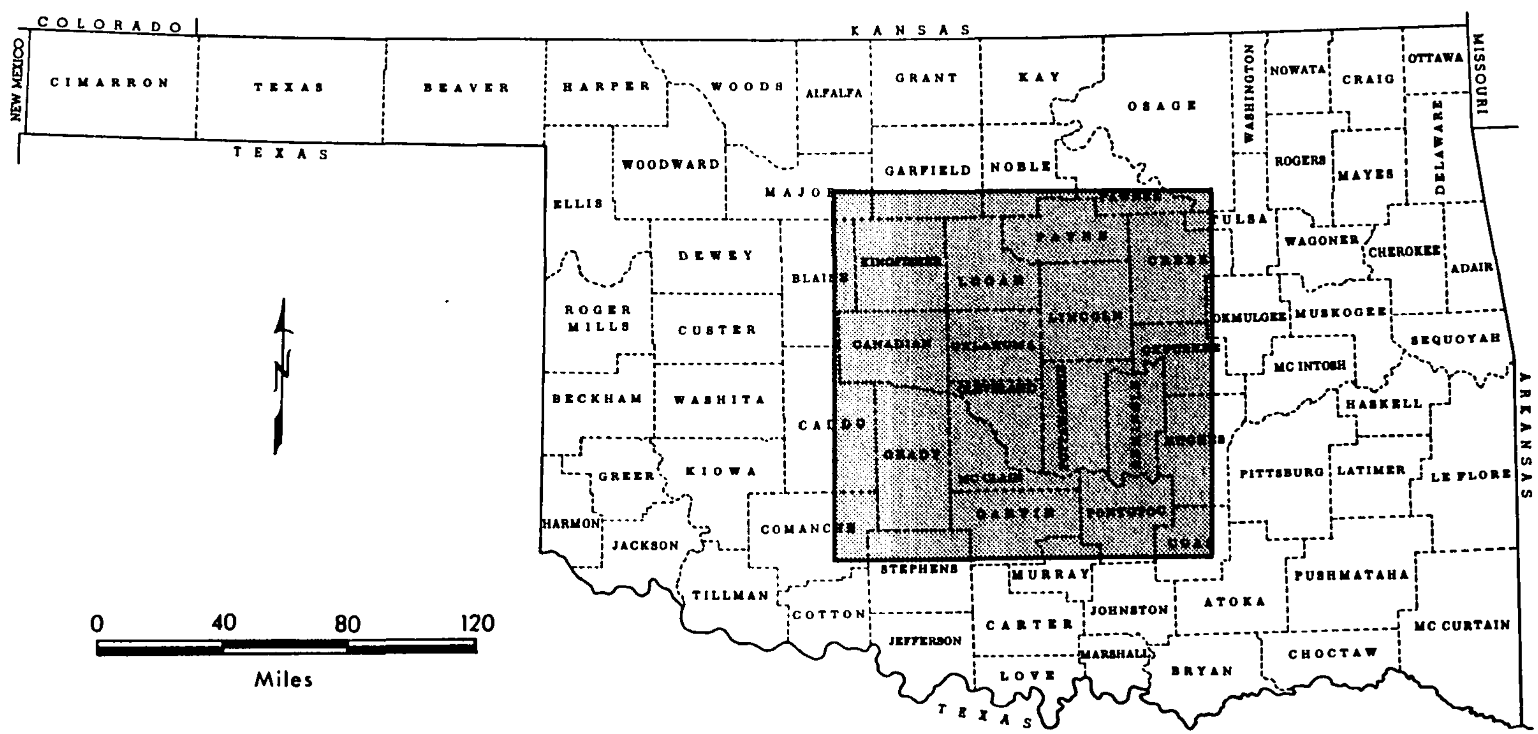
Of secondary interest to this research is the evaluation of the approximate economic benefit of tornado parameter modification. In order to accomplish this the property-at-risk must be taken into consideration. One can approximate the damage value caused by tornadoes to structures by assuming that the structures are uniformly spread throughout the area under consideration. The damage value would then equal the percentage of path area of a specified intensity, times the total structure value. Damage value estimates could then be analyzed with various tornado parameter modifications to approximate economic benefits of such modification. When technological advances are made in tornado modification, these estimates will be helpful in developing a cost-benefit ratio.

2. Collection and Processing of Real World Data

Tornado observations are without question incomplete and inaccurate (Asp, 1963). They have, however, been used by researchers as the basis for investigations (Skaggs, 1970) (Thom, 1963). These researchers reason that although the total population of tornadoes is not known, the sample is large enough that inferences about the total population can be made with confidence. Tornado data have been collected by the U. S. Weather Service since 1916. Since 1953, these data have been much more reliable and complete because of standardized reporting methods and increasing public awareness (Asp, 1963). The data include information on each tornado's time of occurrence, path length and width, point of touchdown, direction of movement, and damage value estimates. These data were collected for the study area which is illustrated in Figure 1.

Figure 1

STUDY AREA



3. Estimation of Parameters of Operating Characteristics from The Real World Data

Summary characteristics of variables are needed to serve as inputs to the computer simulation. It is therefore, necessary to "fit" theoretical frequency distributions to the observed data. Research has shown that tornado path size variations "fit" the lognormal distribution and that annual frequencies "fit" the negative bionomial distribution (Thom, 1963, 732). These two theoretical distributions were fit to the data collected from the Central Oklahoma study area.

4. Evaluation of the Model and Parameter Estimates

Statistical tests were carried out at this step to insure that the parameter estimates represent the object system.

5. Formulation of the Computer Program

The computer program was written in FORTRAN, although a number of simulation languages have been developed for extremely complex simulations. The time required to become proficient with a specific simulation language would probably offset the savings in programming time for this simulation.

6. Validation of the Computer Model

Statistical tests were used to evaluate the "goodness of fit" between the simulated output and the observed historical tornado data.

7. Design of Simulation Experiments

Experiments were conducted to determine the effects that changes in frequency, magnitude and intensity parameters (the factor variables or independent variables) have on tornado path area (the response variable or dependent variable). Systematic factor variable parameter changes were conducted both independently and in combination to determine their effect on the response variable.

8. Analysis of Simulated Data

The analysis was aimed at determining the effects that various tornado parameter changes have on tornado path area and the approximate decrease in damage value that such changes would produce.

CHAPTER 2

POSSIBLE MODIFICATION OF TORNADOES

Information concerning tornado dynamics and characteristics is incomplete. It is necessary to survey the limited data which are available before undertaking a detailed discussion of possible techniques of tornado modification.

Tornado Dynamics and Characteristics

The tornado represents the atmosphere's most extreme concentration of vorticity. It is a funnel shaped, rapidly rotating, intense low pressure area found in association with some severe thunderstorms. The tornado "funnel" is visible because it contains water droplets that result when air expands and cools adiabatically under the influence of the extreme low pressure. Similar to all low pressure areas tornadoes are characterized by low level air convergence which results in rapid rotation around the tornado axis. In order to conserve mass, divergence must also be present in association with the rising updraft. This is manifested above the tornado or any large updraft as an outflowing cloud that is generally known as an anvil layer (Kessler, 1972, 4).

All tornadoes are associated with severe thunderstorms, although relatively few thunderstorms produce tornadoes. The mesoscale synoptic conditions associated with tornado-producing storms have been identified (Tepper, 1958, 34): (1) a warm moist air layer about 5,000 feet (1,523 meters) thick at the surface; (2) a temperature inversion above the warm moist layer; (3) dry air above the inversion layer (4) strong vertical wind shear aloft from a jet stream; (5) a lifting mechanism such as a cold front or a squall line. These conditions are most commonly found in association with the warm sector of a middle latitude wave cyclone. Conditions such as these interact to form a rapidly rising "chimney" of air (Tepper, 1958, 34) whose upward velocities may reach as much as 150 feet per second (45.7 meters/second) (Kessler, 1972, 4).

The "chimney" of rising air results when the lower, moist air layer is displaced vertically by a "triggering mechanism." The triggering mechanism is any mechanism that will force air to rise and is most often a cold front or squall line, although on occasion convection could provide the initial lifting. If the triggering mechanism is of sufficient magnitude to cause enough lifting to produce condensation within the rising air parcel and to force the air above the inversion layer, the air will be convectively unstable. Convective instability refers to the buoyancy gained by rising and condensing air parcels because they are warmer, and therefore lighter, than the surrounding, non vertically moving air. The buoyancy and the updraft velocity are increased if a jet stream is present. This updraft is affected by Coriolis which causes the updraft to rotate. These rotating clouds can be observed at the base of many thunderstorms.

Once a strong rotating updraft is developed (not yet a tornado), horizontal air movement is restricted within the vortex, and the vortex becomes smaller in diameter and more intense. Surrounding warm and moist low level air flows upward and inward toward the vortex center. Rising air within the vortex is replaced by progressively warmer air at lower levels which further intensifies the vortex. The size and intensity of the resulting vortex, or tornado, is therefore related to atmospheric conditions both within the ground layer and the upper layers of the atmosphere. The exact relationships are not completely known (Kessler, 1972, 4-5).

Once the tornado vortex touches or nears the earth's surface destruction is caused by two major factors. Wind speeds probably average about 125 miles per hour (201 km./hour) and may be in some tornadoes as high as 400 miles per hour (644 km./hour) (Battan, 1961, 61). This in itself can cause major destruction to most buildings. In addition to the wind, the rapid pressure drop within a tornado is large enough to explode buildings. A baragraph trace of a St. Louis tornado showed that an atmospheric pressure decrease of 2.42 inches (61.5 mm.) of mercury occurred within less than 30 seconds. This is a pressure drop of eight percent of normal atmospheric pressure. With such a rapid pressure drop, buildings, especially with the doors and windows closed, will develop pressure inequality of nearly 200 pounds per square foot (976.4 KG/m^2). If a house had ceiling area of 20 x 40 feet (6.1 m. x 12.2 m.) the force exerted on it would be approximately 68 tons (61.7 tonnes) (Battan, 1961, 58).

Great variability in tornado path sizes occurs from tornado to tornado and regionally within the United States (Howe, 1974). The average path area for the Central Oklahoma study area was .51 square miles (1.32 km^2) resulting from a 181 yard (165.4 meters) average width and a 4.9 miles (7.88 km.) average path length. Tornadoes were reported within the study area however, with legnths as short as 100 yard (191.4 meters) and as long as 125 miles (201.1 km.). Widths varied from 10 yards (9.14 m.) to 880 yards (804.3 m.). Howe (1974, 345) has reported that average width of path ranges from 62 to 269 yards (56.69 to 245.97 m.) in Maine and Tennessee respectively with corresponding average length ranges from 7.1 to 1.5 miles (11.4 to 2.4 km.).

Possible Tornado Modification Techniques

The Panel on Weather and Climate of the National Academy of Sciences reported in 1973 that "In view of the fact that tornadoes represent such a serious threat to life and property, it is concluded that a vigorous program of tornado research should be mounted with the long range goal of developing an effective means of mitigating the destruction from these storms" (Committee, 1973, 62). The Panel also indicated that the scientific community has been reluctant to speculate about modifying tornadoes, partly because the nature of tornadoes is not completely known and partly because of their small size and short life span.

Theoretical speculation concerning tornado modification techniques could take the form of direct energy addition or subtle controls on the effect and distribution of natural energies. These techniques could also be applied on a micro or meso-scale. All "brute force" or direct energy addition modification schemes on the meso or microscale are cost prohibitive. An example will illustrate this. Tornadoes could be eliminated if the temperature distribution in the atmosphere were changed so that the low level warm moist air did not become convectively unstable upon rising. This could be accomplished by heating the middle layers of the atmosphere. Suppose tornadoes could be eliminated by raising the temperature of the middle layer over a 10 km. square area by one degree centigrade. The energy required would be 6 x 10^{13} calories or equivalent to 80 million kilowatt hours of electricity. At a cost of only one cent per kilowatt hour the total cost of energy alone for such a project would be 8 million dollars. The cost of direct energy additions of all types greatly exceeds the expected damage losses of most tornadoes (Kessler, 1972, 5). Elimination of these direct methods of tornado modification on theoretical grounds leaves us with man's attempt to control the effect and distribution of natural energies by indirect methods on varying scales. A number of plausible techniques exist.

Mesoscale changes in the effectiveness of solar radiation input in heating the atmosphere can directly affect the temperature distribution within the atmosphere. This could, therefore, modify tornado occurrence. Surface and lower layer temperature anomalies over urban areas have been well documented (Changnon, 1971). These temperature changes in urban areas are caused by particulate matter, thermal pollution, lack of evaporative moisture, buildings and concrete acting as heat storage devices, and by surface albedo changes. The net result of these urban effects has been to increase the temperature of the atmosphere at surface and lower levels and thereby increasing the energy available for thunderstorm and tornado development. Present urban temperature changes may not be conducive to decreasing tornado occurrences, but it does illustrate that man's building and engineering techniques can modify temperature distributions significantly.

One of the most promising results of research on man's inadvertent urban temperature modification is the information gained concerning the effects of surface albedoes on temperature. In urban areas solar radiation absorbtion is increased thereby raising low level temperatures.

It is theoretically possible to modify a portion of the earth's surface to increase reflection and therefore decrease the low level temperature by as much as .8°C for a one percent decrease in surface albedo (Manabe, 1967, 250). Such relatively small changes may have some effect on thunderstorm occurrence. These albedo changes could be accomplished by modifying surface colors and/or surface roughness. Since research indicates that small albedo changes result in fairly large lower layer temperature changes, the area of surface albedo modification need not be extremely large. Therefore, such a scheme may be economically feasible.

Surface modification of another type could also affect tornado occurrences without decreasing the beneficial rainfall aspects of thunderstorm occurrence. Surface friction could reduce the net low level air convergence into a tornado. Low level convergence is necessary to maintain the tornado system. Also surface friction reduces the spinning motion of tornadoes and might retard or eliminate their development. It is likely that tornadoes seldom occur in mountainous regions because of surface friction (Kessler, 1972, 7). Surface friction may also be the cause of the apparent sparsity of tornadoes in large urban areas (Fujita, 1973, 83). Increasing surface friction is particularly attractive since there could be a multipurpose benefit. Large windmills would not only provide a non-polluting energy source, but would also decrease the available kinetic energy for tornado development. It is also likely that if wind power generation were employed on a large scale in the future the logical sites would be near and around urban areas where the population and property-at-risk to the tornado hazard is greatest. Even without utilization of wind power, multipurpose mounds, ridges or wind resistent vegetation surrounding densely inhabited areas might decrease the occurrence of tornadoes (Kessler, 1972, 7).

Micro-scale tornado modification possibilities involve the artificial release of latent heat of condensation and fusion by the addition of hydroscopic nuclei to a particular cloud. A large part of a storm's energy is derived from the latent heat released to the surrounding environment when water or water vapor changes to ice. Techniques have been developed to modify this freezing and sublimation process. These techniques are similar to those used in rainfall augmentation. Under ideal conditions when silver iodide or another similar substance is added to the super-cooled water droplet portion of a cloud, the droplets will freeze upon contact with silver iodide and heat will be released. If the liquid content of the cloud is two grams of water per kilogram of air, the freezing will cause the environmental air temperature to rise about .6°C. This magnitude of temperature change is generally large enough to increase updraft development and cause explosive growth (Kessler, 1972, 8). Increased updraft development increases the convergence of warm moist air from below and thus may produce heavy precipitation over a small area. More importantly for our purposes, the explosive growth of one cloud may have an adverse effect on surrounding clouds over a large area by funneling all of the surrounding low level air into one cloud (Flohn, 1969, 221). Thus, a selective technique of cloud seeding might decrease the number of tornadoes occurring from a given thunderstorm cluster or squall line.

Rain augmentation techniques, also using artificial hygroscopic nuclei, have the potential to modify thunderstorm development, thereby decreasing the probability of tornadoes. Thunderstorms occasionally have well developed updrafts before a significant amount of precipitation froms around and within the updraft. Theoretically, the updraft in a cloud with precipitation is likely to be weaker than in a cloud without precipitation because of the frictional drag of the condensation products (Kessler, 1972, 4). Presumably, if rainfall augmentation techniques were used to stimulate condensation before violent updrafts were formed in thunderstorms, tornado occurences would be reduced.

Another relatively well developed micro-scale tornado modification scheme was an outgrowth of the electrical theory of tornado formation (Vonnegut, 1960). The theory involves the observation that the extremely high wind velocities, reportedly near Mach 1, cannot result from air pressure gradients alone. It is suggested that electrical energy "is coupled to the vortex by a sheered horizontal current flow, and that this sheered stress furnishes the required angular momentum" (Colgate, 1967, 1431). Colgate indicates that if the electrical potential buildup within thunderstorms is dissipated the intensity and possibly the frequency of tornadoes would be decreased. He further suggests that by the addition of 2 kilograms of 10 meter long aluminum coated wire per cubic kilometer of cloud, the conductivity of the cloud would be increased to the extent that the electrical potential difference would be nearly eliminated.

Five different tornado modification techniques have been discussed. Table 1 presents a summary of the five techniques in relation to the necessary scale of the modification operation, the tornado parameter in the order they are likely to be reduced and the qualitative relative cost of such an undertaking.

Table 1

Summary of Modification Techniques

Modification Technique	Scale	Parameter	Cost
Surface albedo	meso	frequency, magnitude, intensity	moderate
Surface friction	meso	intensity, magnitude, frequency	high
Explosive growth	micro	frequency, magnitude, intensity	low
Rain augmentation	micro	intensity, magnitude, frequency	low
Electrical reduction	micro	intensity, frequency, magnitude	low

The scale necessary to initiate a given modification technique is likely to be directly related to the cost of such an operation. Surface friction change costs are likely to be high, but could be diminished if these friction reduction methods produced additional benefits. Also the initial costs are high but operating costs would be non-existent. Surface albedo changes are considered to be of moderate cost because of the reported large change in low level temperatures associated with small albedo changes. The micro-scale (individual cloud) techniques would apparently be relatively low cost because of the necessity for only a limited number of aircraft to place artificial substances into clouds. The total aircraft cost would not need to be charged off to weather modification purposes since they could be used for other duties during low tornado hazard periods.

Weather modification programs are operational in many parts of the United States today. These programs can serve as approximate estimates of the cost of microscale (individual cloud) modification. In South Dakota a joint rain augmentation-hail suppression program is now operational. The program covers a 42 county area and involves 19 twin engine aircraft with specially trained pilots. Six ground radars have been built and are manned by professional personnel. The annual budget of the project is approximately one million dollars or about 3.4 cents per acre (Booker, 1974). Using this 3.4 cents per acre figure, which would probably increase with a decrease in coverage size, the entire study area could be covered by a comparable program at a cost of $313,000.

The anticipated effects of these modification techniques indicate that frequency is the most likely tornado parameter to be changed. On theoretical grounds alone, we know that many severe thunderstorms do not produce tornadoes. If, through accurate instrumentation, the apparently minute differences between tornado and non-tornado producing thunderstorms are isolated, the appropriate modification technique theoretically could be applied to reduce the frequency of tornado formation or modify their magnitude or intensity.

CHAPTER 3

SIMULATION MODEL DEVELOPMENT

The computer simulation model was developed using the relatively standard steps as defined by Naylor (Naylor, 1966) and briefly referred to in Chapter 1. These steps insure that, given proper theoretical base and empirical data, the model will be fully tested as representing the real world system before experiments are conducted upon the model. This model development method proceeds from the premise that the researcher must have confidence that the historical model represents reality before any changes in the model operating characteristics would be meaningful. Many of the following steps test the operating characteristics and model output at various stages with the empirical historical data to insure the model's performance.

Collection and Processing of Real World Data

Tornado data were collected for a twenty-year period, 1954-1973, from two sources--Climatological Data for the years 1954 through 1958 and Storm Data for years 1959 through 1973. The twenty-year period was chosen primarily because beginning in 1953 tornado reporting became much more reliable with the implementation of standardized reporting methods. Thus, even though complete information is not available for each reported tornado and some tornadoes are not reported, the data are considerably more complete and accurate after 1953 than before 1953 (Asp, 1963). These publications include information on each reported tornado's time of occurrence, length and width of path, point of touchdown, direction of movement, and estimated damage values.

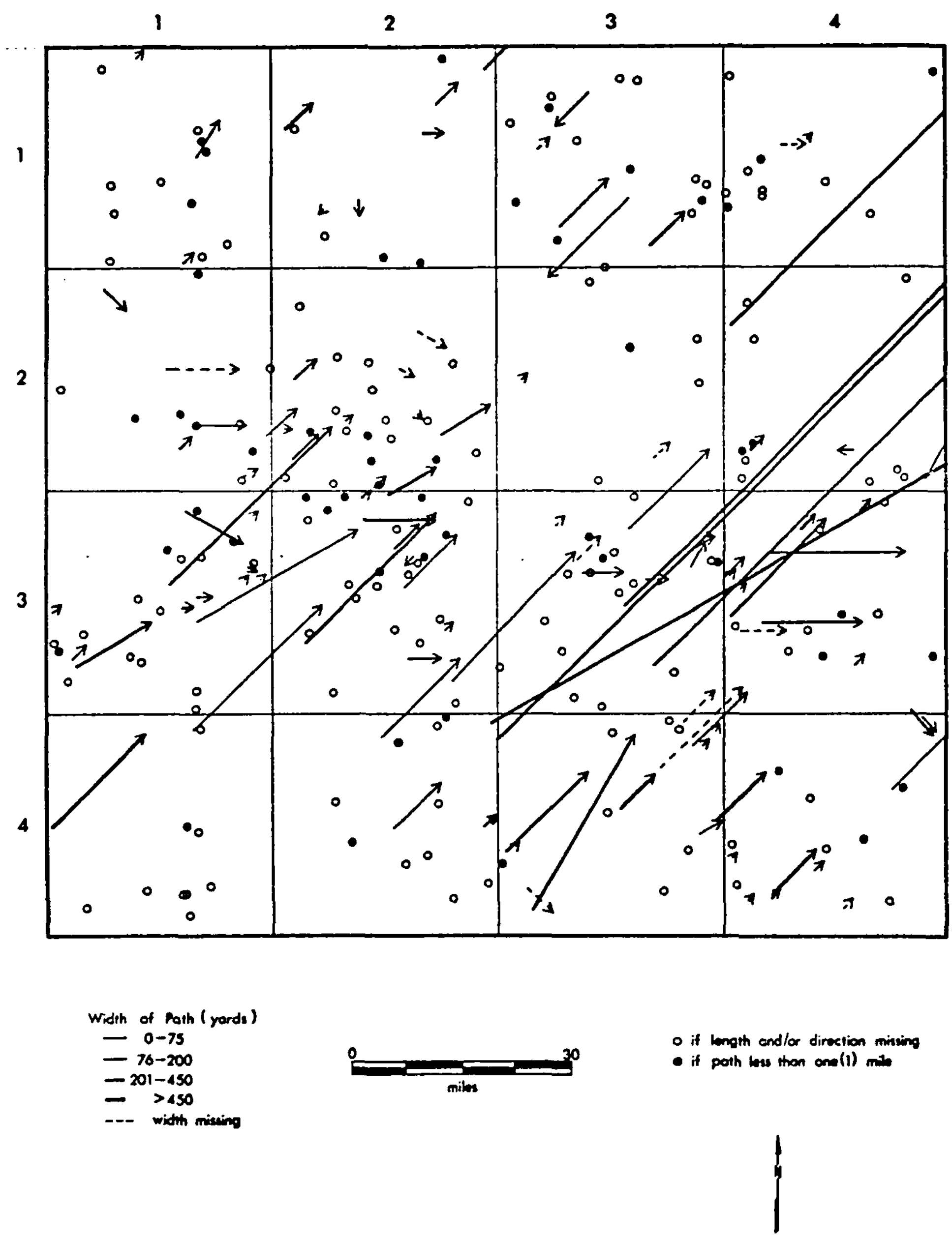
These data were collected for each tornado touching down within the study area.

The Central Oklahoma study area was chosen because it is within the area of highest tornado frequency in the United States (Thom, 1963, 735) and, therefore, may be the area where preliminary tornado modification programs will be attempted. The study area was also chosen because of the familiarity of the researcher with the area, rendering more efficient data collection. The actual study area is by no means critical to the research problem. Any study area where tornado frequency is sufficiently high to produce an adequate sample could have been used to carry out the research.

The location of each tornado touchdown was mapped and is displayed in Figure 2. Path length and width and direction of tornado movement are also illustrated in Figure 2. Path length, width, and direction of movement data were not available for a small percentage of the reported tornadoes. Of the 285 tornadoes reported in the study area, 67% included width information, 84% length information and 72% direction information. Path length was occasionally given as "short." In these instances the length was recorded as .20 miles (.32 Km.). After all tornado data was collected, it was apparent that this value was definitely near the shortest length that is ever reported. Path width was occasionally reported as "narrow." The width was then recorded as 50 yards (45.7 m.). Similar to "short" above, 50 yards (45.7 m.) was definitely near the smallest tornado widths reported. "Touch" was sometimes used to represent path sizes and in this case the average width of the tornadoes in the entire study area, 181 yards (165.5 m.) was recorded for the width and the length.

Figure 2

TORNADO INCIDENCE
1954–1973



SOURCE CLIMATOLOGICAL DATA, 1954–58; STORM DATA, 1959–73

The study area was subdivided into 16 thirty-mile square regions. The size of the quadrats was based on the necessity of theoretical frequency distributions to describe the annual frequency. These distributions are very sensitive to quadrat size and through trial and error methods the 30 square mile size was chosen over others attempted. This subdivision was necessary to retain the pattern of variations of tornado frequency within the study area. Frequency patterns were important to this study because the computer simulation was developed to represent the "real world" as accurately as possible. Variation of frequency was also necessary to approximate the benefit of future tornado parameter modifications because damage value is a function of not only property-at-risk but also tornado frequency.

Estimation of Parameters of Operating Characteristics from the Real World Data

The beginning stage of the actual computer simulation model development involves decisions concerning the variables to be included in the model. Since tornadoes, like other natural hazards, have three parameters controlling the extent of the hazard, the model must contain variables representing these parameters. Therefore, the major variables used in this model were (1) frequency of tornado occurrence for the entire study area and for each quadrat; (2) magnitude, defined as the path area; (3) intensity, defined directly as wind speed and indirectly as the proportion of damage to an average structure. Because of the necessity of representing the real world in the model, direction of tornado movement was included as a variable.

Summary characteristics of these variables are needed to serve as inputs into the computer simulation model. It was necessary to "fit" either empirical or theoretical frequency distributions to the observed data. Discussions of curve fitting deal primarily with the problem of theory development after a given theoretical distribution has been "fit" to the empirical data. King (1969, 59) indicates that for Monte Carlo simulations, probability models may of necessity be used to describe many features of realtiy with weakly structured theory or with none at all. When theoretical distributions can be fit to the data, the resulting model inputs represent sampling from the raw data's theoretical counterpart instead of classical sampling from the raw data (Naylor, 1966, 69). This is more acceptable to most computer simulations because an infinite number of samples are then available.

Frequency Parameters

Annual tornado frequencies have been shown by Thom (1963, 734) to fit the negative binomial distribution in a six county Central Iowa study area. Thom's study area was smaller than the one employed in this study and, even though the time period was twice as large (40 years), the number of tornadoes touching down was only 41. In the Oklahoma study area, used here, 285 tornadoes were reported. The annual frequencies for the twenty year period for the entire study area are shown in Table 2.

The negative bionomial distribution is characterized by a standard deviation that is larger than the mean (Williamson and Bretherton, 1963, 9). In this case the mean annual tornado frequency was 14.25 and the standard deviation was 7.03. When the standard deviation is less than the mean the method of moments estimater of parameter p is not applicable because the p value (probability) would be greater than one. Harvey (1966, 88) estimates the parameters of the negative binomial distribution by using an iterative solution based on the proportion of zeros. This method is also not appropriate as zeros are not present in the empirical frequency distribution. Other distributions were attempted to be fit to the annual frequency data.

Table 2

Annual Tornado Frequencies

Frequency	Year	Frequency	Year
29	1957	13	1955
27	1960	10	1956
23	1961	10	1967
23	1965	9	1962
18	1963	9	1964
17	1954	8	1966
17	1970	8	1969
17	1973	7	1958
16	1959	5	1971
15	1968	4	1972

The annual frequency data were plotted on normal probability paper and had a concave upward slope which is characteristic of the lognormal distribution. Common logarithms (Log_{10}) of the twenty annual frequencies were taken and the log_{10} mean was 1.096 and the standard deviation was .2396. Even though the lognormal distribution is a continuous distribution and annual frequencies are obviously discrete, it was felt that the lognormal distribution would represent the data as well as any discrete theoretical distribution.

Negative binomial parameters, p and k were calculated for the annual frequencies for each of the 16 individual quadrats. The method of moments estimates for the parameters of the binomial distribution with a given mean ($\bar{x}$) and standard deviation (s) are:

$$p = \frac{\bar{x}}{s} \tag{2}$$

and

$$k = \frac{\bar{x}p}{q} \tag{3}$$

where q = 1 - p (Williamson and Bretherton, 1963, 12).

Length and Width

Thom (1963, 731) has also shown that the length and width of path distributions fit the lognormal distribution. The common logarithm of 100 sampled length and width values was taken and the parameters of the lognormal distribution, the mean and standard deviation were calculated. The mean length in $\log_{10}$ miles equaled -.0167, and the standard deviation of the lengths in $\log_{10}$ miles was .8116. The mean and standard deviation of the widths in $\log_{10}$ yards were 1.951 and .4257 respectively. The relationship between the length and width of tornadoes was needed in order to insure accurate computer simulation representation. Intuitively one would expect that length and width are not independent. A tornado that has sustained itself over a great length is likely to have a large diameter (path width). Large diameter tornadoes have large volumes of converging low level air that would be less sensitive to disruption than smaller diameter tornadoes. A simple regression was computed for 100 randomly selected tornadoes having reported path length and width values. The correlation coefficient was statistically significant at the .01 level, therefore, we can conclude with 99% confidence that there is significant positive correlation between the length and width of tornadoes in the study area. The regression equation predicting tornado path width (y) given a certain path length (x) was

$$y = 134.7 + 5.41x + e \quad (4)$$

The coefficient of determination, r^2, was .20 indicating that only 20 percent of the variation in path width was associated with the variation in path length. Because significant positive correlation was present, the error term, e, becomes extrenely important in predicting path width. The error term or residual, e, was assumed to be normally distributed with a mean of zero (Poole and O'Farrell, 1971, 148). The residuals were plotted on a fractile diagram and were found to be normally distributed. The mean of the residuals was .0059 yards. Simulation of the tornado width, y, given a specific tornado length (x) was accomplished by using the prediction equation, and by randomly sampling a normal distribution with a mean of .0059 and a standard deviation of 150.08 to calculate the error term.

Intensity

Tornado intensity (wind speed) data are very difficult to obtain because of infrequent occurrence and high wind speeds that are generally greater than standard anemometers can record. Data that are available are indirectly derived by structural engineers studying the damage caused by tornadoes. Based on these damage patterns Fujita (1973, 59) has developed the Fujita-scale (F-scale).

Three years of tornadoes in the United States, 1965, 1971, and 1972 have been evaluated using the F-scale (Fujita, 1973, 60). The F-scale is designed to be simple enough for an easy assessment of all tornadoes. Categorization of all tornadoes is desired rather than assessing a limited number of storms in a scale with extreme accuracy.

The actual categorization of tornadoes in the F-scale is accomplished by comparing structural damage with reference photographs distributed to the U. S. Weather Service and others (Fujita, 1973, 59). These photographs were shown to three experienced housing insurance adjusters (Adjusters, 1974). All felt confident that F-3, 4, and 5 photographs illustrated 100% or total loss. One adjuster considered the F-2 damage to be 100% while the others noted part of the roof was still present and estimated the loss to be less than total. The adjusters evaluated the F-1 photo as having 20, 25 and 30 percent damage. The average results of these interviews, the F-scale wind speed equivalents, and the average frequency of tornadoes categorized in each F-scale over three years is found in Table 3.

Table 3

F-Scale for Damaging Wind

Scale	MPH	Frequency-U.S.	Percent of Damage
F0	40-72	20%	1%
F1	73-112	45%	25%
F2	113-157	25%	85%
F3	158-206	8%	100%
F4	207-260	1.9%	100%
F5	261-318	.1%	100%

The direction frequencies of all tornadoes in the study area were determined and is included in a parameter summary table, Table 4.

Table 4

Tornado Parameter Summary Table

Frequency

Entire Study Area

Lognormal Distribution

$\bar{x} = 1.096\ (\log_{10})$

$s = .2396\ (\log_{10})$

Individual Quadrats

Negative Binomial Distribution

Quadrat	p	k
(1,1)	.73	1.9
(1,2)	.39	.36
(1,3)	.86	6.0
(1,4)	.89	4.9
(2,1)	.81	3.1
(2,2)	.84	7.0
(2,3)	.84	1.8
(2,4)	.73	1.9
(3,1)	.50	1.4
(3,2)	.50	1.5
(3,3)	.92	14.9
(3,4)	.79	3.8
(4,1)	.70	1.3
(4,2)	.88	6.1
(4,3)	.67	1.9
(4,4)	.88	6.1

Magnitude

Length

Lognormal Distribution

$\bar{x} = .0167 \log_{10}$ miles

$s = .8816 \log_{10}$ miles

Width

Predicated in yards from length (x) by equation:

$\hat{y} = 134.7 + 5.41x + e,$

where e is normally distributed with parameters

$\bar{x} = .0059$

$s = 150.08$

Intensity

F-scale	Freq. U. S.	Percent Damage
F0	20%	1
F1	45%	25
F2	25%	85
F3	8%	100
F4	1.9%	100
F5	.1%	100

Table 4 (Continued)

Direction of Movement	
NE	62%
N	18%
E	9%
SE	6%
S	3%
SW	2%

Evaluation of the Model and Parameter Estimates

This step in the simulation procedure represents the first stage in testing the input parameters to the computer simulation. The tests insure that the parameters represent the object system well, enabling confidence to be placed on the simulated output. The evaluations of the parameter estimates were in the form of goodness of fit tests that test the observed distributions with the theoretical distributions that were fit to the data. The theoretical distribution can be regarded as a "strawman" which was used to determine the degree to which the observed distribution departs from the theoretical distribution (Yeates, 1974, 199). Three major tests are commonly used for testing goodness of fit: Chi-square, Kolmogorov-Smirnov, and for normal distribution, fractile diagrams.

The lognormal distribution representing annual frequency data in the study area was tested by using a fractile diagram. Fractile diagrams are based on the fact that a normal distribution forms a straight line when plotted on probability paper. Therefore, the theoretical distribution can be represented as a straight line representing a calculated mean and standard deviation from the empirical data. Confidence limits can be placed around the theoretical distribution line by using the formula for the standard error of proportion

$$C.L. = (PQ/N)^{1/2}(Z) \tag{5}$$

where P equals the cumulative frequency at any point of the theoretical distribution, Q equals 1 - P, N is the number of observations and Z is the confidence level. When plotted, the empirical data points should randomly vary around the theoretical distribution and be within the selected confidence limits particularly near the middle of the distribution (Hald, 1952, 131). A fractile diagram of the entire study area annual frequencies is shown in Figure 3. The empirical data points are all within the 95 percent confidence limits and we can conclude that the lognormal distribution adequately represents the annual frequency data.

Figure 4 is a fractile diagram of 100 length samples. When this fractile diagram was first plotted it was obvious that sixteen path lengths reported as .2 miles and twelve path lengths reported at .1 miles caused some of the data points to fall outside the confidence limits. Since nearly all the path lengths are estimates it is obvious that they tend to be made in "round" numbers. The actual lengths probably vary normally about the estimated length value.

The numerous .2 and .1 mile values were normally distributed, with the standard deviation based on the distribution of reported values around these values. For example, there were five .25 values and one .125 value adjacent to the .2 values. The standard deviation of this frequency distribution was calculated and used to normally distribute the sixteen .20 values. A similar procedure was used for the twelve .1 values. Figure 4 is therefore a fractile diagram of 100 length samples with normally distributed .20 and .10 mile length estimates. Since all

Figure 3

ANNUAL FREQUENCY – STUDY AREA

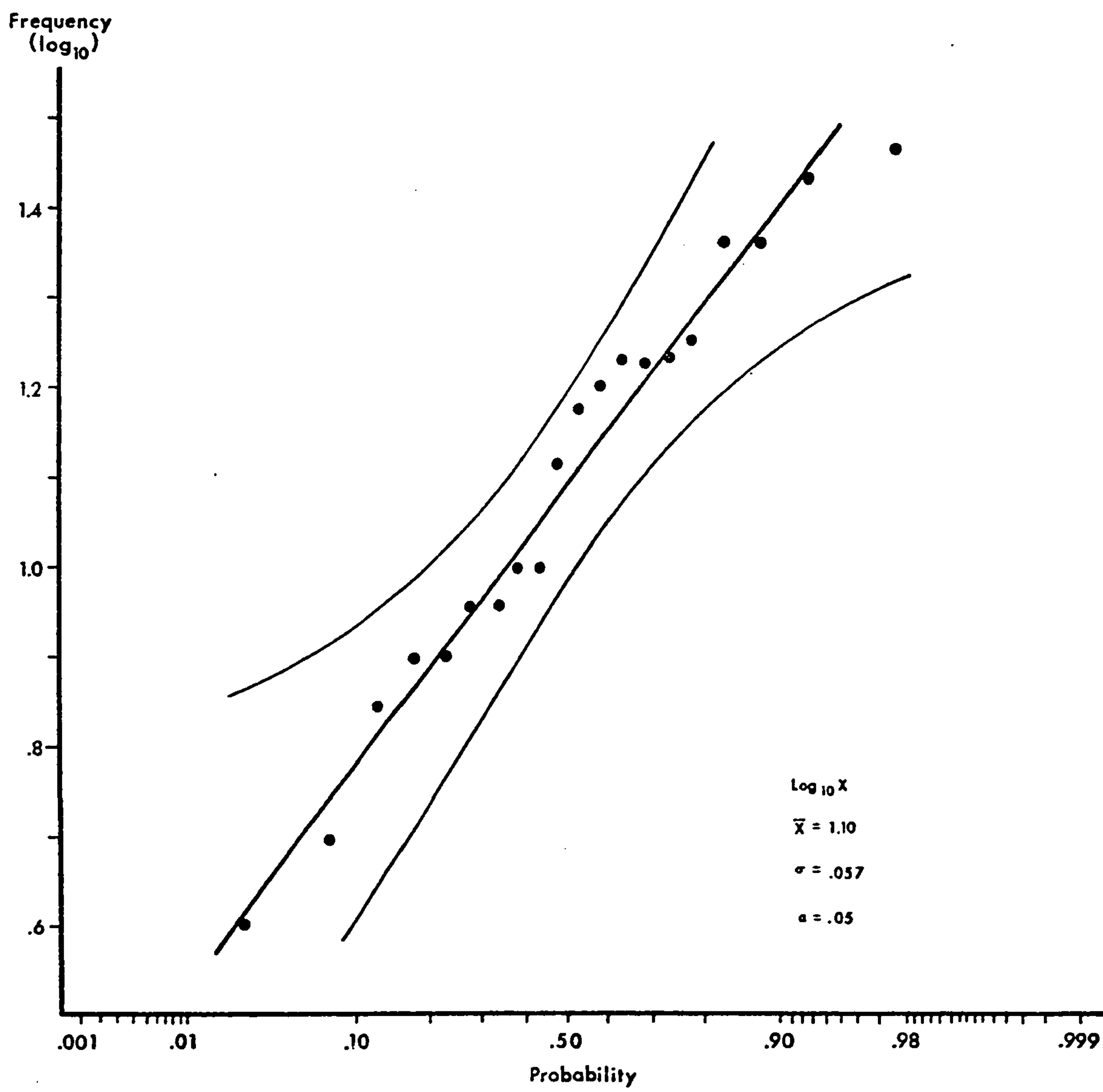
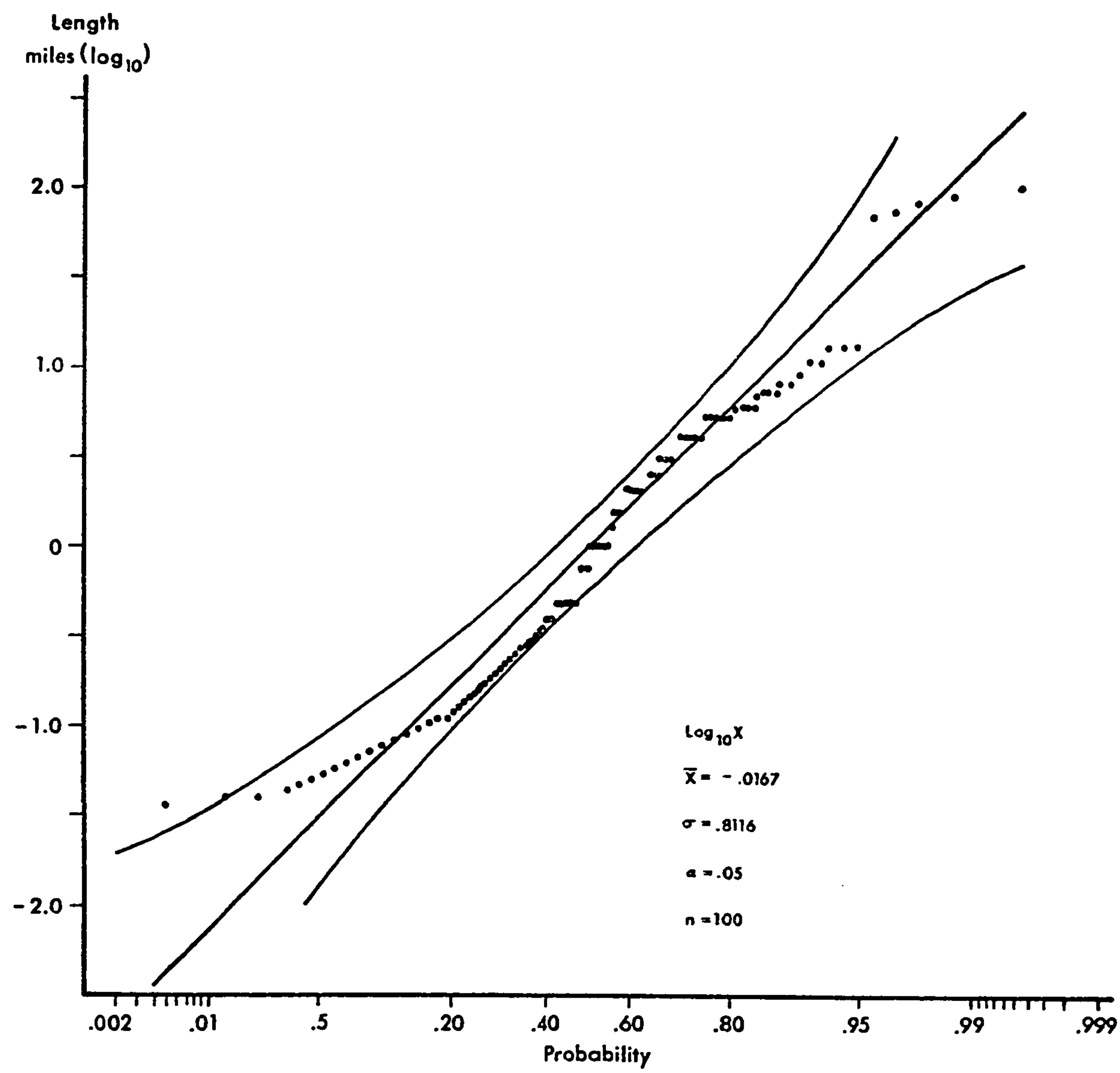


Figure 4

PATH LENGTHS



the data points, except two near the margins of the distribution, are within the 95 percent confidence limits we can conclude that the log-normal distribution accurately represents the length of path data.

The Kolmogorov-Smirnov goodness of fit test was used to test the observed individual quadrat frequency distributions with the theoretical negative binomial distribution. This test was chosen over the more commonly used chi-square test because it treats individual observations separately and thus does not lose information as does the chi-square test when it is necessary to combine cells with low frequencies. The Kolmogorov-Smirnov test only considers that part of the cumulative frequency distribution having the greatest absolute difference (d) from the theoretical distribution. In reality, then, only the extreme was tested. But conceptually, if the fit is acceptable at this point in the cumulative distribution, it will be acceptable everywhere else. Massey (1951, 76) states that information gathered "suggests that the d-test may be always more powerful than chi-square tests: when grouping of classes or when a small sample size is used. Siegal (1972, 753) makes a similar statement. Hayes (1972, 753) notes that methods superior to chi-square tests exist when comparing entire distributions, most notably the Kolmogorov-Smirnov test.

The d-value resulting from the Kolmogorov-Smirnov test can also be evaluated in terms of chi-square equivalents (Siegal, 1956, 131). This transformation is:

$$X^2 = 4d^2 \frac{n_1 n_2}{n_1 + n_2} \qquad (6)$$

This then allows the nature of the fit to be evaluated in terms of chi-square which is advantageous because complete tables are not readily available for the Kolmogorov-Smirnov test. The p-value corresponding to this chi-square value with two degrees of freedom indicates the probability that chi-square values of this magnitude or higher could occur from samples randomly selected from similar distributions. The p-value is therefore an alpha level. In any hypothesis testing, the larger the alpha level the lower the chances are of accepting a false null hypothesis (Type II error). In "goodness of fit" tests this error needs to be reduced. Therefore the higher the p-value the better the fit and the chances of making a Type II error are also reduced.

The results of the Kolmogorov-Smirnov test for each of the sixteen quadrats are found in Table 5. The largest d-value computed for any quadrat is .10. This corresponds to a chi-square value of .40. This value has a p equal to approximately .85 and therefore we conclude that the negative binomial closely represents the individual quadrat annual frequencies.

Table 5

Kolmogorov-Smirnov Goodness of Fit Test of Individual

Quadrat Annual Frequencies

Quadrat (1,1)

p = .73   k = 1.9

	Number of Years		Cumulative Proportion		
N	Observed	Predicted	Observed	Predicted	d-value
0	11	11	.55	.55	
1	6	5.4	.85	.83	
2	1	2.2	.90	.94	.04
3	2	.8	1.00	.98	

Table 5 (continued)

Quadrat (1,2)

p = .40 k = .36

	Number of Years		Cumulative Proportion		
N	Observed	Predicted	Observed	Predicted	d-value
0	14	14.6	.70	.73	.03
1	4	3.0	.90	.88	
2	1	1.2	.95	.94	
3	1	1.2	.95	.97	
4	0	.28	.95	.98	.03
5	1	.16	1.00	.99	

Quadrat (1,3)

p = .86 k = 6.01

	Number of Years		Cumulative Proportion		
N	Observed	Predicted	Observed	Predicted	d-value
0	8	8.0	.40	.40	
1	8	6.8	.80	.74	.06
2	1	3.4	.85	.91	.06
3	3	.15	1.00	.97	

Quadrat (1,4)

p = .89 k = 4.90

	Number of Years		Cumulative Proportion		
N	Observed	Predicted	Observed	Predicted	d-value
0	11	11.8	.55	.59	.04
1	7	6.0	.90	.89	
2	1	1.8	.95	.98	
3	1	.4	1.00	1.00	

Table 5 (continued)

Quadrat (2,1)

p = .81 k = 3.12

N	Number of Years Observed	Predicted	Cumulative Proportion Observed	Predicted	d-value
0	10	10	.50	.50	
1	8	6.2	.90	.81	.09
2	1	2.6	.95	.94	
3	0	.8	.95	.98	
4	0	.2	.95	.99	
5	1	.06	1.00	.993	

Quadrat (2,2)

p = .84 k = 7.01

N	Number of Years Observed	Predicted	Cumulative Proportion Observed	Predicted	d-value
0	4	6	.20	.30	.10
1	10	6.6	.70	.63	
2	4	4.2	.90	.84	
3	0	2.0	.90	.94	
4	1	.8	.95	.98	
5	1	.2	1.00	.99	

Quadrat (2,3)

p = .84 k = 1.81

N	Number of Years Observed	Predicted	Cumulative Proportion Observed	Predicted	d-value
0	15	14.6	.75	.73	
1	3	4.0	.90	.93	.03
2	2	.8	1.00	.97	.03

Table 5 (continued)

Quadrat (2,4)

p = .73   k = 1.90

N	Number of Years: Observed	Predicted	Cumulative Proportion: Observed	Predicted	d-value
0	12	11.4	.60	.57	
1	3	5.4	.75	.84	.09
2	4	2.0	.95	.94	
3	1	.8	1.00	.98	

Quadrat (3,1)

p = .50   k = 1.42

N	Number of Years: Observed	Predicted	Cumulative Proportion: Observed	Predicted	d-value
0	7	7.6	.35	.38	
1	6	5.2	.65	.64	
2	4	3.2	.85	.80	.05
3	1	1.8	.90	.89	
4	0	1	.90	.94	
5	1	.54	.95	.967	
6	1	.28	1.00	.981	

Quadrat (3,2)

p = .50   k = 1.55

N	Number of Years: Observed	Predicted	Cumulative Proportion: Observed	Predicted	d-value
0	8	6.8	.40	.34	.06
1	3	5.2	.55	.60	
2	4	3.4	.75	.77	
3	3	2.0	.90	.87	
4	0	1.2	.90	.93	
5	1	.6	.95	.96	
6	1	.34	1.00	.977	

Table 5 (continued)

Quadrat (3,3)

p = .92   k = 14.88

	Number of Years		Cumulative Proportion		
N	Observed	Predicted	Observed	Predicted	d-value
0	6	4.6	.30	.23	
1	7	6.4	.65	.55	.10
2	4	4.8	.85	.79	
3	2	2.6	.95	.92	
4	1	1	1.00	.97	

Quadrat (3,4)

p = .7917   k = 3.8

	Number of Years		Cumulative Proportion		
N	Observed	Predicted	Observed	Predicted	d-value
0	9	8.6	.45	.43	
1	5	6.6	.70	.76	
2	3	3.2	.85	.92	.07
3	3	1.2	1.00	.98	

Quadrat (4,1)

p = .70   k = 1.28

	Number of Years		Cumulative Proportion		
N	Observed	Predicted	Observed	Predicted	d-value
0	13	13.0	.65	.65	
1	4	4.6	.85	.88	.03
2	2	1.6	.95	.96	
3	1	.4	1.00	.98	

Quadrat (4,2)

p = .88   k = 6.07

	Number of Years		Cumulative Proportion		
N	Observed	Predicted	Observed	Predicted	d-value
0	10	9.2	.59	.46	.04
1	5	6.6	.75	.79	.04
2	4	2.8	.95	.93	
3	1	1.0	1.00	.98	

Table 5 (continued)

Quadrat (4,3)

p = .67   k = 1.92

N	Number of Years: Observed	Number of Years: Predicted	Cumulative Proportion: Observed	Cumulative Proportion: Predicted	d-value
0	8	9.4	.40	.47	
1	9	5.8	.85	.76	.09
2	1	2.8	.90	.90	
3	0	1.2	.90	.96	
4	2	.4	1.00	.98	

Quadrat (4,4)

p = .88   k = 6.08

N	Number of Years: Observed	Number of Years: Predicted	Cumulative Proportion: Observed	Cumulative Proportion: Predicted	d-value
0	10	9.2	.59	.46	.04
1	5	6.6	.75	.79	.04
2	4	.8	.95	.93	
3	1	1.0	1.00	.98	

Formulation of the Computer Program

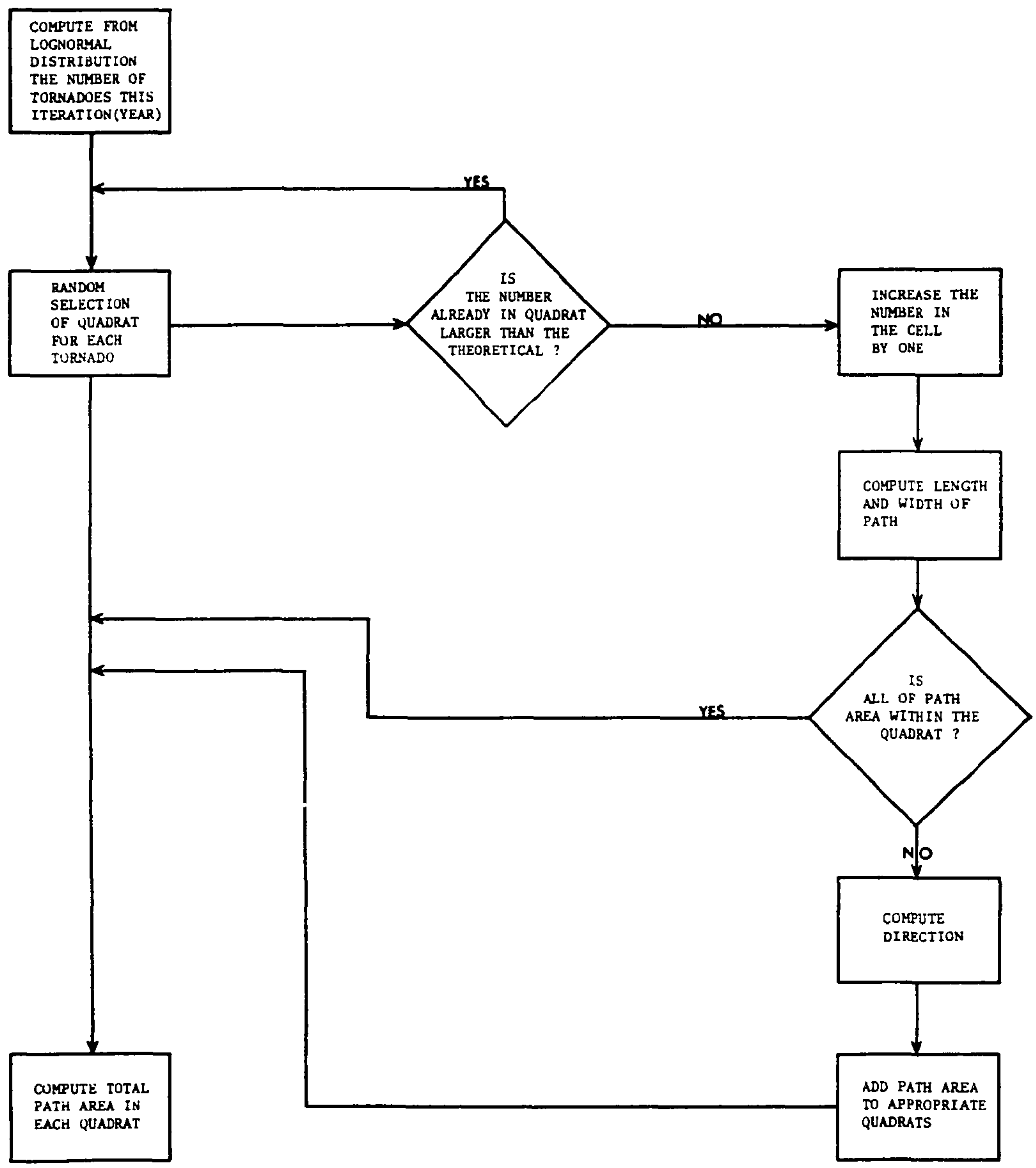
The computer simulation program was written in FORTRAN. A printout of this program is found in Appendix A and a generalized flow chart is presented in Figure 5. The following is an explanation of the computer program.

The first step in the computer program computes the number of simulated tornadoes for each iteration (year) using the lognormal distribution fit to the annual frequency distribution for the entire study area. The random lognormal variates (y) with a mean ($\bar{x}$) of 1.096 and a standard deviation (s) of .2396 were generated by the formula

$$y = \exp[\bar{x} + (s(\text{sumx} - 6.0))] \qquad (7)$$

Figure 5

COMPUTER FLOW CHART



where exp is the exponent and sumx is the sum of 12 random numbers where values range from 0 to 1. The resulting y values were changed to integers by truncation after .50 was added, thereby causing nearest integer rounding.

A quadrat was then tentatively selected at random for each tornado. Before a tornado was allocated to the randomly selected cell, the negative binomial generating function computed an integer representing the total number of tornadoes allowed in that cell. The tentatively selected quadrat accepted the tornado if the computed negative binomial value was greater than or equal to the number of tornadoes already in the quadrat plus one. If the tornado was rejected another quadrat was randomly selected and acceptance or rejection occurred as explained above.

The negative binomial variates (x) were generated with a given p and k by the formula

$$x = \frac{\log_{10} \left({}^{k}_{i=1} r_i \right)}{\log_{10} q} \tag{8}$$

where r equals a random number and q equals 1 - p. Since k was an integer in only two out of sixteen quadrats it was necessary to generate a mixture of negative binomial variates, over many iterations, with the expected value of k equal to the computed value of k.

The path area of each tornado was determined in the simulation by a two step method. The path length was determined by generating a random lognormal variate with a mean of -.0167 miles and a standard deviation of .8116 miles. The procedure used to accomplish this was the same as the explained for the generation of the annual frequencies. The path width (y) was calculated for each generated length (x) by using equation number 4, the regression equation. The error term, e, was a randomly generated normal variate with a mean of .0059 yards and a standard deviation of 150.08 yards. These variates were generated by

$$e = \bar{x} + (s(\text{sumx} - 6.00)) \qquad (9)$$

where sumx equals the sum of 12 random numbers. One-half of the computed error values were added to the prediction equation and one-half subtracted. Upper and lower limits of 880 yards and 15 yards were placed on the calculated path width, consistent with the empirical data.

If the generated path length was less than 15 miles (one-half the length of the quadrat sides) the path area in square miles was added to the total path area for the quadrat selected. If the generated path length was greater than 15 miles the tornado was considered to be intercellular. A random number was then used to select a direction of movement from the empirical direction frequency distribution. This direction was used to determine which adjacent quadrat the tornado moved into. The path area resulting from the first 15 miles, was added to the original "touchdown" quadrat. The remaining path area was added to the adjacent quadrat of tornado movement.

The output from each interation (year) included: (1) the number of tornadoes for each iteration; (2) the quadrat frequencies; (3) the path length in miles, the path width in yards and the path area in square miles for each tornado; and (4) the path area of each quadrat. The total path area of each quadrat for 20 iterations was then computed. A sample output is found in Appendix B.

Validation of the Computer Model

Validation of the model is the second major testing stage in the development of the computer simulation model. This step insures that the already tested parameter estimates are adequately interacting with the operating characteristics to simulate the object system. In this study the "goodness of fit" between the observed and the "standard run" simulated data was tested.

The 20 year observed and simulated annual frequency distributions were tested by using the Kolmogorov-Smirnov goodness of fit test. The calculated d-value as illustrated in Table 6 is .15. The equivalent chi-square value is .90 which corresponds to a p of .60. The low value of chi-square and the high p value indicates that the observed and simulated annual frequencies came from similar distributions.

Table 6

Kolmogorov-Smirnov Test of Annual Frequencies

	Number of Years		Cumulative Proportion		
N	Observed	Generated	Observed	Generated	d-value
1-5	2	0	.10	0.00	
6-10	7	6	.45	.30	.15
11-15	2	4	.55	.50	
16-20	5	4	.80	.70	
21-25	2	3	.90	.85	
26-30	2	2	1.00	.95	
31-35	0	1	1.00	1.00	

The generated path length and width was tested against the observed by applying the Kolmogorov-Smirnov test employing fifty random samples. The d-value equaled .16 for the length samples and .14 for the width samples. The associated chi-square values are 2.56 and 1.96 respectively, with p values equal to .28 and .40. The p values are relatively high indicating that chi-square values of this magnitude or higher could occur quite frequently by chance from samples drawn from the same distribution. The length test is illustrated in Table 7, and the width test in Table 8.

The test of path areas is critical to the validation of the computer simulation model. The path area not only involves the path size but also frequency of tornado occurrence. Therefore, by testing the path area, conclusions can be drawn concerning the interaction of tornado frequency and magnitude within the model.

Table 9 portrays the results of the Kolmogorov-Smirnov test. The calculated d-value is .20. The equivalent chi-square value is 1.6 which has a p value of .45. There is little reason to suspect that the samples were drawn from different distributions.

The validation procedures have shown that the model represents the object system. The parameter estimates and their interaction through the operating characteristics are apparently operating properly to duplicate the "real world" system. Since confidence can now be placed on the model, simulation experiments involving parameter changes can be performed. The next chapter discusses the design and analysis of the simulation experiments.

Table 7

Kolmogorov-Smirnov Test of Path Length

	Frequency		Cumulative Proportion		
Interval (miles)	Observed	Generated	Observed	Generated	d-value
0-2	28	33	.56	.66	
1.01-2	5	8	.66	.82	.16
2.01-3	3	2	.72	.86	
3.01-4	3	3	.78	.92	
4.01-5	2	1	.82	.94	
5.01-6	2	0	.86	.94	
6.01-7	1	2	.88	.98	
7.01-8	1	0	.90	.98	
8.01-9	1	0	.92	.98	
9.01-10	1	0	.94	.98	
10.01-11	0	0	.94	.98	
11.01-12	0	0	.94	.98	
12.01-13	0	0	.94	.98	
13.01-14	0	0	.94	.98	
14.01-15	1	0	.96	.98	
15.01	2	1	1.00	1.00	

Table 8

Kolmogorov-Smirnov Test for Path Width

	Frequency		Cumulative Proportion		
Interval (yards)	Observed	Generated	Observed	Generated	d-value
0-100	26	23	.52	.46	
101-200	15	11	.82	.68	.14
201-300	3	11	.88	.90	
301-400	2	5	.92	1.00	
401-500	3	0	.98	1.00	
501-600	0	0	.98	1.00	
601-700	0	0	.98	1.00	
700	1	0	1.00	1.00	

Table 9

Kolmogorov-Smirnov Test for Annual Path Area

Interval (miles)	Frequency Observed	Frequency Generated	Cumulative Proportion Observed	Cumulative Proportion Generated	d-value
0-3	8	4	.40	.20	.20
3.01-6	3	3	.55	.35	.20
6.01-9	3	4	.70	.55	
9.01-12	2	1	.80	.60	.20
12.01-15	1	2	.85	.70	
15.01-18	1	2	.90	.85	
18.01-21	0	1	.90	.85	
21.01-24	0	0	.90	.85	
24.01	2	3	1.00	1.00	

CHAPTER 4

DESIGN AND ANALYSIS OF THE SIMULATION EXPERIMENTS

Computer simulation techniques are used primarily to predict changes that will occur within a given system if certain parameters and/or operating characteristics controlling that system are modified. The design of these system modifications is therefore extremely important because the experimental output must have a form that is compatable to analytical techniques enabling the system's performance to be evaluated. The analysis must be carried out with precision to insure proper interpretation of the system's performance.

Design of the Computer Simulation Experiments

The major objectives of this research was to determine and evaluate the effects that changes in tornado parameters have on the extent of the tornado hazard. The extent of the tornado hazard was defined for this primary objective, as the path area of tornadoes. The simulation model includes two tornado parameters that interact to produce the tornado path area, frequency and magnitude. Systematic 10% changes were made upon the frequency and magnitude parameters. The changes involved 10% decreases in the expected value of the overall annual frequencies and length of path, and did not involve changes in the variance. Since the generated length of path is used with a regression equation to predict the width, the regression equation was not modified. Twenty year "runs", similar to the "standard run", were produced for each of the 100 combinations possible when 10% changes are made on two parameters, extending from 0% to 90%. For each of these changes the output consisted of path areas which were used to evaluate the parameter modifications.

A secondary research objective involved the evaluation of the extent of the tornado hazard in relation to the property-at-risk. This not only consists of the relationship between path area and property-at-risk but also tornado intensity (wind speed). Intensity directly influences the percent of damage that the property-at-risk will receive if "hit" by a tornado. As was indicated in Chapter 2, various techniques may be used in the future to modify tornado intensity. Speculation concerning quantitative estimates of intensity reduction is, of course, entirely lacking. For simulation purposes, a modified F-scale was arrived at by assuming the future intensity modification would decrease the F-scale of all tornadoes, except F-0, by 1. The modified F-scale distribution along with the unmodified distribution is listed in Table 10.

Table 10

F-Scale for Damaging Wind

Unmodified			Modified		
F	% Frequency	% Damage	F	% Frequency	% Damage
0	20.0	1	0	65.0	1
1	45.0	25	1	25.0	25
2	25.0	85	2	8.0	85
3	8.0	100	3	1.9	100
4	1.9	100	4	0.1	100
5	0.1	100	5	0.0	100

Accurate data on the value of the property-at-risk is difficult, if not impossible, to obtain. The assessed value, by county, of rural and urban improvements (excluding land) was obtained from the Oklahoma Tax Commission (Oklahoma, 1973). These data contained not only the assessed value but also included information concerning the percent of assessed valuation in relation to the improvement's fair market value. Therefore, the property-at-risk was defined as the value of rural and urban improvements as reported by the Oklahoma Tax Commission in 1973. The total value of rural and urban improvements for each quadrat was determined using a method illustrated in Appendix C.

The steps used in this computer simulation experiment are numbered below. (1) The two quadrats having the extreme values of property-at-risk were selected for study. (2) The path area for each of these quadrats was determined from the simulation output for each of the systematic frequency and magnitude modifications. (3) The damage value to the property-at-risk was estimated by using the following equation which incorporates the unmodified F-scale distribution:

$$D = \sum_{i=0}^{5} (FPi)(FDi)[(PA \cdot R\% \cdot RV) + (PA \cdot U\% \cdot UV)] \qquad (10)$$

where D equals the dollar value damage, FPi equals the proportion of tornadoes occurring for a specified F-value, FDi is the proportion of damage for a specified F value, PA is the path area within the quadrat, FV and UV are the values of rural and urban improvements (property-at-risk) and R% and U% are the percentages of quadrat area classed as rural and urban. (4) The damage value to the property-at-risk was again computed using formula number 10 but with the modified F-scale distribution.

Analysis of Computer Simulation Experiments

The analysis of the simulation experiments was directed at the two-fold objectives of this study. The primary objective, to evaluate the effects changes in parameters controlling tornado path area, was analyzed first. In association with this objective the relationship between frequency and magnitude is investigated, and the expected 20 year path area considering this relationship is estimated. The secondary objective, to evaluate the effects that changes in tornado parameters have on the expected damage value, was then analyzed.

Path Area Analysis--Independent Frequency and Magnitude

Two parameters, frequency and magnitude, control the extent of the tornado hazard when it is defined in terms of total path area. The expected values of the theoretical distributions controlling these parameters in the simulation were systematically decreased by 10%. Therefore, one hundred experiments were run with all possible combinations of 10% changes of the frequency and magnitude parameters. Each of the 100 experiments was run for a total of 20 years, consistent with "standard run." Table 11 lists the path area in square miles for the entire study area for each of the 100 runs.

The output in Table 11 indicates that, as expected a decrease in path area generally occurs with a decrease of a tornado parameter. The output also indicates that this expected relationship does not occur in all cases. This unexpected relationship of some high path areas with parameter decreases, resulted from the occurrence of 1 or 2 extremely large tornadoes during the 20 year "run." These large tornadoes, of course, also occur in the "real world" and no attempt

Table 11

Path Area ($Mile^2$)

Magnitude Change (%) \ Frequency Change (%)	0	10	20	30	40	50	60	70	80	90
90	10.3	10.4	8.3	12.0	9.2	8.2	4.3	1.9	2.4	2.4
80	43.5	53.4	25.6	12.6	22.1	17.1	11.6	1.2	1.8	2.9
70	57.9	51.8	24.3	69.9	44.6	17.1	19.9	9.2	7.0	7.79
60	84.6	69.9	52.8	61.9	51.9	40.1	23.3	6.2	3.8	.9
50	113.8	52.3	58.0	46.5	66.4	50.7	14.6	20.3	13.1	6.4
40	184.4	90.2	48.7	142.5	42.3	69.1	48.8	1.1	10.9	6.7
30	97.5	111.2	88.4	95.9	124.2	76.9	59.9	61.3	13.6	4.2
20	138.0	176.0	136.0	120.0	107.6	104.0	43.9	45.6	15.8	7.6
10	225.5	146.3	156.4	118.6	169.1	88.9	48.0	20.4	30.0	27.0
0	199.7	192.0	158.0	153.8	158.4	60.9	33.0	40.8	69.4	8.4

was made to remove them from the analysis. This occasional higher than expected path area in the output could have been partially or completely eliminated by increasing the length of each "run" to 100 or 200 years. This would increase the probability of each "run" having at least one of these extremely large tornadoes and thus reduce their overall path area contribution. Increasing the length of the "run" by a factor of 5 or 10 would, of course, increase the computer time by the same factor. Since analytical methods are available to deal with these anomalous results and also include them in the analysis, the decision was made to analyze the 20 year "runs" rather than increase the length of the "run."

Analysis of the "standard run" (no frequency or magnitude modification) reveals the amount of annual variance in tornado path area. The mean annual path area for this run was 9.985. But as would be expected the variation around the mean was great. The range of the path area was from 26.3 $miles^2$ to 1.5 $miles^2$. Twelve years had values below the arithmetic mean and eight years were above the mean. This relationship would be expected because previous investigators (Thom, 1963) have shown that path area distributions are lognormal. The lognormal distribution is characterized by a few extremely high values that greatly influence the sensitive arithmetic mean.

Matrix surface analysis, a modification of multiple regression, can be used to smooth a surface represented by a set of data values plotted using orthogonal coordinates. Even though this technique is normally used to investigate "surfaces" in mapped data, the 10 x 10 output matrix of Table 11 meets the necessary requirements. Similar to multiple regression, this method considers all the data values and an equation is derived that predicts the value of the dependent variable for a given pair of coordinates based on the surface fitted.

Matrix surface analysis was performed on the path area matrix of Table 11. The best "fit" surface was determined by the use of orthogonal polynomials since the coordinates were equally spaced (King, 1969, 152). Fourier methods were not employed since there was no reason to assume that recurring wave or cyclical patterns existed in the data (Yeates, 1974, 148). Surfaces up to and including a sixth degree polynomial were fit to the matrix data. The second degree polynomial was chosen as "best" representing the trend in the data. The first degree surface (linear) explained 74.4% of the total variance, whereas the second degree explained 85.7%. The percent of explained variance increased slowly with each successively higher degree polynomial up to 90.4% for the sixth degree fit. Analysis of variance can be used to determine if the next higher order surface adds a significant degree of explanation to the surface (Krumbien and Graybill, 1967, 337). The results of the analysis of variance are shown in Table 12.

Table 12

Analysis of Variance of Path Area Surfaces

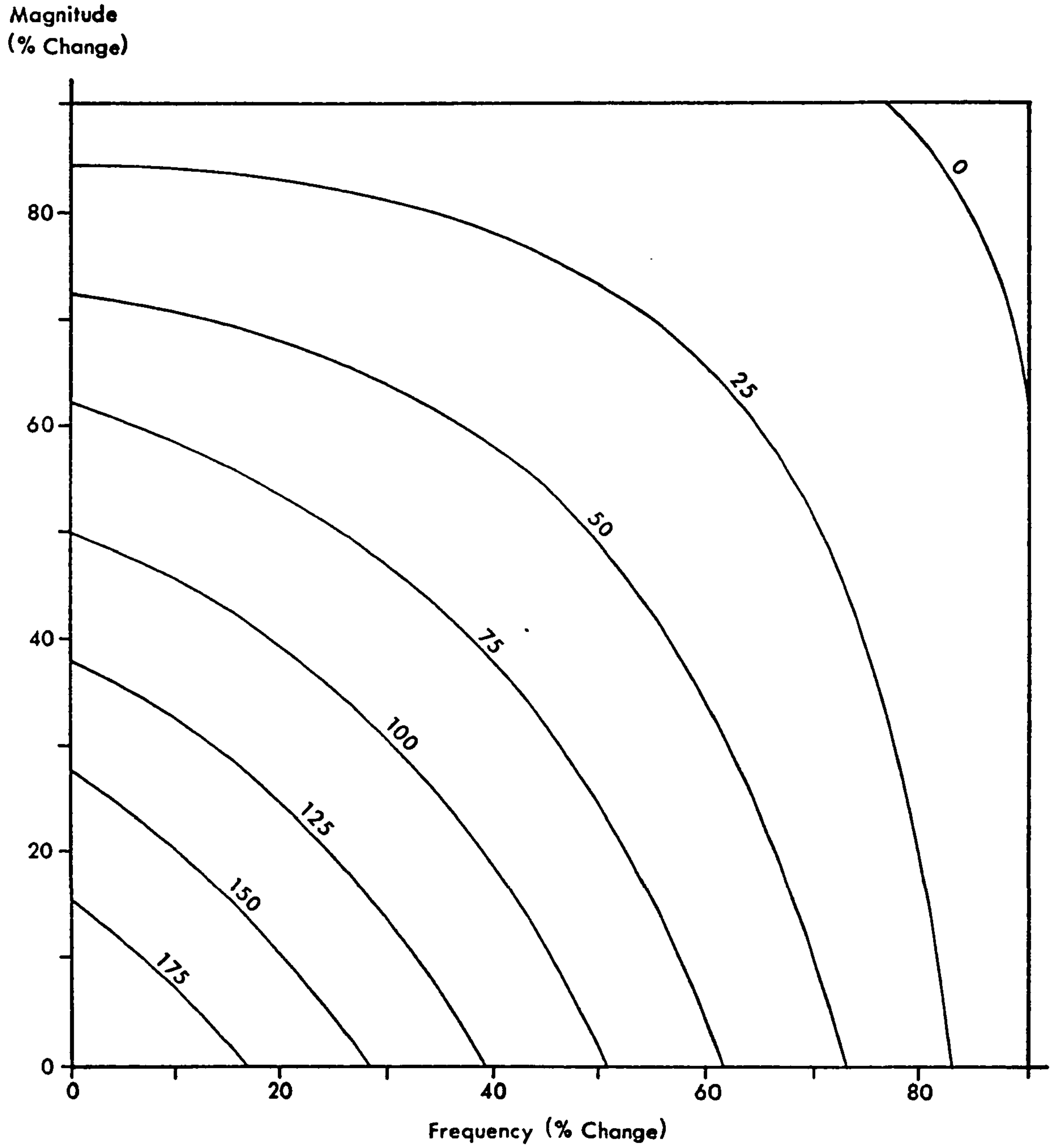
Source	Sum of Squares	d.f.	Mean Square	F
Due to Linear	231451	2	115726	141.02
Deviations from Linear	79597	97	820.59	
Due to Quadratic	35180	3	11726	24.8
Deviations from Quadratic	44416	94	472.51	
Due to Cubic	595	4	148.7	.305
Deviations from Cubic	43821	90	486.9	
Total	311047	99		

crit. F(4,90) at .05 = 2.48

The method used assigns the increase in explained variance to the appropriate surface and the total residual sum of squares or unexplained variance to the same surface. The linear surface (first degree) has a high F ratio, indicating that the major surface is linear. The quadratic (second degree) surface also added a significant amount of explained variance, but not of the magnitude of the linear, indicating that the secondary surface is quadratic. The increase in explained variation by the cubic (third degree) surface was so small (595), that the resulting F of .305 could have occurred by chance. Changes in the frequency and magnitude of tornadoes result in modified path areas that can be explained primarily by a linear model. However, a quadratic model increases the explanation of the linear model significantly and its effect can be seen in the concave surface of Figure 6.

Figure 6

PATH AREA - SECOND DEGREE TREND



Contour Interval: Twenty Five (25) Square Miles

SOURCE: AUTHOR'S COMPUTATIONS

The general form of the predictive equation for a second degree polynomial is:

$$Z = a + bX + b_2Y + b_3X^2 + b_4XY + b_5Y^2 + e \qquad (11)$$

The computed values of the polynomial coefficients (b_i) and the intercept, a, where

$$Z = 209.02 + (-20.64)X + (-21.70)Y + (-.182)X^2 + 2.27XY + .013Y^2 + e \qquad (12)$$

This equation can be used to estimate the expected path area (Z) with any combination of frequency and magnitude percent decreases. The error term, e, has a standard deviation of 21.18. Therefore, when the predicted values are compared to the generated matrix values, approximately 60% (area of normal curve within ± 1 standard deviation) of the predicted values are within ± 21.18 miles^2 of the actual value. This error measure thus illustrates the variability in tornado path area over a 20 year period within the study area. The predicted path area represents the expected 20-year tornado path area total for the entire study region. The predicted path area also represents the areal probability of a tornado striking a point within the study area. The areal probability equals the path area divided by the total area under consideration. Thus, if a 50% reduction in frequency and magnitude of tornadoes occurs in the future, the areal probability of a tornado striking a point in a given year equals

$$\frac{49.1 \text{ miles}^2 \text{ (predicted path area)}}{14{,}400 \text{ miles}^2 \text{ (total study area)}} \quad 20 \text{ yrs.} = .000171 \qquad (13)$$

When this compared with the areal probability predicted for the present (no parameter changes) of .00073, the 50% changes in frequency and magnitude reduce the areal probability by 76%. Also note that the present areal probability as predicted by this model is considerably lower than the .0036 estimated by Thom (1963, 73) for an area in Central Oklahoma. Thom estimated the average path area for all tornadoes in the United States to be 2.8 miles^2 (7.25 Km^2) whereas the findings of this study indicate Central Oklahoma tornadoes average .51 miles^2 (1.53 Km^2). Thom also used a higher frequency per unit area for Central Oklahoma than was used in this study. These differences of course account for the higher probabilities recorded by Thom.

Observation of the data in Table 11 and the second degree trend surface contour diagram in Figure 6 indicates that frequency and magnitude are nearly equally sensitive to parameter changes. For example, the predicted path area for a 40% frequency decrease equals 123 miles^2, and the predicted path area for a 40% magnitude decrease equals 122 miles^2. This is indicated in Figure 6 by the equal spacing of the contours on the X (frequency) and Y (magnitude) axes. The spacing of the contours is not uniform away from the X and Y axes. The surface slope decreases outwardly away from the origin producing the concave surface. The convavity indicates that the combined effect path area of frequency and magnitude changes diminishes with increased modification.

Path Area Analysis--Dependent Frequency and Magnitude

The computer simulation model was developed under the assumption that frequency and magnitude of tornadoes are independent. If they are in fact dependent even greater path area decreases will result from modification efforts aimed at frequency or magnitude or both because the change in one parameter will cause a corresponding change in the other. The data collected from the study area were evaluated and the relationship between frequency and magnitude was determined. The expected total path area for twenty years was then compared from the independent path area estimates taking this relationship or dependency into account.

One method of evaluating the relationship between two variables is correlation analysis. The correlation coefficient is a measure of the strength of the relationship between two variables. If the sample correlation coefficient is tested and found to be statistically different than zero, the variables are then dependent. The average path area of observed tornadoes in the study area was calculated and the results for twenty years are shown in Table 13.

Table 13

Average Path Area Per Tornado

Year	Frequency	Total Path Area ($mile^2$)	Average Path Area ($mile^2$)
1957	29	69.53	2.39
1960	27	81.68	3.02
1961	23	7.32	.31
1965	23	5.59	.24
1963	18	3.63	.15
1954	17	9.44	.55
1970	17	11.71	.69
1973	17	15.34	.90
1959	16	7.02	.41
1968	15	1.82	.12
1955	13	3.06	.23
1956	10	14.70	1.47
1967	10	2.90	.29
1962	9	1.19	.13
1964	9	.82	.09
1966	8	.30	.04
1969	8	1.57	.20
1958	7	6.06	.87
1971	5	1.13	.23
1972	4	1.48	.37

In order to test the significance of the correlation coefficient, the variables must be normally distributed. It has been previously shown that the annual frequency distribution is lognormal. The average path areas were plotted on a fractile diagram with a $\log_{10}$ scale and all points fell within the 95% confidence limits. The Kolmorgorov-Smirnov test was also performed resulting in a d of .10, which corresponds to chi-square of .40. This value has an associated p of approximately .85, indicating a good agreement between the lognormal distribution and the observed data.

The correlation coefficient between frequency and average path area was .41. The t-test can be used to determine if the correlation coefficient differs significantly from zero (Croxton, 1955, 722). The t value equaled 1.91 with the critical value of t at alpha .05 equal to 1.73. Consequently the value of r is significantly different than zero.

These results indicate that frequency and magnitude of tornadoes are dependent. This conclusion can only be made specifically for the study area under consideration here. However, there is no reason to assume that conditions causing the dependency in one area should be absent in another. One would expect a dependency to result from simple probabilities alone. When frequency is high, the probability of an infrequent high magnitude tornado would be greater. Also in years when frequency is high, it is likely that conditions spawning tornadoes also have an effect on tornado magnitude.

Regression equations were determined by regressing frequency on average path area and by regressing average path area on frequency. These equations in $\log_{10}$ values were:

$$Ymag = -1.389 + .8465X_{(freq.)} \quad (14)$$

and

$$Yfreq. = 1.188 + .1988X_{(mag.)} \quad (15)$$

The residuals from the prediction equations are necessarily large because the coefficient of determination is only .17. The residuals from both regressions were plotted on a fractile diagram and all points were well within 95% confidence limits. The parameter of these two normal distributions were used in conjunction with the regression equations to simulate predicted values of the dependent variable from the actual empirical value of the independent variable. This was done to insure that the normal distributions correctly represented the error terms of the regression equations. The resulting output from these simulations were tested using the Kolmorgorov-Smirnov test. The results of this test is shown in Tables 14 and 15.

Table 14

Kolmorgorov-Smirnov Test of Observed and Generated Average Path Area

Interval Log_{10} miles	Frequency Observed	Frequency Generated	Cumulative Proportion Observed	Cumulative Proportion Generated	d-value
0- .24	9	10	.45	.50	
.25- .49	4	4	.65	.70	
.50- .74	2	2	.75	.80	
.75- .99	2	2	.85	.90	
1.00-1.24	0	1	.85	.95	.10
1.25-1.49	1	0	.90	.95	
1.50-1.74	0	0	.90	.95	
1.75-1.99	0	0	.90	.95	
2.00	2	1	1.00	1.00	

Table 15

Kolmorgorov-Smirnov Test of Observed and Generated Annual Frequencies

	Frequency		Cumulative Proportion		
Interval	Observed	Generated	Observed	Generated	d-value
0- 3	0	0	0	0	
4- 7	3	2	.15	.10	
8-11	6	5	.45	.35	
12-15	2	6	.55	.65	
16-19	5	1	.80	.70	
20-23	2	1	.90	.75	.15
24-27	1	4	.95	.95	
27	1	1	1.00	1.00	

The d-value of .10 corresponding to the average path area test is equivalent to a chi-square value of .40. This chi-square value has a p of approximately .85 indicating a good agreement between the observed and generated average path area values. A d-value of .15 was obtained from the frequency test which is equivalent to a chi-square value of .90. The p corresponding to this value is equal to approximately .60 indicating that the chances of getting a chi-square value of this magnitude or higher from samples taken from the same distribution is equal to .60. Therefore there is no reason to suspect that the samples came from different distributions. Since the residuals from the regression equations have been shown to be normally distributed and since the equations with the error terms generated values similar to the actual frequency and magnitude values, the regression equations can be used with confidence to predict the expected value of the dependent variable with changes in the independent variable.

The regression equations 14 and 15 were used to predict the value of the dependent variable for each 10% decrease in frequency and magnitude. The absolute decrease in frequency and magnitude for each 10% change is shown in Table 16.

Table 16

Predicted Values of Decrease

Frequency Dependent		Magnitude Dependent	
% X mag. change	Decrease in Y	% X freq. change	Decrease in Y
0		0	
10	.25	10	.03
20	.53	20	.06
30	.85	30	.09
40	1.19	40	.122
50	1.60	50	.154
60	2.07	60	.187
70	2.64	70	.221
80	3.41	80	.258
90	4.60	90	.297

The values found in Table 16 form the basis for the computation of new matrices representing the expected 20 year path area when frequency and magnitude are considered dependent. The expected value of decrease is known for various combinations of independent modifications. Therefore, the amount of decrease resulting from the dependency can be subtracted from the expected independent value corresponding to various frequency and magnitude modifications. This can be accomplished by two different methods. Frequency modifications can be held constant at a certain level, and then attempts can then be made to decrease magnitude or magnitude modifications can be held constant and decrease can then be made on frequency. Such a technique does not evaluate the exact nature of the dependency, because complex feedback mechanisms operate between frequency and magnitude. The technique will however be accurate enough to evaluate the relative extent of the dependency relationship between frequency and magnitude.

Table 17 illustrates the results when frequency is held constant and changes in magnitude are performed. The values along the bottom row, considering only frequency changes, were determined by

$$DCV = CV - (DA \cdot \bar{x}\ freq._i \cdot 20) \tag{16}$$

where DCV is the dependent cell value, CV is the independent cell value, DA_i is the predicted decrease in average path area for a given frequency change i, and $\bar{x}$ $freq._i$ is the expected frequency at a given frequency change i. These values were then used to determine the values up each column, frequency held constant and magnitude changes performed, by

$$DCV = TCV - (DF_i \cdot \bar{x}\ mag._i \cdot 20) \tag{17}$$

where DCV is the dependent cell value, TCV is the temporary cell value resulting from a 10% decrease in the previous cell, DF_i is the predicted frequency decrease at a given magnitude change i, $\bar{x}$ $mag._i$ is the expected average path area at a given magnitude change i.

Table 17

Path Area—Frequency Primary Dependent Variable

Magnitude Change %										
90	17.77									
80	37.1	1.48			APPROACHING ZERO					
70	57.21	24.27	16.40	9.29	1.93					
60	77.89	47.88	37.39	27.76	18.12	9.29	1.17			
50	98.86	71.69	58.60	46.47	34.53	23.53	13.37	3.95		
40	120.45	95.33	79.64	65.01	50.77	37.60	25.40	14.11	3.80	
30	142.16	118.38	100.08	82.96	66.42	51.08	36.84	23.68	11.64	1.24
20	164.26	140.59	119.72	100.10	81.26	63.75	47.47	32.44	18.67	6.73
10	186.55	161.65	138.16	116.04	94.90	75.22	56.90	40.00	24.50	10.57
0	209.02	181.35	155.22	130.59	107.15	85.3	64.94	46.17	28.95	13.47
	0	10	20	30	40	50	60	70	80	90

Frequency Change %

Table 18 illustrates the results of the dependency relationship when magnitude is held constant and frequency changes are performed. The method used to determine the cell values is similar to that used above in Table 17 except the value of the first column is determined first and then calculations proceed across the rows.

Table 18

Path Area--Magnitude Primary Dependent Variable

90	17.77	9.24								
80	37.10	26.65	10.98		APPROACHING ZERO					
70	57.21	44.74	27.05	5.62						
60	77.89	63.35	43.59	20.09						
50	98.86	82.22	60.36	34.76	6.62					
40	120.45	101.70	77.73	50.02	19.77					
30	142.16	121.21	95.04	65.13	32.68					
20	164.26	141.10	112.74	80.63	45.98	10.38				
10	186.55	161.10	130.43	96.02	59.09	21.17				
0	209.02	181.35	155.22	130.59	107.15	85.3	64.94	46.17	28.95	13.47
	0	10	20	30	40	50	60	70	80	90

Frequency Change %

The comparison between Tables 17 and 18 indicates that changes in frequency result in larger total path area decreases than do changes in magnitude. If a decision has to be made concerning which parameter to modify the obvious decision, considering the dependency relationship found here, is to modify frequency. As was indicated in the previous section on possible tornado modification techniques, frequency may be the most likely parameter to be modified. If this assumption is true, frequency would also provide a greater decrease than magnitude in expected path area and therefore produce the greatest decrease in expected tornado damage value.

Damage Value Analysis

The data gathered from the Oklahoma Tax Commission indicated that quadrats (2,4) and (2,2) had the extreme low and high assessed value of improvements. These quadrats were therefore chosen for damage value analysis. Quadrat (2,4) was calculated to have approximately 95% of its total area classed as rural and a total assessed value of improvements equal to $57.6 million, of which $31.1 million were urban improvements. Quadrat (2,2) centered on Oklahoma City, had a total assessed value of $2,370.4 million, of which $38.1 million was rural. Urban and built up area accounted for 22% of the area in quadrat (2,2). These calculations are found in Appendix C.

The simulated path area in square miles for the two selected quadrats for each of the 100 "runs" is listed in Table 19.

The path areas generally decrease with decreases in frequency and magnitude as did the path area distribution for the entire study area in Table 11. However, the occurrence of a few large tornadoes within any given "run" caused exceptions to this generalization. For example, the rural quadrat value of 22.86 square miles with 50% frequency and 40% magnitude decreases, resulted when a tornado that originated in the quadrat to the southwest, passed through the entire rural quadrat producing a 21.21 square mile path area. This example is typical of all the anomalies found in Table 19.

The damage value in dollars for each element of Table 19 was calculated using the formula number 10. The results of these calculations for the selected quadrats and for the unmodified and modified intensity distributions are listed in Table 20 in millions of dollars.

TABLE 19

Path Areas of Selected Quadrats

Quadrat (2.4)

Magnitude Change (%) \ Frequency Change (%)	0	10	20	30	40	50	60	70	80	90
90	.8532	.1719	.0256	.0606	.2037	.0416	.0416	.0385	.1417	0.0
80	1.7331	2.0883	3.4454	.0160	.1714	.2952	2.5343	.0152	.0011	0.0
70	1.0720	3.7714	.9279	3.2994	3.8216	.6137	.1819	.4488	.0280	.1777
60	2.2478	1.3070	1.3629	0.0	3.7484	.8079	1.8400	.1248	.0044	.0380
50	4.4055	1.0235	.8013	.5967	1.3614	1.0567	.4100	37.25	.0816	.8127
40	2.7217	3.4461	1.4778	19.0648	2.4070	22.86	.1112	.1786	.9211	.7752
30	14.0480	4.3250	7.0464	6.8697	1.7450	21.3593	3.1208	1.7961	.1276	.0074
20	11.6409	.9666	2.2587	11.1651	10.8124	5.0872	.6588	2.3023	.1616	.0578
10	31.8645	14.4061	26.2036	3.7970	9.0253	.3358	2.1364	1.1412	3.2630	16.0056
0	42.81	7.33	7.9547	.7698	10.1719	5.2380	.4728	.0289	4.2501	1.0604

Quadrat (2.2)

Magnitude Change (%) \ Frequency Change (%)	0	10	20	30	40	50	60	70	80	90
90	1.7107	.3441	.3906	1.1280	.8862	.5771	.9675	.0321	.0520	.0307
80	7.6382	.6031	1.6831	.6208	1.9788	1.2104	.2686	.0709	.0178	.0118
70	9.2914	5.0870	4.0314	7.0690	.1726	.3409	.5148	.8223	.1656	1.9259
60	11.6951	.4420	3.7166	.0022	1.1634	7.8744	7.8150	.0225	.3767	.3324
50	13.9414	1.5137	7.2998	3.4457	3.5709	7.0753	2.4348	.1270	4.4201	2.5061
40	15.5676	4.0592	2.6296	1.4150	4.3226	3.9654	1.2272	.3007	.0536	.2604
30	8.9441	12.5797	7.3421	21.0804	1.1931	11.9932	.5922	5.9203	.7051	2.7631
20	8.0537	23.9886	13.0089	11.6012	.5690	8.3572	1.9978	.1252	.7822	.4452
10	11.95	8.8284	6.0063	4.7726	5.1323	7.5006	1.4438	.2449	.0038	.1787
0	12.98	32.57	3.3619	2.743	5.9757	1.0265	2.9643	6.7829	1.8864	1.9597

TABLE 20

Rural Modified
in Millions of Dollars

Magnitude Change (%) \ Frequency Change (%)	0	10	20	30	40	50	60	70	80	90
90	.0233	.0047	.0007	.0017	.0056	.0039	.0011	.0011	.0039	0.0
80	.0473	.0570	.0940	.0004	.0047	.0081	.0691	.0004	0.0	0.0
70	.0292	.1029	.0253	.0900	.1042	.0167	.0050	.0122	.0008	.0048
60	.0613	.0357	.0372	0.0	.1022	.0220	.0502	.0034	.0001	.0010
50	.1202	.0279	.0219	.0163	.0371	.0288	.0112	.0102	.0022	.0222
40	.0742	.0940	.0403	.5200	.0657	.6235	.0030	.0049	.0251	.0211
30	.3832	.1180	.1922	.1874	.0476	.5826	.0851	.0490	.0035	.0002
20	.3175	.0264	.0616	.3046	.2949	.1388	.0180	.0628	.0044	.0016
10	.8692	.3929	.7149	.1036	.2462	.0092	.0583	.0311	.0890	.4366
0	.1677	.1999	.2170	.0210	.2775	.1429	.0129	.0008	.1159	.0289

Rural Unmodified

Magnitude Change (%) \ Frequency Change (%)	0	10	20	30	40	50	60	70	80	90
90	.0086	.0017	.0003	.0006	.0020	.0014	.0004	.0004	.0014	0.0
80	.0174	.0209	.0346	.0002	.0017	.0030	.0254	.0002	0.0	0.0
70	.0108	.0376	.0093	.0331	.0383	.0062	.0018	.0045	.0003	.0018
60	.0225	.0131	.0137	0.0	.0376	.0081	.0185	.0013	0.0	.0004
50	.0442	.0103	.0080	.0060	.0137	.0106	.0041	.0037	.0008	.0082
40	.0273	.0346	.0148	.1913	.0241	.2293	.0011	.0018	.0092	.0078
30	.1409	.0434	.0707	.0689	.0175	.2143	.0313	.0180	.0013	.0001
20	.1168	.0097	.0227	.1120	.1085	.0510	.0066	.0231	.0016	.0006
10	.3197	.1445	.2629	.0381	.0905	.0034	.0214	.0114	.0327	.1606
0	.4295	.0735	.0798	.0077	.1020	.0525	.0047	.0003	.0426	.0106

TABLE 20 continued

Urban UnModified

Magnitude Change (%)	0	10	20	30	40	50	60	70	80	90
90	1.9232	.3870	.4393	1.2685	.9966	.6490	1.0880	.0797	.0585	.0345
80	8.5898	.6782	1.8928	.6981	2.2253	1.3612	.3021	.0797	.0200	.0133
70	10.4490	5.7208	4.5337	7.9497	.1941	.3834	.5789	.9248	.1862	2.1658
60	13.1522	.4971	4.1796	.0025	1.3083	8.8555	8.7887	.0253	.4236	.3738
50	15.6784	1.7023	8.2093	3.8750	4.0158	7.9568	2.7381	.1428	4.9708	2.8183
40	17.5072	4.5649	2.9572	1.5913	4.8612	4.4594	1.3801	.3382	.0603	.2928
30	10.0584	14.1470	8.2568	23.7068	1.3417	13.4874	.6660	6.6579	.7929	3.1074
20	9.0571	26.9773	14.6293	13.0466	.6399	9.3984	2.2467	.1408	.8797	.5007
10	13.4388	9.9283	6.7546	5.3672	5.7717	8.4351	1.6237	.2754	.0043	.2010
0	14.5972	36.6279	3.7808	3.0847	6.7202	1.1544	3.3336	7.6280	2.1214	2.2039

Frequency Change (%)

Urban Modified

Magnitude Change (%)	0	10	20	30	40	50	60	70	80	90
90	.7063	.1421	.1613	.4659	.3660	.2384	.3996	.0133	.0215	.0127
80	3.1547	.2491	.6952	.2564	.8173	.4999	.1109	.0293	.0074	.0049
70	3.8376	2.1010	1.6651	2.9197	.0713	.1408	.2126	.3396	.0684	.7954
60	4.8303	.1826	1.5350	.0009	.4805	3.2523	3.2278	.0093	.1556	.1373
50	5.7581	.6252	3.0150	1.4232	1.4649	2.9223	1.0056	.0525	1.8256	1.0351
40	6.4298	1.6765	1.0861	.5844	1.7853	1.6378	.5069	.1242	.0221	.1076
30	3.6941	5.1957	3.0324	8.7067	.4928	4.9535	.2446	2.4452	.2912	1.1412
20	3.3264	9.9078	5.3728	4.7916	.2350	3.4517	.8251	.0517	.3231	.1639
10	4.9356	3.6463	2.4807	1.9712	2.1198	3.0979	.5963	.1011	.0016	.0738
0	5.3610	13.4521	1.3285	1.1329	2.4681	.4240	1.2243	2.8015	.7791	.8094

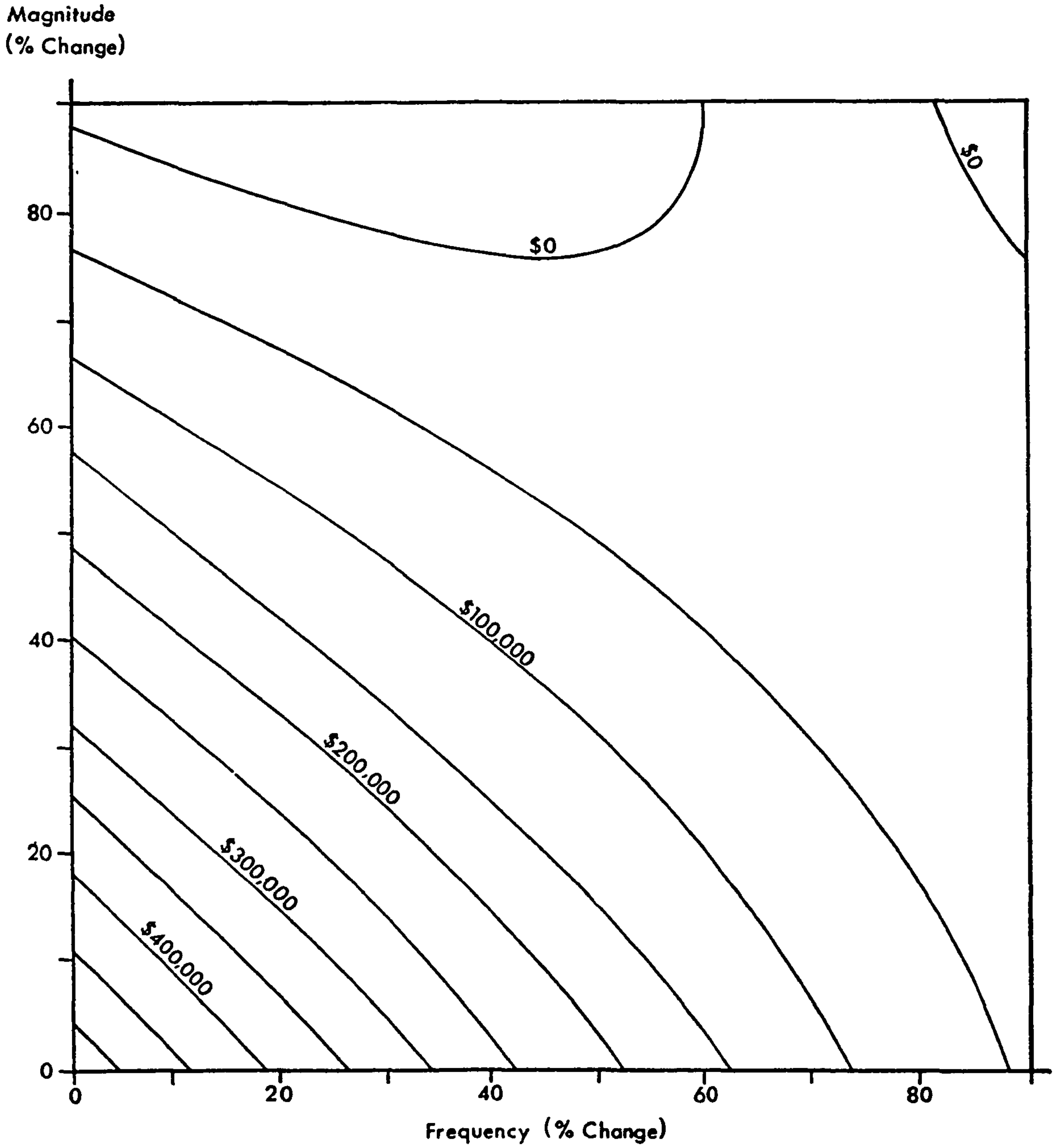
Frequency Change (%)

Because of the random variation in the damage value data shown in Table 20 and because of the advantages of a predictive equation, matrix surface analysis was performed on each of the damage value matrices. The second degree orthogonal polynomial surface was chosen for analysis in each instance. This decision was made because the damage value is directly and positively related to the path area. The relationship between path area and various frequency and magnitude modifications has previously been shown to be well represented by the second degree surface. A similar relationship would be expected to exist between damage value and frequency and magnitude changes for the two quadrats under consideration. However, the nature of the relationship and therefore the nature of the surface fit would not be expected to be as good for these selected quadrats. The total number of tornadoes involved in the simulation experiment for each quadrat would equal approximately 1/16 of the total number included in the entire study area analysis. Since the sample size for each quadrat is considerably smaller, the random occurrence of large tornadoes within a selected quadrat caused the damage value estimates to be inflated for a given simulated "run." The matrix surface model takes these large values into account when the surface is "fit", therefore the model would be expected to predict the system's characteristics. The second degree surfaces for unmodified and modified intensity of quadrat (2,4) are illustrated in Figures 7 and 8 respectively.

The contour patterns in Figure 7 and 8 are very similar to the pattern exhibited by the contours of the second degree surface of path are for the entire study area. This is to be expected because as already indicated the damage value is directly and positively related

Figure 7

RURAL UNMODIFIED TREND-SECOND DEGREE

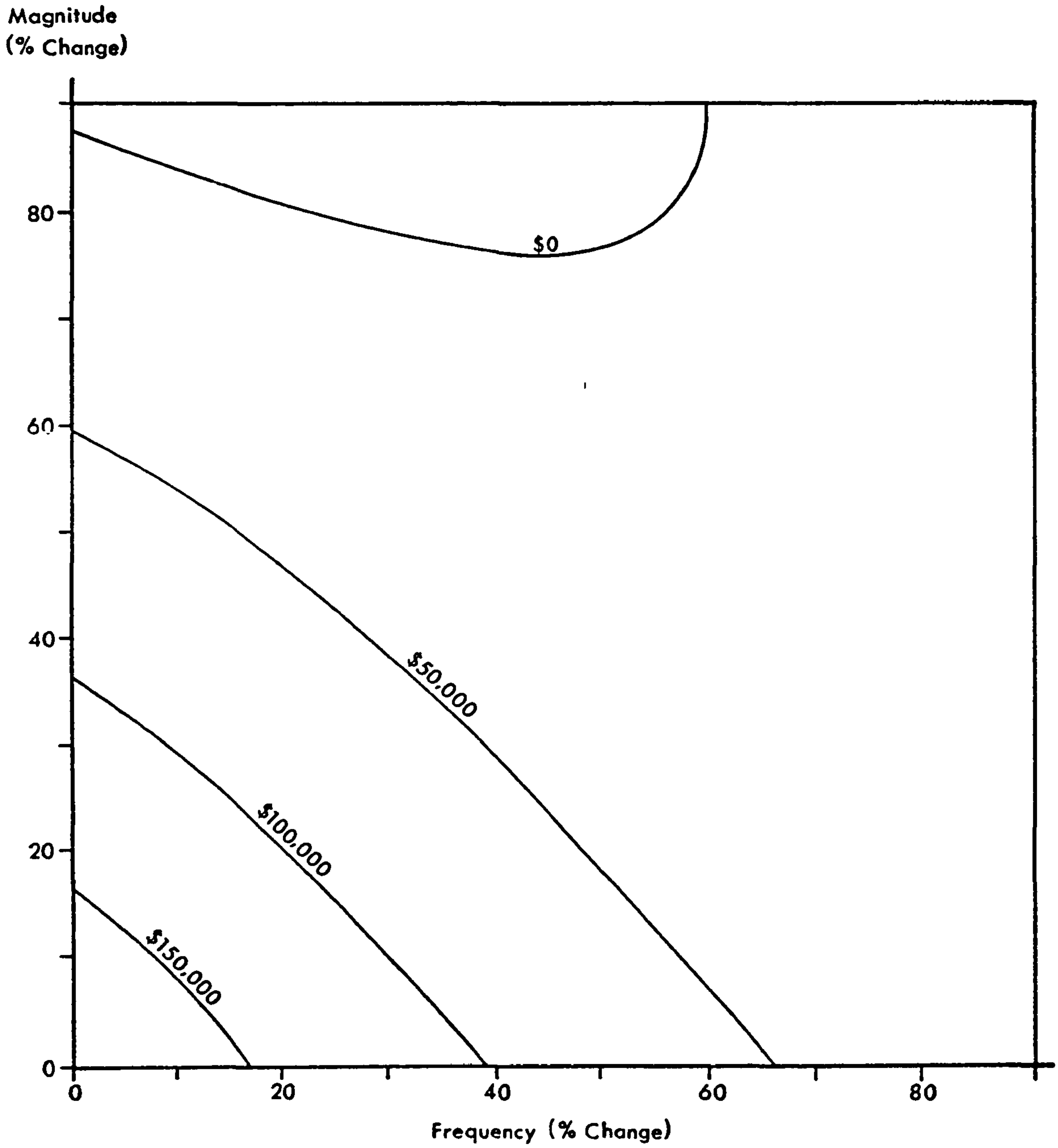


Contour Interval: Fifty Thousand Dollars ($50,000)

SOURCE: AUTHOR'S COMPUTATIONS

Figure 8

RURAL MODIFIED TREND - SECOND DEGREE



Contour Interval: Fifty Thousand Dollars ($50,000)

SOURCE: AUTHOR'S COMPUTATIONS

to path area. The patterns are also similar to the path area surface in that equal percent decreases in frequency or magnitude result in n nearly equal changes in damage values.

The predicted damage value in millions of dollars for unmodified intensity in quadrat (2,4) can be calculated for a given percent change in magnitude (Y) and frequency (X) by

$$Z = .5389 + (-.0784)X + (-.0786)Y + .0026X^2 + .0071XY + .0020Y^2 \quad (18)$$

The correlation coefficient for the second degree surface was .63 which indicated that 40% of the total variance of the damage value data was explained by the surface.

The predicted damage value in millions of dollars for modified intensity in quadrat (2,4) can be calculated by

$$Z = .1982 + (-.0289)X + (-.0289)Y + .0010X^2 + .0026XY + .0007Y^2 \quad (19)$$

The correlation coefficient and therefore the percent of explained variance are equal to the unmodified surface because they are constant multiples of each other.

The contoured second degree damage value surfaces for quadrat (2,2) the predominately urban quadrat, are shown in Figures 9 and 10.

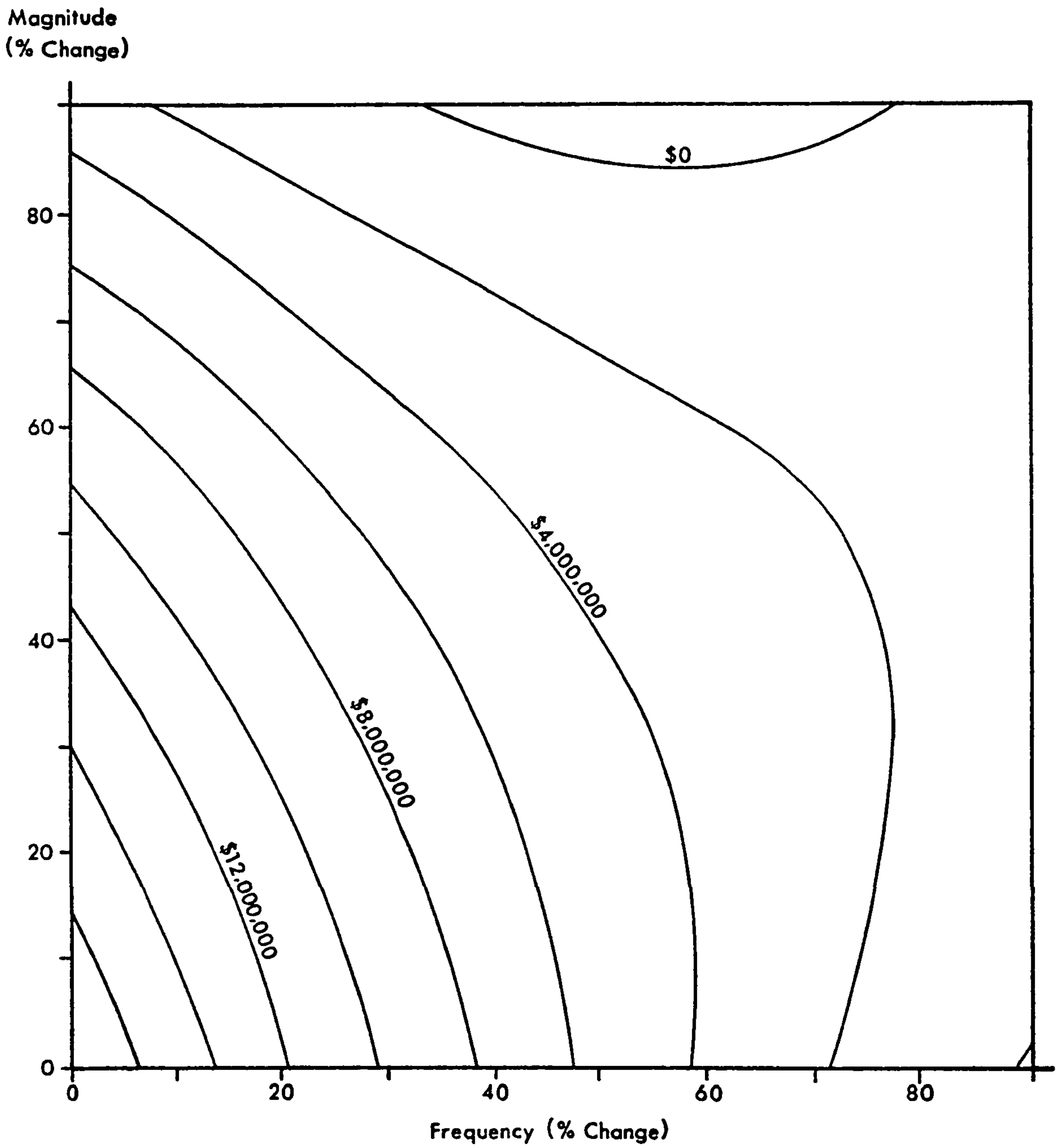
The contour pattern is once again similar to the patterns found on the previous surfaces. The prediction equation for the unmodified intensity surface is

$$Z = 17.8470 + (-3.0778)X + (-1.0646)Y + .1211X^2 + .1926XY + (-.0630)Y^2 \quad (20)$$

This quadratic surface explains 48.4% of the total variance of the input data matrix. If intensity is held constant in the future and the ability to decrease tornado frequency and/or magnitude is developed, this model predicts that with only a 10% decrease in frequency and

Figure 9

URBAN UNMODIFIED TREND-SECOND DEGREE

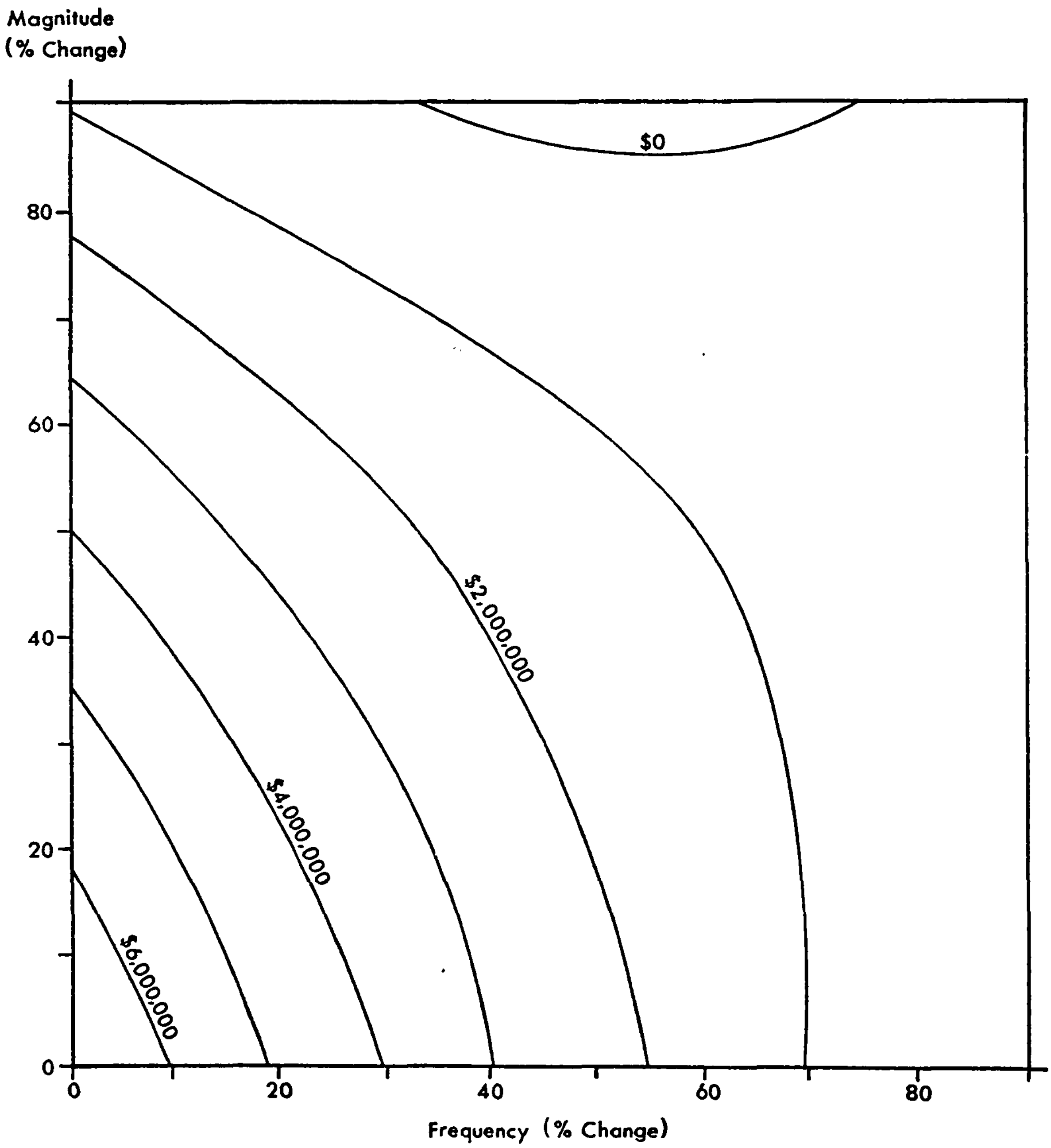


Contour Interval: Two Million Dollars ($2,000,000)

SOURCE: AUTHOR'S COMPUTATIONS

Figure 10

URBAN MODIFIED TREND - SECOND DEGREE



Contour Interval: One Million Dollars ($1,000,000)

SOURCE: AUTHOR'S COMPUTATIONS

magnitude the savings would amount to nearly $4 million over a 20 year period. Realizing that a small percentage of tornadoes cause most of the damage, the modification effort may not be extremely expensive in relation to the expected savings. This would be especially true if instrumentation were available to determine conditions when and approximately where an especially high magnitude tornado were likely to occur.

The prediction equation for the modified intensity quadratic surface is

$$Z = 7.0984 + (-1.1702)X + (-.55159)Y + .0417X^2 + .0803XY + (-.0175)Y^2 \quad (21)$$

The surface explained 48.4% of the total variance of the input data matrix.

This chapter has described the design of the simulation experiments and has analyzed the effects of tornado parameter modifications based on those experiments. The expected path area changes were estimated considering the apparent dependency between frequency and magnitude. Matrix surface analysis was used to produce predictive models for various tornado parameter changes for a predominately rural and a predominately urban quadrat within the study area. These models of course only apply to the selected quadrats, but could be easily applied to other quadrats in the study area.

CHAPTER 5

CONCLUSIONS

The stages of development of this computer simulation model produced a number of findings that may have implications to future tornado hazard research. The results of the computer simulation experiments, which are directly applicable only to the study area, form the basis for generalizations that have no spatial bounds. Before detailed and accurate assessments of the extent of the tornado hazard can be produced, more information is needed concerning tornado intensity and its relationship to an accurate measure of the property-at-risk.

In the development of the computer simulation model the log-normal distributions has proved extremely useful. As Thom (1963, 731) originally showed and Howe (1974, 343) recently reported the lognormal distribution "fits" the path length, width and area distributions. This distribution was used in the computer simulation as a sampling distribution for path length after the goodness of fit was evaluated. Before the decision was made to generate path width from a regression equation, path widths were fit with a lognormal distribution. There can be little doubt remaining that the path length, width and area are all lognormally distributed.

Two theoretical frequency distributions were utilized in this simulation to generate annual tornado frequencies. The lognormal distribution was used to generate annual frequencies for the entire study area and the negative binomial to generate annual frequencies for the individual quadrat. The ability of these distributions to describe the annual frequency was very sensitive to scale changes.

The negative binomial distribution is a contagious distribution, meaning the occurrence of one event increases the probability of another event (Williamson and Bretherton, 1963, 9). On theoretical grounds, this distribution would appear to be capable of describing tornado frequency since tornadoes tend to form in clusters or families. However, the quadrat size must be small enough to identify this clustering effect. The individual quadrats used in this research were reduced from 50 $miles^2$ (129.5 Km^2) to 30 $miles^2$ (77.7 Km^2) because the annual frequencies of all quadrats of larger size did not fit the negative binomial distribution.

The lognormal distribution, is sometimes, referred to as the distribution of proportionate effect because it describes distributions where growth of equal proportionate increments have an equal chance of occurring regardless of the previously attained size (King, 1969, 53). Therefore this distribution theoretically indicates that the number of tornadoes that have already occurred during a given time period has no effect on the proportionate number that will occur in the future. This relationship is sensitive to quadrat size directly or indirectly through frequency, because a large frequency is necessary to produce a discrete distribution that can be approximated by a continuous distribution.

The ability of these two distributions to represent annual frequency raises questions concerning their future use in tornado hazard research. Both apparently have scale limitations which would greatly influence their range of application. Also depending on the research problem, one may produce better results than the other in a manner similar to various geological models (Krumbein and Graybill, 1965, 28). The ranges of applications and scales, and the limitations of these distributions need to be determined because knowledge of an appropriate frequency distribution to describe natural events is an essential requirement for many types of hazard research.

Conclusions based on the computer simulation experiments involve the need for further tornado hazard research and the applicability of these results to regions other than Central Oklahoma. Thom (1963, 731) suggested that the expected path area of tornadoes may be invariate over space, but also suggested that path areas be analyzed from other areas to evaluate the validity of this suggestion. This research as well as the research by Howe (1974, 344) has shown that tornado path sizes in other areas of the United States are significantly different than the Iowa tornadoes analyzed by Thom. Thom used his path area estimates from Iowa in conjunction with annual frequencies throughout the United States to determine areal probabilities for the entire United States. Thom's expected path area was much higher (nearly five times) than the Central Oklahoma study area used in this research and 50% higher than any reported by Howe (1974, 345). Therefore Thom's probabilities are over estimated. A re-evaluation of Thom's often used tornado probabilities is necessary to more accurately evaluate the extent of the tornado hazard.

The second degree polynomial (quadratic) fit to the path areas with various frequency and magnitude changes can be applied to any area to determine the expected percent of path area with any percent decrease in frequency and magnitude. The polynomial coefficients in the original equation were expressed as a percent of the predicted path area without frequency or magnitude changes. The general quadratic equation with these changes incorporated is

$$Z\% = 100 + (.99)X + (-1.04)Y + (0.00087)X^2 + .0108XY + (-.00006)Y^2 \qquad (22)$$

This equation can be applied, for example, to evaluate the effect on path area of a 30% change in magnitude (Y) and a 40% change in frequency (X) by substituting these values into the equation. It becomes:

$$Z\% = 100 + (-.99)40 + (-1.04)30 + (-.00087)40^2 + .0108(40)(30) + (-.00006)30^2 \qquad (23)$$

The result, 40.7%, indicates that with these parameter changes the path area is 40.7% of that normally expected. This equation, of course, can be indirectly applied to expected value of damage figures for any area. If data concerning theoretical or empirical expected damage value per time unit is available, estimates can be made on the savings that would result from various frequency and magnitude modifications.

The influence of tornado intensity on damage value has been difficult to accurately identify in this research. A decrease of one intensity level in the overall F-scale frequency distribution, as was performed here, resulted in 63.2 percent decrease in expected damage value. This indicates that intensity may be the most sensitive of the tornado parameters or that the reduction assumption was overly optimistic. The damage value would be greatly reduced if the F-3, 4 and 5 tornadoes could be modified. The exact relationship between intensity and magnitude is not known. It was therefore impossible to simulate the effect that intensity modifications have on damage value, because no theoretical or empirical distribution exists that describes this relationship. The United States Weather Service is now collecting data on intensity of tornadoes in addition to frequency and magnitude. As the sample size increases in the future the relationship of tornado intensity ot magnitude will hopefully be evaluated. With this needed information, the sensitivity of intensity modifications to the damage value can be evaluated.

The simulation experiments have also shown that tornado frequency and magnitude are equally sensitive to modifications when independence is assumed. This becomes important when techniques are in the developmental stage. Techniques used to modify these parameters may be, as indicated in Chapter 2, quite different. One technique is likely to be less costly than the other and with this information the decision as to the most appropriate technique to employ could be made.

The concavity of the path area surface (Figure 6) indicates that the combined effect of frequency and magnitude changes diminish with high percent modifications. The strategy used in the future to modify tornadoes may be directly related to this relationship. Once frequency and magnitude are both modified by approximately 50%, it will be advantageous to concentrate further modification on either frequency or magnitude and not on both. The decision as to which to choose may be dictated by the cost of modification alone or by other indirect motivations. For example, by choosing to further modify frequency, tornado damage would be concentrated in fewer areas, which may have greater economic benefit than having less tornado damage spread over additional areas.

Path area reductions are more sensitive to frequency modification than to magnitude modifications when the apparent dependency between frequency and magnitude is considered. For example, a 10% decrease in frequency will result in an 18% decrease in expected path area, while a 10% decrease in magnitude will result in a 12% reduction in path area. This information in relation to the likely ability of tornado modifiers to modify frequency, presents a strong case for concentration of efforts in developing frequency modification techniques.

The decrease in damage value, estimated in this research are conservative. The exact value of the property-at-risk is impossible to obtain. With inflation constantly increasing the dollar value of property, and construction and repair costs rising even more rapidly than inflation, data gathered today are out of date tomorrow. The assessed value of rural and urban improvements used in this research is the best surrogate available, although it undoubtedly underestimates values in relation to fair sale values and especially underestimates in relation to replacement cost. Even though this conservative property-at-risk value was used, the benefits of various tornado parameter modifications are great. A 40% decrease in magnitude and frequency in the Oklahoma City quadrat resulted in a 12.5 million dollar savings over the expected twenty year value. Without considering human lives, with benefits of this magnitude, future tornado modification efforts are likely to be economically feasible.

APPENDIX A

COMPUTER PROGRAM

```
      REAL TOR(100),LNTH(100),WDT(100),Q(6,6),ACELL(6,6),TACEL(6,6),FREQ
     C(7)
      INTEGER ICELL(6,6),NBIK(6,6),L(2)
      IX=5397
      STDY=.2396
      XBARL=-.7167
      STDL=.8116
      XBARR=.0059
      STDR=150.08
      READ(5,600)(FREQ(IR),IR=1,10)
  600 FORMAT(10F7.4)
      READ(5,7)((Q(JA,JB),JB=1,6),JA=1,6)
    7 FORMAT(6F4.2)
      READ(5,8)((NBIK(JC,JD),JD=1,6),JC=1,6)
    8 FORMAT(6I2)
      DO 1003 MQ=1,10
      DAMT=0.0
      DO 90 KZ=1,6
      DO 90 KW=1,6
   90 TACEL(KZ,KW)=0.0
      DO 500 IW=1,20
      DALY=0.0
      DO 2 IJ=1,6
      DO 2 JI=1,6
      ACELL(IJ,JI)=0.0
    2 ICELL(IJ,JI)=0
C
C     THIS DETERMINES THE NUMBER OF TORNADOES IN YEAR X FROM THE LOG
C     NORMAL DISTRIBUTION
      CALL LOG(IX,FREQ(MQ),STDY,X)
      JJ=X+.50
      WRITE(6,9)JJ,IQ
    9 FORMAT('1',4X,'THE NUMBER OF TORNADOES THIS YEAR =',I3,10X,'YEAR='
     C,I3)
C
C     THIS RANDOMLY SELECTS A CELL AND CHECKS WITH THAT CELLS NEGATIVE
C     BIONOMIAL DISTRIBUTION FOR ACCEPTANCE OR REJECTION
      DO 20 II=1,JJ
   11 DO 15 M=1,2
      CALL RANDU(IX,IY,YFL)
      IX=IY
   15 L(M)=(YFL*4.0)+2.00
      CALL NEGBI(IX,NBIK(L(1),L(2)),Q(L(1),L(2)),NX)
      IF(ICELL(L(1),L(2))+1.GT.NX)GO TO 11
      ICELL(L(1),L(2))=ICELL(L(1),L(2))+1
   20 CONTINUE
      WRITE(6,10)((ICELL(IE,IF),IF=2,5),IE=2,5)
   10 FORMAT(1X,4I8)
      NA=0
C
C     THIS DETERMINES THE LENGTH AND WIDTH OF EACH TORNADO USING THE
C     LOG NORMAL DISTRIBUTION FOR LENGTH AND A REGRESSION EQUATION
```

```
C      WITH AN ERROR TERM FOR THE WIDTH
      DO 30 IA=2,5
   25 DO 30 IB=2,5
      IC=ICELL(IA,IB)
      IF(IC.EQ.0)GO TO 30
      DO 29 ID=1,IC
      CALL LOG(IX,XBARL,SIDL,A)
      PRED=134.7+(5.41*A)
      CALL GAUSS(IX,SIDR,XBARR,C)
      CALL RANDU(IX,IY,YFL)
      IX=IY
      IF(YFL.LT..50)GO TO 201
      B=PRED+C
      IF(B.GT.880.0)B=880.0
      IF(B.LT.15.0)B=15.0
      GO TO 210
  201 B=PRED-C
      IF(B.LT.15.0)B=15.0
      IF(B.GT.880.0)B=880.0
  210 NA=NA+1
      TOR(NA)=A*(B/1760.)
      LNTH(NA)=A
      WDT(NA)=B
C
C      THIS ASSIGNS DIRECTION FREQUENCIES TO INTERCELLULAR TORNADOES
      IF(A.LT.15.0)GO TO 27
   50 CALL RANDU(IX,IY,YFL)
      IX=IY
      IF(YFL.LT.0.62)GO TO 51
      IF(YFL.LT.0.80)GO TO 52
      IF(YFL.LT.0.89)GO TO 53
      IF(YFL.LT.0.95)GO TO 54
      IF(YFL.LT.0.98)GO TO 55
      IF(YFL.LT.1.00)GO TO 56
   51 ACELL(IA-1,IB+1)=ACELL(IA-1,IB+1)+(A-15.0)*(B/1760.)
      GO TO 60
   52 ACELL(IA-1,IB)=ACELL(IA-1,IB)+(A-15.0)*(B/1760.)
      GO TO 60
   53 ACELL(IA,IB+1)=ACELL(IA,IB+1)+(A-15.0)*(B/1760.)
      GO TO 60
   54 ACELL(IA+1,IB+1)=ACELL(IA+1,IB+1)+(A-15.0)*(B/1760.)
      GO TO 60
   55 ACELL(IA+1,IB)=ACELL(IA+1,IB)+(A-15.0)*(B/1760.)
      GO TO 60
   56 ACELL(IA+1,IB-1)=ACELL(IA+1,IB-1)+(A-15.0)*(B/1760.)
   60 ACELL(IA,IB)=ACELL(IA,IB)+15.0*(B/1760.)
      GO TO 29
   27 ACELL(IA,IB)=ACELL(IA,IB)+(A*(B/1760.))
   29 CONTINUE
   30 CONTINUE
      WRITE(6,61)
   61 FORMAT(1X,///,8X,'          TORAREA            LENGTH            WID')
```

```
      WRITE(6,12)(KA,TOR(KA),LNTH(KA),WDT(KA),KA=1,NA)
   12 FORMAT(1X,I8,3F15.4)
      WRITE(6,100)
  100 FORMAT(1X,///,'     TORNADO DAMAGE AREA PER CELL')
      WRITE(6,13)((ACELL(IW,IZ),IZ=1,6),IW=1,6)
   13 FORMAT(1X,6F15.4)
      DO 305 NW=1,6
      DO 305 NZ=1,6
  305 TACEL(NW,NZ)=TACEL(NW,NZ)+ACELL(NW,NZ)
      DO 306 IP=2,5
      DO 306 IO=2,5
  306 DAMY=DAMY+ACELL(IP,IO)
      WRITE(6,307)DAMY
  307 FORMAT(1X,///,' DAMAGE AREA FOR YEAR=',F12.4)
  500 CONTINUE
      WRITE(6,300)
  300 FORMAT(1X,///,'          20 YEAR DAMAGE AREA PER CELL')
      WRITE(6,301)((TACEL(NN,NM),NM=1,6),NN=1,6)
  301 FORMAT(1X,6F15.4)
      DO 310 IQ=2,5
      DO 310 IS=2,5
  310 DAMT=DAMT+TACEL(IQ,IS)
      WRITE(6,311)DAMT
  311 FORMAT(1X,///,' DAMAGE AREA FOR ENTIRE RUN=',F12.4)
 1000 CONTINUE
      STOP
      END
```

APPENDIX B

SAMPLE COMPUTER OUTPUT

THE NUMBER OF TORNADOES THIS YEAR = 19 YEAR= 20

0	0	1	3
1	1	1	0
0	2	4	2
0	0	1	3

	TORAREA	LENGTH	_WID
1	0.0035	0.4172	15.0000
2	0.0842	0.7137	217.4841
3	0.0622	0.9050	121.0503
4	0.0664	1.2213	95.6564
5	0.0953	0.4972	348.0642
6	0.0455	1.0292	79.5257
7	0.4937	7.6529	113.5321
8	0.1070	0.9410	200.0682
9	0.0468	0.4474	169.0568
10	0.0347	2.0246	73.6298
11	4.0138	24.7729	285.1611
12	5.5556	44.0369	225.7800
13	1.8805	13.4273	246.4854
14	0.0102	0.1375	130.6809
15	0.0982	3.7466	45.6316
16	0.0401	1.0707	64.7517
17	0.0057	0.7818	15.0000
18	0.3593	1.4298	442.2639
19	0.0140	1.6433	15.0000

TORNADO DAMAGE AREA PER CELL

0.0	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0036	0.2168	0.0
0.0	0.0983	0.0465	0.4937	0.0	0.0
0.0	0.0	0.1538	6.3198	3.8398	0.0
0.0	0.0	0.0	1.6236	0.3800	0.0
0.0	0.0	0.0	0.0	0.0	0.0

DAMAGE AREA FOR YEAR= 13.1758

20 YEAR DAMAGE AREA PER CELL

0.0	0.0	0.0	0.6974	0.0	0.0
0.0	4.1879	5.7632	6.7748	1.8009	9.7939
0.0	2.7459	1.0265	1.6532	5.2380	8.4134
0.0	0.2838	3.4642	7.8413	11.9427	0.0
0.0	0.2611	5.3159	1.7397	0.6680	0.0
0.0	0.0	0.0	0.0	0.0	0.0

DAMAGE AREA FOR ENTIRE RUN= 60.9249

APPENDIX C

CALCULATIONS OF VALUE OF IMPROVEMENTS FOR SELECTED QUADRATS

APPENDIX C

CALCULATION OF VALUE OF IMPROVEMENTS FOR SELECTED QUADRATS

The value of improvements (rural and urban) were collected by county from the Oklahoma Tax Commission. These data had to be converted for use in the selected quadrats. The method used consisted of determining the percentage of rural and urban land area of each county that was within a quadrat, and allocating that percent of the value of rural and urban improvements to the qudrat.

The percent of "built-up area" of each county was collected from Oklahoma Agriculture-1970-71, Oklahoma Crop and Livestock Reporting Service, State Board of Agriculture, 1971, 100 p.

The population of "built-up areas" (any town or city listed) was gathered from the 1970 Census of Population-Oklahoma. A planimeter was used to determine the area of the county within each quadrat.

The following formulas were used to determine various values for each county in the selected quadrat.

The percent of "built-up" area of county in quadrat

$$\%\ \text{"built-up"} = \frac{\text{Total "urban" population in quadrat}}{\text{Total "urban" population in county}}$$

The number of square miles of county in quadrat considered "built-up"

$$\text{miles}^2\ \text{"built-up"} = \%\ \text{"built-up"} \times \text{"built-up" area in county}$$

The percent of rural area of county in quadrat

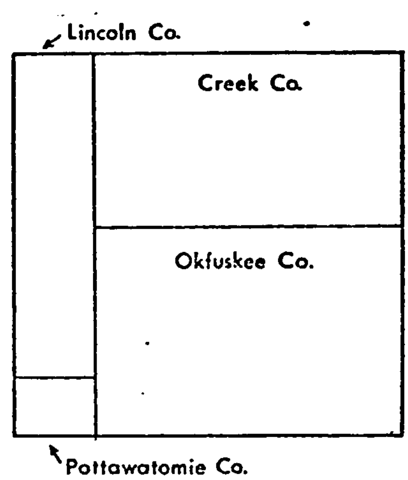
$$\% \text{ rural} = \frac{\text{Total miles}^2 \text{ in quadrat} - \text{miles}^2 \text{ "built-up"}}{\text{Total miles}^2 \text{ county}}$$

The number of square miles in county considered rural

$$\text{miles}^2 \text{ rural} = \% \text{ rural} \times \text{Total miles}^2 \text{ in quadrat}$$

SUMMARY TABLE OF SELECTED QUADRATS

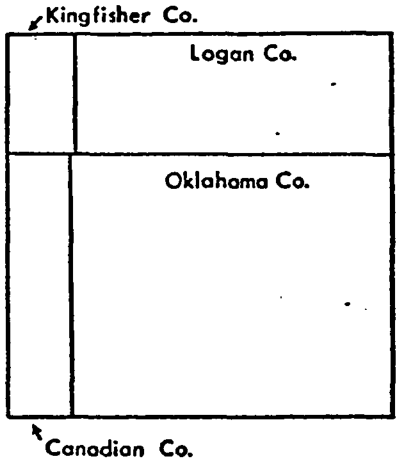
Quadrat (2,4)



	Miles^2 "built-up"	Miles^2 rural	% of rural	% of "built-u
Creek	1.4	306.5	.3185	.0368
Okfuskee	16.1	408.4	.6348	.9876
Lincoln	20.5	122.5	.1218	.6298
Pottawatomie	0.0	24.6	.0303	.0000
TOTAL	38.0	862.0		

$ Rural Improvements	$ Urban Improvements
17.8	3.3
4.4	11.2
2.8	16.6
1.5	0.0
26.5	31.1

Quadrat (2,2)



	Miles^2 "built-up"	Miles^2 Rural	% of Rural	% of Urban
Oklahoma	178.2	344.5	.5209	.9916
Canadian	21.1	110.4	.1290	.5166
Kingfisher	1.4	47.1	.0531	.0529
Logan	0.0	197.3	.2681	.0000
TOTAL	201.7	699.3		

$ Rural Improvements	$ Urban Improvements
25.3	2,278.5
5.2	52.1
1.4	1.7
6.2	0.0
38.1	2,332.3

REFERENCES

Adjusters, 1974, Personal Interview with: Carl Wimberly and William Hiss, Universal Claims Service, Norman, Oklahoma, and James L. Gasaway, General Adjustment Bureau, Norman, Oklahoma.

Asp, M. O., 1963, "History of Tornado Observations and Data Sources," Key to Meteorological Records Documentation, No. 3.131, U. S. Weather Bureau, Washington, D. C.

Barton, Richard F., 1970, A Primer on Simulation and Gaming, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Battan, Louis J., 1961, The Nature of Violent Storms, Anchor Books Doubleday and Company, Inc., New York.

Battan, Louis J., 1969, "Weather Modification in the U.S.S.R.-1969," Bulletin of the American Meteorological Society, Vol. 50-12, pp. 924-945.

Booker, Ray, 1974, Weather Sciences Inc., Telephone conversation.

Changnon, Huff, and Semonin, 1971, "Metromex: An Investigation of Inadvertent Weather Modification," Bulletin of the American Meteorological Society, Vol. 52, pp. 958-67.

Colgate, S. A., 1964, "Tornadoes: Mechanism and Control," Science, Vol. 156, pp. 1431-34.

Committee on Atmospheric Sciences of the National Research Council, 1973, Weather and Climate Modification: Problems and Progress, National Academy of Sciences, Washington, D. C.

Croxton, F. E. and D. J. Cowden, 1955, Applied General Statistics, Prentice-Hall, Inc., New Jersey, 2nd edition, 843 pp.

Curry, L., 1966, "Chance and Landscape," In J. W. House (ed.), Northern Geographical Essays in Honour of G. H. J. Doysh, Oriel Press.

Flohn, Hermann, 1969, Climate and Weather, World University Library, New York.

Fujita, T. Theodore, 1974, "Tornadoes Around the World," Weatherwise, Vol. 2602, pp. 56-62 and 79-83.

Hald, Anders, 1952, Statistical Theory with Engineering Applications, John Wiley and Sons, New York, pp. 783.

Harvey, David, 1966, "Geographic Processes and the Analysis of Point Patterns," Transactions of the Institute of British Geographers, No. 40, pp. 81-95.

Hayes, William L., 1973, Statistics, Holt, Rinehart and Winston, Chicago, 2nd edition.

Howe, George M., 1974, "Tornado Path Sizes," Journal of Applied Meteorology, Vol. 13-3, pp. 343-47.

Kates, Robert W., 1971, "Natural Hazard in Human Ecological Perspective: Hypothesis and Models," Economic Geography, Vol. 47, pp. 438-51.

Kessler, Edwin, "On Tornadoes and Their Modification," Technology Review, Vol. 74, pp. 2-9.

King, Leslie, J., 1969, Statistical Analysis in Geography, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Krumbein, W. C. and Graybill, F. A., 1965, An Introduction to Statistical Models in Geology, McGraw-Hill Book Company, New York.

Manabe, S. and Wetherwald, R. T., 1967, "Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity," Journal of Atmospheric Sciences, Vol. 24, pp. 241-59.

Massey, Frank J., Jr., 1951, "The Kolmorgorov-Smirnov Test for Goodness of Fit," American Statistical Association Journal, pp. 69-77.

Naylor, Balintfy, Burdick, and Chu, 1966, Computer Simulation Techniques, John Wiley and Sons, New York.

Oklahoma Tax Commission-Ad Valorem Tax Division, 1973 Progress Report to the Legislature on Property Revaluation, Submitted in Compliance with 68 O. S. 1971.

Poole, M. A. and O'Farrell, P. N., 1971, "The Assumptions of the Linear Regression Model," Transactions of the Institute of British Geographers, Vol. 52, pp. 145-58.

Siegal, Sidney, 1956, Non-Parametric Statistics, McGraw-Hill Book Company, New York.

Skaggs, Richard H., 1970, "On Tornado Probabilities," Proceedings of the Association of American Geographers, Vol. 2, pp. 123-26.

Tepper, Morris, 1958, "Tornadoes," Scientific American, Vol. 198-5, pp. 31-37.

Thom, H. C. S., 1963, "Tornado Probabilities," Monthly Weather Review, Vol. 91-10, pp. 730-36.

U. S. Department of Commerce, 1958-1973, Storm Data, Monthly, Asheville, North Carolina.

Vonnegut, B., 1960, "Electrical Theory of Tornadoes," Journal of Geophysical Research, Vol. 65, pp. 203-12.

Williamson, E. and Bretherton, M., Tables of the Negative Binomial Distribution, John Wiley and Sons, New York.

Yeates, Maurice, 1974, An Introduction to Quantitative Analysis in Human Geography, McGraw-Hill Book Company, New York.