WSRC-TR-98-00329

Tornado, Maximum Wind Gust, and Extreme Rainfall Event Recurrence Frequencies at the Savannah River Site

by

A. H. Weber

Westinghouse Savannah River Company
Savannah River Site
Aiken, South Carolina 29808

DOE Contract No. **DE-AC09-96SR18500**

WSRC-TR-98-00329

Tornado, Maximum Wind Gust, and Extreme Rainfall Event Recurrence Frequencies at the Savannah River Site(U)

Westinghouse Savannah River Company
Savannah River Site
Aiken, SC 29808

Prepared for the U.S. Department of Energy under contract no. DE-AC09-96SR18500

WSRC-TR-98-00329
September 1998

Tornado, Maximum Wind Gust, and Extreme Rainfall Event Recurrence Frequencies at the Savannah River Site(U)

A. H. Weber 9/30/98
A. H. Weber, Author, MTD/NTS
Westinghouse Savannah River Company

J. H. Weber 9/30/98
J. H. Weber, Author, ESTD/SCS
Westinghouse Savannah River Company

M. J. Parker 9/30/98
M. J. Parker, Author, MTD/NTS
Westinghouse Savannah River Company

C. H. Hunter 9/30/98
C. H. Hunter, Author, MTD/NTS
Westinghouse Savannah River Company

C. O. Minyard 10/3/98
C. O. Minyard, Author, MTD/NTS
Westinghouse Savannah River Company

A. L. Boni 9-30-98
A. L. Boni, Manager, NTS
Westinghouse Savannah River Company

R. P. Addis 9.30.98
R. P. Addis, Responsible Manager, MTD/NTS
Westinghouse Savannah River Company

G. P. Shine 9/30/98
G. P. Shine, Technical Reviewer, ESTD/SCS
Westinghouse Savannah River Company

Prepared for the U.S. Department of Energy under contract no. DE-AC09-89SR18035

Contents

List of Figures

List of Tables

List of Appendices

Executive Summary

This report explains the data sources and the methods used for determining probabilistic hazard curves for tornadic winds, wind gusts, and extreme rainfall events for the Savannah River Site (SRS). Probabilistic hazard curves are used to help determine design requirements for onsite structures for hazard analyses.

The tornado data for this study were obtained from NOAA's Storm Prediction Center in Norman, Oklahoma, and from tornado investigations carried out by the Atmospheric Technologies Group (ATG) at the Savannah River Site. The model used to determine tornado risk probabilities is based on work done by J. R. McDonald and D. Lu (1995).

The wind gust data were obtained from the National Climatic Data Center (NCDC) records and from computer data archives maintained by the Atmospheric Technologies Group (ATG). The extreme value distribution used for the wind gusts and extreme rainfall is based on the Fisher and Tippett (1928) formulation and the parameter estimation for fitting the distributions was done using the methods of J. Eliasson (1997) and J. R. M. Hosking, et al. (1985).

Results for the extreme value statistics are presented in both tabular and graphical form.

Introduction

DOE Order 420.1, Facility Safety, outlines the requirements for Natural Phenomena Hazards (NPH) mitigation for new and existing DOE facilities. Specifically, NPH include tornadic winds, maximum wind gusts, and extreme rainfall events. Probabilistic hazard curves for each phenomenon indicate the recurrence frequency, and these hazard curves must be updated at least every 10 years to account for recent data, improved methodologies, or criteria changes. Previous studies for SRS by McDonald (1985 and 1997) and Fujita (1980) have been used to comply with Order 420.1 with respect to NPH mitigation. In 1997, the Structural Mechanics Department requested that the Atmospheric Technologies Group (ATG) update probabilistic hazard curves for tornadic winds, maximum wind gusts, and extreme rainfall events for the SRS. The primary deliverable is this report, which includes the aforementioned curves, descriptions, and verifications. Calculations are included in a separate calculation note (Weber, 1998).

Tornadoes

Databases

The tornado databases for this project were problematic, not because there was insufficient data, but because there is no undisputed, official source of data. Instead of a single, official source of data, there are a few "semiofficial" sources of data that, unfortunately, differ substantially from one another. As the existence and nature of the different data sets were uncovered, the computer codes had to be revised to accommodate changes in the data format.

Initially the tornado data for this project was obtained through a request to the Director of the Storms Prediction Center (SPC), in Norman, Oklahoma. Data for a region bounded by 30.5°N, 77.5°W and 35.5 °N, 84.5°W (covering the states of South Carolina, Georgia, parts of North Carolina, Alabama, and Florida) was requested and subsequently received via FTP over the internet. The tornado data abstracted from this initial data source was a small fraction of the total data set, which consisted of tornadoes, waterspouts, and hail-containing thunderstorms within the requested region. Since the data had originated at the SPC and the data were slated to become the SPC's primary database, this data set was referred to as the "official" database.

SPC's "official" dataset was compared to a tornado dataset from the Southeast Regional Climate Center (Purvis, et al., 1990). Purvis assembled this database while performing work as the State Climatologist for South Carolina. Upon examination it became apparent that there were a significant number of differences between the official database and the State Climatologist's database. The main differences were that tornadoes appeared in the State Climatologist's database that were not contained in the Storm Prediction Center's official database.

Shortly after these data discrepancies were discovered, a second tornado database was located on the Storm Prediction Center's web site. This web-posted database was called the "unofficial" database to differentiate it from the earlier official SPC database. This database was downloaded, transferred to the SRTC1 computer, and compared to the other databases. The database compiled by Purvis and a similar database prepared by the Georgia State Climatologist (Plummer, 1991) were apparently taken from the same source as the web-posted, unofficial database since all tornadoes could be matched when compared.

Further investigation showed a large fraction of the tornadoes in the unofficial database were not contained in the Storm Prediction Center's official database. After studying the unrecorded tornado entries in the official database, it was found that the unrecorded entries were missing lift-off points, i.e., tornadoes were not included in the official database whenever their lift-off point was missing. An example is shown in Table I. Lines 4-8 show no entry in the official database whereas lines 13-17 from the unofficial database show 5 tornadoes missing their lift-off latitude and longitude.

Another difference in the databases was that tornado path segments from the same storm were combined into a single entry in the official database. For example, the storm listed in Table I, line 10 (from the official database), is a composite of three separate segments in the unofficial database (see lines 19-21).

Tornado data entries without a lift-off point are just as valid as are those with complete data entries. (In the aftermath of a tornado, if a National Weather Service (NWS) investigator was not able to determine the lift-off point, none was reported.) It was decided to adopt the SPC web-page database since the number of tornado occurrences are more accurately reflected in the data. To improve the format and comparability of the database, all tornado segments of a given tornado path were combined into a single entry whenever these were easy to identify. This also aided in determining an accurate damage path length for a given storm.

Tornadoes at the Savannah River Site

Nine tornadoes are known to have occurred at the Savannah River Site since its inception—Pepper and Schubert (1978), Garrett (1983), Parker and Kurzeja (1990), and Parker (1991). All nine have been formally documented by the Atmospheric Technologies Group (or its predecessors) four of which were found in the "unofficial" database. The additional tornadoes from SRS investigations were entered into the database to make it complete. Each of the documented tornadoes is described in Table II.

The most damaging tornado occurred on October 1, 1989, over the southern part of the SRS. Major damage to forested areas was observed. Most of the damage from the other tornadoes was relatively minor; although, in most cases, merchantable timber was harvested as a result of tree losses. No significant site building damage has been observed due to any of the nine tornadoes at the SRS.

Table I. Examples of the Differences Between the SPC's "Official" and "Unofficial" Databases

1	Date	Time	Starting Latitude	Starting Longitude	Lift-off Latitude	Lift-off Longitude	Length	Width	F-Scale
2		EST	dec. degrees	dec. degrees	dec. degrees	dec. degrees	miles	ft	
3	**Official**								
4	No entry								
5	No entry								
6	No entry								
7	No entry								
8	No entry								
9									
10	23-Apr-83	20:19	33.17	81.45	33.33	80.87	33	600	3
11									
12	**Unofficial**								
13	5-Apr-57	20:30	34.70	80.78	No entry	No entry	1	100	1
14	8-Apr-74	16:33	34.42	82.75	No entry	No entry	1	300	3
15	16-Aug-94	11:00	33.88	81.33	No entry	No entry	0.1	150	2
16	16-Aug-94	12:35	33.92	81.25	No entry	No entry	0.3	220	3
17	7-Nov-95	16:38	34.20	79.70	No entry	No entry	0.5	120	2
18									
19	23-Apr-83	20:20	33.17	81.45	33.23	81.22	13	600	3
20	23-Apr-83	20:46	33.23	81.22	33.32	80.93	16	600	3
21	23-Apr-83	21:18	33.32	80.93	33.33	80.87	4	600	3

Table II. Documented Tornadoes at SRS

Date/Time (local)	Location	Path	Width	Length	F-Scale	Counties
May 28, 1976 1530	Central Shops to F Area	N33° 14', N33° 17' W81° 39', W81° 41'	300 ft	5 miles	F1	Barnwell, Aiken
May 28, 1976 2043	near Road 8 and Road 8-1	N33° 20', N33° 20' W81° 31', W81° 32'	400 ft	0.5 mile	F1	Barnwell
July 2, 1976 N/A	near A Area to old SR-Ecology Lab	N33° 19', N33° 22' W81° 46', W81° 39'	300 ft (est)	7.5 mi (est)	F1	Aiken
April 23, 1983 2015	Jackson to near A Area	N33° 20', N33° 21' W81° 48', W81° 42'	300 ft	6.0 miles	F1	Aiken
October 1, 1989 1930	large swath over the southern part of the SRS from the Savannah River to offsite near Snelling, SC	N33° 6', N33° 13' W81° 40', W81° 27'	1.0 mile	16 miles	F2	Barnwell
March 1, 1991 2215	south of SRFS	N33° 21' 15", N33° 21' 56" W81° 40' 54", W81° 40' 29"	450 ft	1.0 mile	F2	Aiken
March 3, 1991 1500	north of Z Area northeastward toward	N33° 18', N33° 23" W81° 38", W81° 34' US 278	600 ft	7.5 miles	F2	Aiken
March 3, 1991 1500	north of F Area North-eastward toward US 278	N33° 18', N33° 23" W81° 40" W81° 35"	600 ft	7.5 miles	F2	Aiken
March 29, 1991 1415	SC 125 just north of D Area	N33° 13' 46", N33° 13' 58" W81° 44' 20", W81° 44' 0"	450 ft	0.5 mile	F2	Aiken

Four of the SRS tornadoes cited above were not part of the database supplied by the SPC. These tornadoes occurred on May 28 (2043 local time), 1976; July 2, 1976; March 1, 1991; and March 29, 1991. The path coordinates for the May 28 (1530), 1976; March 3 (both storms), 1991; and October 1, 1989 tornadoes were adjusted from the Severe Storms Laboratory listing to more accurately reflect the path coordinates documented in the references in Table II.

The SPC's "unofficial" database with additional SRS tornadoes as described above was felt to be the one most appropriate to use for SRS in this study.

Database for Tornado Frequency and Intensity

Tornado intensity is conveniently measured by the F-scale which is based on a damage assessment system devised by Fujita (1971, 1973). The F-scale definitions are related to tornadic wind gust speeds as shown in Table III below.

A one-degree square centered on the site of concern was recommended by Lu (1995) to create a suitable database for a tornado touchdown frequency and intensity analysis. However, other geographical regions have been recommended and used in tornado risk studies. In order to determine the appropriate region for estimating the tornado risk to SRS, consideration was given to geographical homogeneity with respect to tornado formation and occurrence around the SRS. Increasingly larger area concentric squares were statistically compared to determine if the tornado touchdown occurrence was equivalent for each non-overlapping region segment.

The smallest region considered was a one-degree square centered at SRS. Since there were no occurrences of F-4 or F-5 tornadoes and very few F-3 tornadoes within this one-degree square, a two-degree square was also considered. The two-degree square was divided into two disjoint areas, and the tornado frequency was compared based on the assumption that a given tornado would be equally likely to touchdown anywhere within the two-degree square. Tornadoes were counted that (1) either touched down or lifted off within the one-degree square or (2) outside the one-degree square but within the two-degree square. The effective area for the one-degree square was 3,971.37 sq. mi. The effective area for the two-degree square was 15,588.85 sq. mi. The area outside the one degree square but within the two square was 11,617.48 sq. mi. Assuming the number of expected tornadoes within each of the two non-overlapping areas is proportional to the region's area, a chi square test was used as a test statistic to determine if the observed occurrences came from the same population.

In addition to comparing the one-degree and two-degree squares for equality of tornado occurrence, time periods over the 1951 through 1996 range were compared. Because of improvements in reporting and identifying tornado occurrences, there is the chance that the tornadoes reported in the database will increase over time. (This does not violate the assumption that the true tornado occurrence remains the same throughout the time period but is a test of the reporting of tornado occurrences.) The occurrence frequency for earlier time periods was compared with the frequency for later time periods under the assumption of constant occurrence over the entire time period using a chi-square test statistic. Several different time periods were considered but these were ultimately reduced to two: 1951-1966 and 1967-1996.

Table IV gives the number of tornadoes by F-scale for each of the two time periods and the two areas being compared. There are two hypotheses to be considered. The first assumes the frequency of tornado touchdown occurrence is the same for a two-degree square as for a one-degree square assuming the tornado occurrence is proportional to area. The second hypothesis assumes the reporting and occurrence rate per year of tornado touchdowns within the chosen area is the same for the two time periods. It is not possible to separate the reporting and occurrence rate since only the reported tornado occurrences for previous years are available.

Table III. Relationships Between the Fujita Scale and Wind Gust Speeds (after McDonald, 1997). Note: A three-second gust is considered to be identical to an instantaneous 1.5 second sampled gust.

Fujita Scale	F0	F1	F2	F3	F4	F5
Fastest 1/4 mile (mph)	40-72	73-112	113-157	158-206	207-260	261-318
3-Second gust (mph)	45-78	79-117	118-161	162-209	210-261	262-318

Table IV. Expected and Observed Tornadoes by Area Centered at SRS

Years: 1951-1966	1° Square		Outside 1° Square		
F-Scale	Actual	Expected	Actual	Expected	Total
F-0	1		6		7
F-1	10		15		25
F-2	2		7		9
F-3	0		0		0
F-4	0		0		0
F-5	0		0		0
Totals	13	10.45	28	30.55	41

$\chi^2 = [(13-10.45)^2/10.45] + [(28-30.55)^2/30.55] = 0.836$

Years: 1967-1996	1° Square		Outside 1° Square		
F-Scale	Actual	Expected	Actual	Expected	Total
F-0	7		28		35
F-1	17		66		83
F-2	12		25		37
F-3	2		6		8
F-4	0		2		2
F-5	0		0		0
Totals	38	42.03	127	122.97	165

$\chi^2 = [(38-42.03)^2/42.03] + [(127-122.97)^2/122.97] = 0.518$

Grand Totals	51	52.48	155	153.5	206

$\chi^2 = [(51-52.48)^2/52.48] + [(127-122.97)^2/122.97] = 0.056$

The chi-square test statistic was used to determine if the two hypothesis were likely to be true given the number of tornado occurrences observed and recorded on the database. Non-overlapping areas were needed for a valid test of the null hypothesis. If the tornado touchdown occurrence rate can be considered equal for these two regions, then the expected occurrence rate is assumed proportional to the area (or number of years). Furthermore, the assumption is made that the tornado occurrence rate is uniform over the entire region of concern.

The test statistic is given in Eq. (1). The chi-square sum is then compared with the 95th percentile of the chi-square distribution with 1 degree of freedom since two groups are being compared for both region and time period.

$$\chi^2 = \Sigma\,(\text{observed} - \text{expected})^2/\text{expected} \qquad (1)$$

The test could be done within region and time period. However, the decision was a two-step process. First, a test of the two regions was done. Then within the selected region, a test of the two time periods was done. As an additional check, the chi-square test was applied separately to the two time periods for the two regions.

A total of 206 tornadoes was observed within the two-degree square. Fifty-one tornadoes were within the one-degree square and the remaining 155 were outside the one-degree square but within the two-degree square. The expected number of tornadoes within each of these two areas is:

$$\text{Expected number within } 1° = (206)(3971.37)/(15{,}588.85) = 52.48$$

$$\text{Expected number within } 2°\text{-}1° = (206)(11{,}617.48)/(15{,}588.85) = 153.52.$$

The chi-square statistic is listed in Table IV. For the two areas, the chi-square sum was 0.056. The 95th percentile for 1 degree of freedom is 3.84. Thus, there is no significant difference between a one-degree square and a two-degree square in the tornado frequency occurrence rate.

For the comparison of the two time periods within the two-degree square, 41 tornadoes occurred in the 16 years between 1951 and 1966, and 165 occurred in the 30 years between 1967 and 1996. The expected number for each group is given by

$$\text{Expected number (1951-1966)} = (206)(16/46) = 71.65 \text{ and}$$
$$\text{Expected number (1967-1996)} = (206)(30/46) = 134.35.$$

The chi-square statistic for the time period comparison is

$$\chi^2 = [(165-134.35)^2/134.35] + [(41-71.65)^2/71.65] = 20.10,$$

which exceeds the 95th percentile for the chi-square distribution with 1 degree of freedom. Thus, there is a significant difference in the reported tornado frequency rate for these two time periods. If the tornado frequency is determined from all 46 years, the estimate will be too low. Only those tornado occurrences between 1967 and 1996 should be used to determine the tornado frequency. The same two-degree square region and 1967-1996 time period was used to estimate the tornado intensity distribution. However, all tornado occurrences within the two-degree square over the both time periods were used in the process to estimate the tornado damage path area by intensity distribution.

After determining that there was a difference in occurrence rate between the two time periods, a second chi-square test was done to compare the two separate regions within each time period. The concern was that there could be a difference in region due to time periods that might be confounded with time. The frequency rate of occurrence by area was not significantly different for each of the two time periods.

Database for Damage Path Area versus Tornado Intensity

In order to determine the damage path area versus tornado intensity distribution and to avoid extrapolation, data for all tornado intensity classes were needed. Because there were no F- 5 tornadoes and few F-4 and F-3 tornadoes within the two-degree square used for tornado frequency, the database needed to be expanded to include additional F-3, F-4, and F-5 tornadoes. The tornadoes used to estimate the area by intensity distribution should be similar to the damage area expected at SRS given a tornado of a specific intensity were to occur. The relationship between the damage path and the tornado intensity (F-scale) is not necessarily limited to the same region used for the tornado occurrence. In the Lu (1995) model the entire United States region east of the Rocky Mountains was used to model the predicted width of a tornado path given the observed length and F-scale.

It is extremely important in predicting the average damage path for each F-scale category tornado to have a sufficient number of tornadoes. With a void of tornadoes in the higher F-scales, the regression equation will be extrapolating outside the data region. It is also important that the region used to estimate the damage path versus F-scale be similar with respect to the damage area. Unless a weighted linear regression relationship is used to model the area versus the intensity, the damage path area variability should be approximately the same across the six F-scale category tornadoes.

Since there were no F-5 scale tornadoes in the two-degree square and only two F-4 scale tornadoes, additional tornadoes of the higher intensities needed to be added to the database to determine the damage path area by intensity distribution. The following set of tornado damage path areas were used:

- All tornadoes within the two-degree square over both time periods,
- All F-3 tornadoes occurring in the states of Georgia and South Carolina over both time periods, and
- All F-4 and F-5 tornadoes occurring in the states of Georgia, South Carolina, and Alabama over both time periods.

Alabama was chosen over North Carolina or Florida because of the state's similar climatology, and the fact that frontal systems usually approach South Carolina from the west rather than from the south or north. This does not change the tornado occurrence probabilities but enhances the reliability of the damage area-intensity relationship. The tornadoes used for the damage area relationship are listed in Appendix I. The tornadoes for the frequency and intensity are a subset of these are indicated as such in the Appendix.

Summary of Database Used

The final database used for the risk probability determination was a two-degree square centered at the Savannah River Site (33.25°N 81.63°W) in which the tornado frequency and the intensity frequency distributions were determined using only the tornado data from 1967 through 1996. A larger database was used to determine the damage path area versus tornado intensity relationship. This larger database included all the tornadoes within the two-degree square between 1951 and 1996, plus all F-3, F-4, and F-5 tornadoes that occurred within Georgia and South Carolina, and all F-4 and F-5 tornadoes that occurred within Alabama between 1951 and 1996 (see Figure 1). Additional breakdowns of the tornado database can be found in Appendices II and III.

Model

The model used to determine the tornado risk probabilities was based on the Lu-McDonald modified IDTR model as described by Lu (1995). The features of this model include: (1) geometric point interpretation of the tornado hazard probability, (2) estimating the tornado occurrence using a Poisson process, (3) log-linear regression for estimating the average damage path per F-scale category tornado, (4) tornado F-scale misclassification errors based on a truncated normal distribution, and (5) intensity variations within the average damage path as a function of the tornado wind field model obtained from the Super Outbreak Tornadoes of April 3-4, 1974 (Mehta, et al., 1974).

Tornado hazard probability is expressed as the probability of tornado wind speeds exceeding some threshold value per year in a defined local region, $P(V \geq V_t)$. A number of assumptions are required for this model. These are:

- Tornado occurrences are independent; that is, the occurrence of one tornado occurs independently of any other tornado within a specific area and time frame.
- Tornado characteristics (damage path and intensity) are homogeneous in the geographical area and over the time period considered for the modeling process.
- Tornado F-scale misclassification errors are normally distributed based on a truncated normal distribution.
- The tornado intensity variation within the damage path is the same throughout the contiguous United States.

Formulation of the Tornado Hazard Probability Model

The probability of the tornado wind speed being equal to some value V_j at least once in a time period T in a given region A is

$$P_T(V = V_j) = \sum_{N=0}^{\infty} P(V_j|N) P_T(N) \quad (2)$$

where V_j is a range of wind speed associated with the F-scale category tornado F_j,

T is the number of years considered in estimating the occurrence probability,

N is the number of tornadoes during the time period T in the region A,

$P_T(N)$ is the probability of N tornado occurrences in the time period and region, and

$P(V_T|N)$ is the conditional probability of tornado wind speed in the range V_j given N tornadoes.

The tornado arrival process is assumed to be a Poisson process, where u is the mean or expected value of the Poisson distribution. The mean or expected value is estimated as the number of tornadoes observed in the region divided by the number of years considered. The tornado probability in Eq. (2) is interpreted as the probability of a tornado of wind speed equal to a threshold value in any year touching down or lifting off anywhere within the specified area of concern. The T index can be omitted or assumed to be for 1 year and Eq. (2) becomes

$$P(V=V_j) = u\,P(V_j). \quad (3)$$

$P(V_j)$ is based on the geometric point interpretation of probability where a_j is the expected damage area associated with a tornado of wind speed V_j and A_{eff} is the total area for the region of concern (minus any areas for which tornadoes are unlikely to occur such as large bodies of water or very mountainous regions).

$$P(V_j) = a_j / A_{eff} \quad (4)$$

If the wind speed were constant over the entire damage path of a tornado of F-scale, F_j, then the expected damage area would be equal to the expected damage area for a tornado of intensity F_i. However, given a tornado of F-scale F_k, the true expected damage area associated with only those wind speeds in the range V_j is given by

$$a_j = \sum_{k \geq j}^{5} P(V_j|V_k) a'_k \quad (5)$$

where a'_k is the area represented by Eq. (6), below.

If $P_A(F_k)$ represents the percent of the tornado population that are true F_k tornadoes, then the contribution to the damage path area from an F_k tornado is the probability of seeing an F_k tornado times its damage path area and is given by

$$a'_k = P_A(F_k) a''_k \quad (6)$$

where a_k'' is the average or expected total damage path area associated with an F_k tornado. $P_A(F_k)$ is the probability that an F_k tornado has occurred and is correctly classified as an F_k scale tornado. $P_A(F_k)$ is estimated by the proportion of observed tornadoes that are recorded as F_l scale tornadoes modified by the chance that the F-scale classification was in error and the tornado should have been classified as an F_k tornado summed over all recorded F-scales.

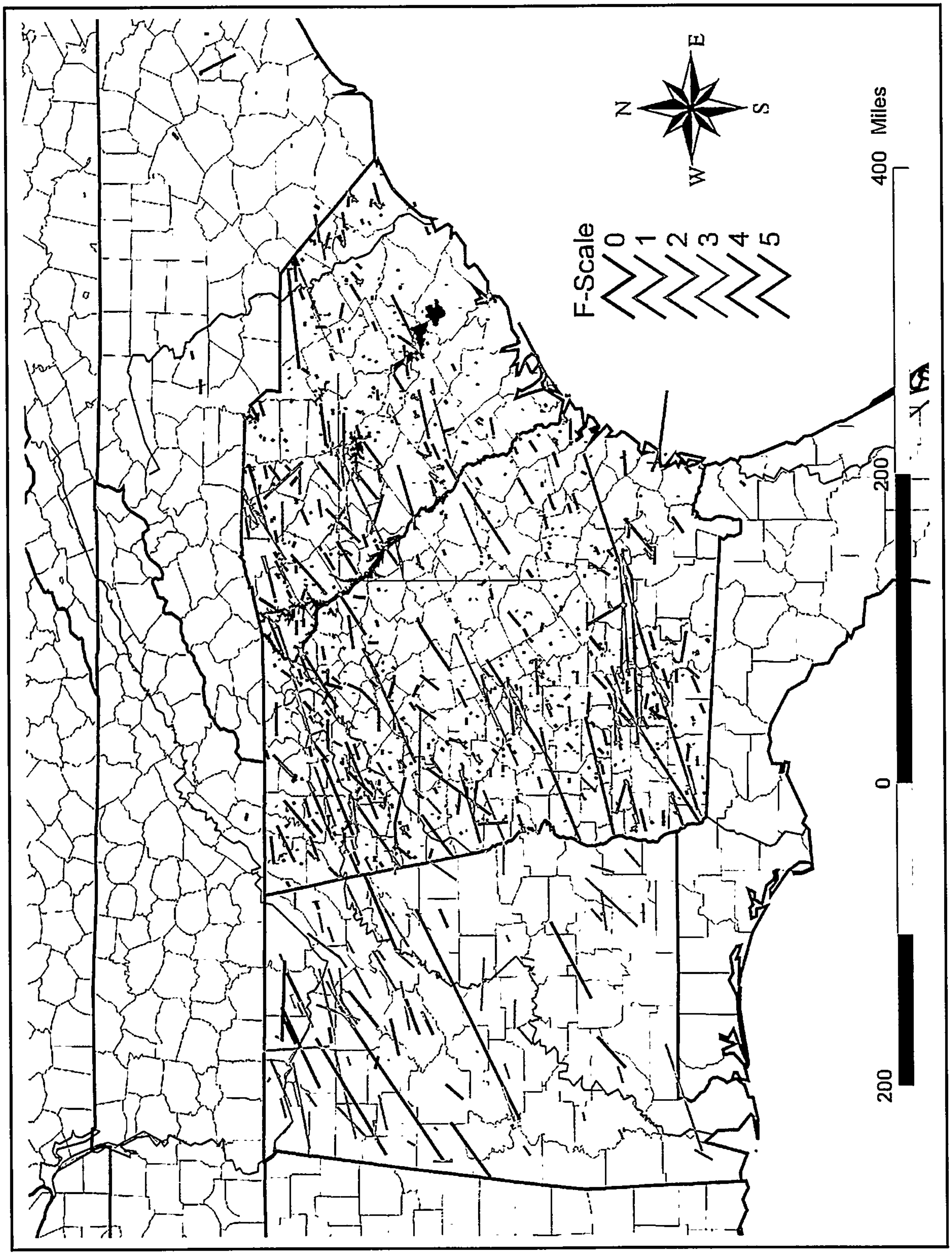


Figure 1. Tornadoes over the Southeast (F-Scales 0 to 5) and Alabama (F-Scales 3 to 5). The two-degree square area of study centered on the SRS is also shown.

Let $P_{A|0}(F_k|F_l)$ be the conditional misclassification probability in which the tornado was recorded as an F_l scale tornado but should have been recorded as an F_k tornado, and $P_0(F_l)$ be the distribution of recorded F_l scale tornadoes. Then the true proportion of F_k scale tornadoes is given by

$$P_A(F_k) = \sum_{l=0}^{5} P_{A|0}(F_k|F_l)P_0(F_l) \qquad (7)$$

Combining these equations gives the probability of experiencing a wind speed of V_j in a year anywhere in the region defined by A_{eff}

$$P(V = V_i) = (u / A_{eff}) \sum_{i \le k}^{5} P(V_i|V_k) \left[\sum_{l=0}^{5} P_{A|0}(F_k|F_l)P_0(F_l)\right] a'''_k \qquad (8)$$

The terms in Eq. (8) are estimated by

$\hat{u}$: number of tornadoes that occurred in the region A divided by the number of years considered (N/T),

$\hat{P}_0(F_l)$: proportion of F_l scale tornadoes observed in the region A over the time period,

$\hat{P}_{A|0}(F_k|F_l)$: misclassification conditional probability of reporting a tornado as F_l, given the tornado was an F_k category,

$\hat{a}''_k$: expected average damage path area associated with an F_k scale tornado for the given region, and

$\hat{P}(V_i|V_k)$: conditional probability of the wind speed being V_i given a tornado is an F_k-scale tornado, $i \le k$.

Since the probability of interest is for tornadic winds of equal to or greater than V_i, the total probability is summed for all wind speeds exceeding V_i or

$$\hat{P}(V \ge V_i) = \sum_{i=j}^{5} \hat{u}P(V_j) = (\hat{u} / A_{eff}) \sum_{i=j}^{5} \sum_{k=0}^{5} \hat{P}(V_i|V_k) \left[\sum_{l=0}^{5} \hat{P}_{A|0}(F_k|F_l)\hat{P}_0(F_l)\right] \hat{a}''_k \qquad (9)$$

The wind speed ranges for three-second gusts for each F-class were used in Eq. (9). In particular, the minimum wind speed for a three-second gust was used for V_i.

Estimation of Average or Expected Damage Area

Different methods can be used to estimate the mean damage area per F-scale category tornado. One method is to use the actual recorded damage area (recorded path length times recorded path width); another method is to use the Pearson path length and Pearson path width scales (PP Scales) (Fujita Pearson, 1973); and another is to use the observed lengths and predict the width to model the average damage area. This last method was employed by Lu (1995) to give a smoothed and more reliable estimate of the expected damage path area for each F-scale.

Based on a correlation analysis among path length, path width and intensity for tornadoes east of the Rocky Mountains, Lu (1995) showed these three parameters are not independent. An empirical relationship was derived from 19,831 tornado records on the database east of the Rocky Mountains. This relationship gives a predicted or modified path width based on the observed length, L in miles, and V_j in mph as the median of the range three-second gust wind speed for each F_j tornado. The relationship is given in Eq. (10)

$$\tilde{W}_0(j) = -0.05363 + 0.00138L + 0.0011V_j + 0.00001(V_j)(L). \qquad (10)$$

For each observed tornado, a predicted width is obtained using Eq. (10). The damage area for each tornado is computed by multiplying the predicted width (miles) from Eq. (10) times the observed length (miles). Using the predicted damage path width instead of the reported damage path width is based on expert opinion (McDonald) and reflects the belief that the reported width is in error and the predicted width is a better estimator.

Log-Linear Regression to Predict the Average Damage Area per F-Scale Tornado

There is considerable variation in the damage areas within F-scales. Damage area can vary by geographical region and depends on the local topography and meteorological conditions. The set of tornadoes used to derive an expected damage path area for a given F-scale intensity tornado should reflect the expected damage path by intensity distribution expected for the region of concern.

Lu (1995) recommended using a log-linear regression to estimate the expected damage path area for each F-scale class tornado. The method recommended is to first transform the damage path area by taking the logarithm to the base 10 as the dependent variable. Next the logarithm to the base 10 is taken of the median of the range of wind speeds for the three-second gusts for each F-scale class as the independent variable. A linear regression is fit to the log-tranformed variables. The relationship is given in Eq. (11).

$$\text{Log (Area)} = C_o + C_1 \text{Log (median Wind speed } V_j) \quad (11)$$

Eq. (11) can be fit using two methods that (under some conditions) will give essentially the same results. All methods use the log of the median wind speed as the independent variable in the regression. One method is to calculate the average of the log-transformed areas for each F-scale category for the dependent variable. The regression is done using the average of the log-transformed areas. If this method is used, it is important that each mean be estimated with approximately the same reliability (same number of tornadoes per F-class). This method will have only 4 degrees of freedom for the mean square error in the regression. The other method is to use a weighted estimate based on all the data. Both methods are acceptable, but if there are not approximately equal numbers of tornadoes per F-scale or there are missing F-scale tornadoes, the two methods will give different regressions. In using either method, it is important to compare the variability within each F-scale since the regression assumes a pooled estimate of error. Using all the data permits a test of (1) whether the pooled error is appropriate and the variances are the same for all F-classes and (2) whether the lack of fit of the model is significant compared with the pooled error variance. There are also more degrees of freedom for the mean square error. (If the regression is done using only the means of the transformed variables, then the mean square error is the lack of fit of the model confounded with the variability in estimating the means, and cannot be separated.)

Non-Rated and Unreported Tornadoes

If there are a large number of non-rated tornadoes, then several methods can be used to assign an F-scale to these tornadoes. If there are few non-rated tornadoes compared with the total number of rated tornadoes, then one can omit the non-rated tornadoes when determining the tornado intensity and area-intensity occurrence, but include them when counting the total tornado frequency. Most methods assume the distribution for the non-rated tornadoes is the same as for the rated tornadoes. There was only one non-rated tornado within the two-degree square used for the tornado analysis. Non-rated tornadoes in Georgia and South Carolina were randomly assigned an F-scale based on the distribution of the rated tornadoes.

More troublesome are unreported tornadoes. The Lu-McDonald model does not include a mechanism for including unreported tornadoes. Unreported tornadoes generally occur in the lower F-scale categories. Using more recent time periods lowers the chance for unreported tornadoes since the reporting and identification process has improved considerably since 1950.

There is no consensus on how to handle unreported tornadoes. Consequently, it is important to ensure that the database is up-to-date, as complete as possible, and compared with all available sources of tornado data so as to minimize the possibility of unreported tornadoes.

Misclassification Errors

A truncated normal probability distribution function is used by Lu-McDonald to model the probabilities of misclassification error. Let $P_{AIO}(F_i|F_j)$ represent the conditional probability of reporting a true F_j tornado as an F_i tornado. For each tornado classified as F_i, the mean value is estimated as the F_i scale (i) and the standard deviation is estimated assuming the misclassification is plus or minus one F-scale category (at the 95% confidence level). The standard deviation is determined by solving

$$1 = Z_{(1-\alpha/2)}\sigma,$$

where $Z_{(1-\alpha/2)}\sigma$, is the $100(1-\alpha/2)$ percentile of the normal distribution. For the 95% confidence level, $\alpha = 0.05$ and $Z_{(0.975)} \approx 2$ so that

$$\sigma = 1/2 = 0.5.$$

The conditional probabilities $P_{AIO}(F_i|F_j)$ can be found as

$$P_{AIO}(F_o|F_o) = \Phi((0.5\text{-}0)/0.5) = \Phi(1.0) = 0.8413$$

$$P_{AIO}(F_1|F_o) = \Phi((1.5\text{-}0)/0.5) - \Phi((0.5\text{-}0)/0.5) = \Phi(3) - \Phi(1) = 0.1574$$

$$P_{AIO}(F_2|F_o) = \Phi((2.5\text{-}0)/0.5) - \Phi((1.5\text{-}0)/0.5) = \Phi(5) - \Phi(3) = 0.0013.$$

A matrix of conditional probabilities are constructed similar to those given for the F_o scale tornado.

$$P(F_i F_j) = \begin{array}{c|cccccc} & F_o & F_1 & F_2 & F_3 & F_4 & F_5 \\ \hline F_o & 0.8413 & 0.1587 & 0.0013 & 0 & 0 & 0 \\ F_1 & 0.1574 & 0.6826 & 0.1574 & 0.0013 & 0 & 0 \\ F_2 & 0.0013 & 0.1574 & 0.6826 & 0.1574 & 0.0013 & 0 \\ F_3 & 0 & 0.0013 & 0.1574 & 0.6826 & 0.1574 & 0.0013 \\ F_4 & 0 & 0 & 0.0013 & 0.1574 & 0.6826 & 0.1574 \\ F_5 & 0 & 0 & 0 & 0.0013 & 0.1587 & 0.8413 \end{array} \quad (12)$$

The matrix in Eq. (12) is then multiplied in matrix fashion by the probability of reporting an F_i tornado estimated from the observed region.

Intensity Variations within the Damage Path

The tornado intensity can be represented by the variation of tornado intensity along the path length and path width. The variation of intensity along the length of a tornado path in the Lu-McDonald model was obtained from the Super Outbreak Tornadoes of April 3-4, 1974 (Mehta, et al., 1975). McDonald proposed a combined Rankine vortex model to emulate tornado intensity variation across the path width. The combinations of these two variations are the conditional matrix given in (13).

$$K = 1.875 \bullet \begin{array}{c} \\ F_0 \\ F_1 \\ F_2 \\ F_3 \\ F_4 \\ F_5 \end{array} \begin{array}{cccccc} F_0 & F_1 & F_2 & F_3 & F_4 & F_5 \end{array} \atop \begin{bmatrix} 1.0000 & 0.7605 & 0.5744 & 0.5136 & 0.5227 & 0.5221 \\ 0 & 0.2395 & 0.2715 & 0.2453 & 0.2245 & 0.2075 \\ 0 & 0 & 0.1541 & 0.1488 & 0.1403 & 0.1221 \\ 0 & 0 & 0 & 0.0923 & 0.0843 & 0.0848 \\ 0 & 0 & 0 & 0 & 0.0283 & 0.0480 \\ 0 & 0 & 0 & 0 & 0 & 0.0155 \end{bmatrix} \quad (13)$$

The elements of this matrix can be interpreted as conditional probabilities, which adjust for variation of wind speed along the damage area. If the maximum wind speed associated with tornado scale F_j is V_j then the area associated with a maximum wind speed for tornado scale F_i, $i \le j$, is $\hat{p}(V_i|V_j)$. The coefficient 1.875, which multiplies all the elements in the matrix, is the ratio of the actual damage path area bounded by 40 mph wind speed to visible damage path area which is bounded by 75 mph wind speed (McDonald, 1981).

Results for Tornadoes

As stated earlier, the region used for estimating the tornado occurrence and the occurrence-intensity distribution was a two-degree square centered at 33.25 N 81.63 W. There were 165 tornadoes used for the occurrence-intensity distribution for an average frequency in those 30 years (between 1967-1996) of 5.5 tornadoes per year. The area of the two-degree region excluding the area in the Atlantic Ocean and covering large bodies of water or steep mountainous regions is 15,588.85 sq mi. Thus for the SRS

$\hat{u}/A_{eff} = 5.5/15{,}588.85 = 0.000352816.$

The occurrence-intensity distribution is given in Table V.

After adjusting for misclassification (multiplying by the conditional probabilities given in [(12)]), the intensity/occurrence relationship is given in Table VI.

There are no F-5 tornadoes and only two F-4 and eight F-3 tornadoes within the two-degree square. In order to estimate the average path area per tornado, additional F-3, F-4, and F-5 tornadoes are needed. All F-3 and F-4 tornadoes that occurred in Georgia and South Carolina and all F-4 and F-5 tornadoes that occurred in Alabama were included as well as all the F-0, F-1, and F-2 tornadoes within the two-degree square between 1951 through 1966. This yielded 206 tornadoes between F-0 and F-4 from within the two-degree square, an additional 51 F-3 and 15 F-4 tornadoes from South Carolina and Georgia, and 17 F-4 and 6 F-5 tornadoes from the state of Alabama for a total of 295 tornadoes to determine the area-intensity relationship.

Table V. Occurrence-Intensity Distribution for the Two-Degree Square Centered at 33.25 N 81.63 W from 1967 through 1996

F-Scale	F-0	F-1	F-2	F-3	F-4	F-5
No. Tornadoes	35	83	37	8	2	0
Proportion	0.21212	0.50303	0.22424	0.04848	0.01212	0.0

Table VI. Intensity-Occurrence Distribution Adjusted for Misclassification

F-Scale	F-0	F-1	F-2	F-3	F-4	F-5
No. Tornadoes	35	83	37	8	2	0
Adjusted Proportion	0.25858	0.41212	0.24017	0.07095	0.01620	0.00199

Before computing the average area for each F-class, the path width for each of the 295 tornadoes was predicted using Eq. (10). The damage path area for individual tornadoes was computed by

Area-j = predicted width-j times observed length-j.

Then a log-linear regression model was fit to the logarithm (base 10) of the area as the dependent variable and the logarithm (base 10) of the median three-second gust wind speed for the observed F-scale category as the independent variable. The regression was done for three models: (1) the observed areas (prior to replacing the observed width by the predicted width), (2) the observed areas after replacing the observed width by the predicted width), and (3) computing the average log-transformed area (with predicted width) and fitting the regression using only the six F-class mean transformed areas.

Methods (2) and (3) compare the results due to unequal numbers of tornadoes by F-class. Comparing results from methods (2) and (1) define the effect of replacing the observed damage path width by the predicted damage path width. Replacing the observed width by the predicted width decreased the variability within F-class. The F-class log-transformed area variability was essentially the same across all classes for Method (2). Thus Method (2) is preferred over Method (1). Method (2) is also preferred over Method (3) since Method (3) assumes equal numbers of tornadoes per F-class. The results of the regression for each of the three methods are:

(1) Using observed widths, all tornadoes: Area = $10^{(4.645358*\log(V) - 10.606158)}$.
(2) Using predicted widths, all tornadoes: Area = $10^{(4.917048*\log(V)-11.000696)}$.
(3) Using predicted widths, average per class: Area = $10^{(4.892737*\log(V)-10.992590)}$.

The regressions using all three methods will result in similar but not identical expected areas for each F-class tornado. Table VII gives the observed average area, the average area using the predicted widths, and the smoothed and predicted average area per F-class tornado based on Method (2).

The predicted areas were multiplied by the intensity-occurrence conditional probabilities (adjusted for misclassification) to get the occurrence-intensity areas, and then multiplied by the conditional wind speed proportions (matrix from (13)). The area due to each F-class tornado is then given in Table VIII.

These areas were multiplied by $\hat{u}/A_{eff}$ or 0.000352816 and summed to get the probabilities given in Table IX for three-second wind speeds (minimum value for the wind speed range in each F-class).

To get probabilities for other wind speeds, interpolation is required. The wind speed is considered to be linear within each F-class if the base 10 logarithm of the corresponding probability is used. Inversely, the wind speed correspond-

Table VII. Predicted and Observed Average Areas per F-Class Tornado

F-Scale	F-0	F-1	F-2	F-3	F-4	F-5
No. Tornadoes	42	108	46	59	34	6
Average Observed Area	0.02888	0.19046	1.25662	5.67431	9.83199	8.63068
Width Predicted Average Area	0.0179	0.2749	1.1790	4.2061	10.8504	17.2693
Predicted Area using Method (2)	0.0062	0.0617	0.3502	1.4220	4.5973	12.7938

Table VIII. Area by F-Scale Tornado after Adjusting for Misclassification and Path Area Variation

F-Scale	F-0	F-1	F-2	F-3	F-4	F-5
Average Area (sq mi)	0.32411	0.14154	0.07765	0.03315	0.00620	0.00074

ing to a given probability can be obtained by log-linear interpolation from Table IX. Two wind speeds of interest in the risk analyses are the wind speeds corresponding to a probability of 2×10^{-5} and 2×10^{-6}. These can be obtained following the example for 2×10^{-5} or

$$V(2 \times 10^{-5}) = 118+(162-118)[(\log_{10}(2 \times 10^{-5})-\log_{10}(4.15 \times 10^{-5})]/[(\log_{10}(1.41 \times 10^{-5})-\log_{10}(4.15 \times 10^{-5})]= 147.8.$$

The wind speed, V_0, such that $P(V \geq V_0) = 2 \times 10^{-5}$ is 148 mph.

The wind speed, V_0, such that $P(V \geq V_0) = 2 \times 10^{-6}$ is 215 mph.

The set of tornadoes used in the analysis is given in Appendix I. SAS® was used to do the analyses and the regression.

To ensure that the Lu-McDonald model was correctly implemented, the Kansas City example given in Lu (1995) was verified using the same computer code. Individual tornado data was not provided for the Kansas City data, but by using the intensity-occurrence distribution and the average damage path area for each F-class, a set of tornadoes was formulated. The average damage path area was computed by replacing the observed width by the predicted width in Eq. (10). The Kansas City example ensures that the misclassification and wind speed variation conditional probabilities were correctly implemented and the regression was correctly done. For the Kansas City data, the regression had to be done using the log-transformation of each F-class average since individual damage path information was not available. The Kansas City example was also based on the F-class wind speeds for the fastest quarter mile rather than the three-second gust wind speeds.

Wind Gusts

Wind Gust Data

Wind gust data were obtained from a 1990-1996 SRS meteorological database and regional National Weather Service (NWS) observation stations. Data from the NWS stations was obtained from the National Climatic Data Center in Asheville, NC. Stations included were Columbia, SC; Augusta (Bush Field), Athens, and Macon, GA. Table X shows the available period of record for each NWS station. The wind gusts contained in these data most closely

Table IX. Probabilities for Three-Second Tornadic Wind Speeds (Minimum Value F-Class Wind Speed)

Minimum Wind speed (mph)	45	79	118	162	210	262
Probability of equal or greater wind speed	0.000206	0.0000925	0.0000415	0.0000141	0.00000245	0.000000261

Table X. Wind Gust Data Sources

Daily/Regional			
Augusta, (Bush Field), GA	September 1972	to	April 1994
Columbia, SC	September 1971	to	November 1995
Athens, GA	July 1980	to	January 1996
Macon, GA	July 1972	to	April 1994
SRS	January 1, 1990	to	December 31, 1996
Annual Maximum			
Augusta (Bush Field)	1950	to	1971

resemble the 'three-second wind gust' for the purpose of hazard analyses. A daily highest three-second gust (in knots) was given for each day of the month in the period of record.

In each case, the end of the period of record fell within the period of record used for the SRS gust data. Therefore, no gaps existed in the wind gust data set after each period of record ended for the regional locations. Additionally, annual maximum wind gust data from Augusta dating back to 1950 were taken from Hunter (1989) to complete the data record through 1971. The combination of the above data bases provides wind gust data for the 1950 through 1996 period.

Model

An extreme-value distribution was assumed for the yearly maximum wind gusts per 24-hour period. The maximum wind gust for each month was obtained for each station of interest, then the maximum wind gust by year for each station was determined. The average and standard deviation of the maximum yearly 24-hour wind gusts was computed using Eqs. 13 and 14. The individual yearly maximum wind gusts for each station were standardized (Eq. 15) and fit to the extreme-value distribution.

Let X_{ij} be the ith yearly maximum 24-hour wind for station-j; then the mean, standard deviation, coefficient of variation (divided by 100%), and standardized ijth value are given by

$$\overline{X}_j = \sum_{i=1}^{n_j} X_{ij} / n_j . \qquad (13)$$

$$S_j = \sqrt{\sum_{i=1}^{n_j}\left(X_{ij}-\overline{X}_j\right)^2 \Big/ \left(n_j-1\right)} \qquad (14)$$

$$\tau_{ij} = \frac{X_{ij}-\overline{X}_j}{S_j} \qquad (15)$$

$$CV_j = S_j / \overline{X}_j . \qquad (16)$$

Table XI gives the means, standard deviations, and coefficient of variation for each station.

The standardized variables, were used to fit a generalized extreme-value distribution and to determine which of the three extreme type distributions were appropriate.

A single form of the three possible types of limiting distributions for extreme values has been derived by Fisher and Tippett (1928) and can be modeled by

$$F(\tau) = \exp\left[-\{1 - k(\tau-\xi)/\alpha\}^{1/k}\right],\ k\neq 0, \qquad (17)$$
$$F(\tau) = \exp\left[-\exp\{-(\tau-\xi)/\alpha\}\right],\ k=0. \qquad (18)$$

τ is bounded by $\xi+\alpha/k$ from above if $k>0$ and from below if $k<0$. Here ξ and α are location and scale parameters, respectively. The shape parameter, k, determines which extreme-value distribution is best represented by the data. Fisher-Tippett Types I, II, and III correspond to k=0, k<0, and k>0, respectively. In practice the shape parameter usually lies in the range $-(1/2) < k < (1/2)$. When this is the case, the following can be used to estimate the parameters, ξ, α, and k (Hosking, et al., 1985).

Table XI. Means, Standard Deviations, and Coefficient of Variation by Station

Station	No. of Years	Mean	Standard Deviation	Coefficient of Variation (÷100%) (CV)
Augusta	44	49.9910	11.0853	0.221747
Athens	18	54.9187	12.6914	0.231094
Columbia	25	53.8574	8.8395	0.164127
Macon	23	57.7401	11.4432	0.198185
SRS	9	62.3139	0.7352	0.011798

$$\hat{k} = 7.8590c + 2.9554c^2, \text{ where}$$
$$c = \frac{2b_1 - b_o}{3b_2 - b_o} - \frac{\log 2}{\log 3} \quad (19)$$

The error in estimating k using Eq. (19) is less than 0.0009 through the range -(1/2) < k < (1/2).

Given $\hat{k}$, the scale and location parameters can be estimated successively by

$$\hat{\alpha} = \frac{(2b_1 - b_o)\hat{k}}{\Gamma(1+\hat{k})(1-2^{-k})} \quad (20)$$

$$\hat{\xi} = b_o + \hat{\alpha}\left\{\Gamma(1+\hat{k}) - 1\right\}\hat{k} \quad (21)$$

The Type I extreme-value distribution, or Gumbel distribution, is a particularly simple, special case of the generalized extreme-value (GEV) distribution, and it is often useful to test whether a given set of data is generated by a Gumbel rather than a GEV distribution. This is equivalent to testing whether the shape parameter, k, is zero in the GEV distribution. Assuming the null hypothesis H_o: k=0, the estimator $\hat{k}$ is asymptotically distributed as N(0,0.5633/n). The test may be performed by comparing the statistic $Z = \hat{k}(n/0.5633)^{1/2}$ with the critical values of a standard normal distribution. Significant positive values of Z imply rejection of H_o in favor of the alternative k>0, and significant negative values of Z imply rejection in favor of k<0.

For the wind gusts, the estimate of $\hat{k}$ was 0.10957, the Z-ratio was 1.59261, and the probability Z-ratio less than or equal to the value observed is 0.94438. The probability of getting a larger Z-ratio is 1 - 0.944 or 0.056. Since the test is whether the true k is zero, a two-tailed test is desired (to detect a positive or negative k). Values of Z (k-ratio) between -1.96 and +1.96 indicate that k is not significantly different from zero with 95% confidence. For the wind gust, we can conclude the true k is zero and an extreme value of type I can be used to determine the probability of getting a given maximum wind speed.

The values, b_0, b_1, and b_2 are estimated from the data using Eqs. (22) through (24) where the standardized variables τ_{ij} are ordered by size and ij is the rank.

$$b_o = \sum_{ij=1}^{N} \tau_{ij} \div N. \quad (22)$$

$$b_1 = \frac{1}{N(N-1)} \sum_{ij=1}^{N} (ij-1)\tau_{ij} \quad (23)$$

$$b_2 = \frac{1}{N(N-1)(N-2)} \sum_{ij=1}^{N} (ij-1)(ij-2)\tau_{ij}. \quad (24)$$

Since the wind gusts fit a Gumbel (type I) distribution, the parameters are re-estimated assuming k=0 using the method of moments (Eliasson, 1997). For a Type I distribution,

$$\hat{\alpha} = 1/1.28255$$
$$\hat{\xi}/\hat{\alpha} = \hat{\beta} = 0.57722. \quad (25)$$

In order to determine the wind speed for return periods of concern τ, Eq. (18) must be solved for each return period. τ is the standardized variable so that either the individual station's mean and standard deviation or the average CV over all stations and the individual station's 5-year wind speed is used (Eliasson, 1997).

Let P be the return period of interest. Then (1-1/P) is the probability corresponding to a wind speed $\geq V_p$ or

$$\text{Prob}(V \geq V_p) = (1-1/P) = \exp$$
$$[-\{\exp[-(1.28255(\tau_p) + 0.5772)]\}], \quad (26)$$

where

$$\tau_{ij'} = (X_p - X_j)/S_j, \quad (27)$$

and $\overline{X}_j$ is the j-th station mean and S_j is the station standard deviation.

$$X_p = S_j(\log[-\log\{-(1-1/P)\}] - 0.57722)$$
$$(1/1.28255) + \overline{X}_j \quad (28)$$

Eliasson (1997) indicates that oftentimes a smoother fit can be obtained by using the coefficient of variation averaged over all stations. Eliasson also gives an alternate method to Eq. (28) using the 5-year return wind speed, which should always be within the observations. Both Eq. (28) and Eq. (29) in which the individual station's CV_j and the 5-year return wind speed, denoted by $M5_j$ are used to obtain the wind speed for station j and return period P.

$$X_p = M5_j[1 + C_i(y - 1.5)]. \quad (29)$$

where y = log(-log(1(1-1/P))),

$$M5_j = S_j\{(0.8 - 0.57722)/1.28255\} + X_j, \quad (30)$$

and

$$C_i = 0.78 / \{(1/CV_j) + 0.72\}. \quad (31)$$

If the coefficient of variation, CV, is averaged over all stations, CV_a, then replace the C_i in Eqs. (31) and (29) by C_a where

$$C_a = 0.78 / \{(1/CV_a) + 0.72\}. \quad (32)$$

For all but the SRS station, the individual station's coefficient of variation and the average coefficient of variation are approximately the same, so either could be used. However for the SRS station, the station mean is approximately the same as the other stations, but the variability is very small. This may be due to the fewer number of years for which data has been collected or the method of measuring the wind gust. For this station, the average coefficient of variation was used to compute the wind speed using Eq. (29) instead of Eq. (28). This gave more realistic values that were comparable to other stations within the same area.

The average coefficient of variation was 0.1917 compared with the individual station values of 0.2217 for Augusta, 0.2311 for Athens, 0.1641 for Columbia, 0.1982 for Macon and 0.0118 for SRS. There is not much difference between the station CV and the average CV except for SRS.

Summary of Tornadic Wind and Wind Gusts

Figure 2 shows the return frequencies for maximum wind speeds associated with tornadoes and wind gusts for the SRS. Key points on the curve for the tornadic winds include 148 mph every 50,000 years (2×10^{-5}) and 215 mph for every 500,000 years (2×10^{-6}). For wind gusts, a speed of 83 mph can be expected in a 50 year period (2×10^{-2}), 107 mph in a 1,000 year period (1×10^{-3}), and 126 mph in a 10,000 year period (1×10^{-4}). Tables XII-XIII show the data in a tabular format.

Table XII. Tornadic Wind Speeds (Three-Second Gusts) with Return Period and Probability

Tornadic Winds (Three-Sec. Gusts) (mph)	ReturnPeriod (yrs)	Probability
45	4858.4	0.00020583
79	10931.4	0.00009148
118	24073.2	0.00004154
162	70721.4	0.00001414
210	408163.3	0.00000245
262	3846153.8	0.00000026

Extreme Rainfall

Databases

Calculations of extreme precipitation frequencies were based on 15-minute rainfall data from three National Climatic Data Center (NCDC) cooperative stations near SRS, hourly rainfall from eight nearby National Weather Service (NWS), and four cooperative stations, and daily rainfall from four rain gauge stations located on the SRS. Data sources are summarized in Tables XIV and XV.

The eight cooperative and NWS stations were selected based on: (1) proximity to the SRS (within about 100 km) and (2) geographic similarity, i.e., located either in the upper coastal plain or lower piedmont regions of South Carolina and Georgia. The fifteen-minute and hourly data for

Table XIII. Wind Gusts (Three-Second Gusts) with Return Period and Probability

Wind Gusts (Three-Sec. Gusts) (mph)	Return Period (yrs)	Probability
62.8424	5	0.2
69.0377	10	0.1
76.8654	25	0.04
82.6725	50	0.02
88.4367	100	0.01
91.798	150	0.0067
94.1799	200	0.005
96.0262	250	0.004
101.7569	500	0.002
107.4835	1000	0.001
110.8322	1500	0.00067
113.2079	2000	0.0005
120.7738	5000	0.0002
126.4966	10000	0.0001
139.7839	50000	0.00002
145.5064	100000	0.00001

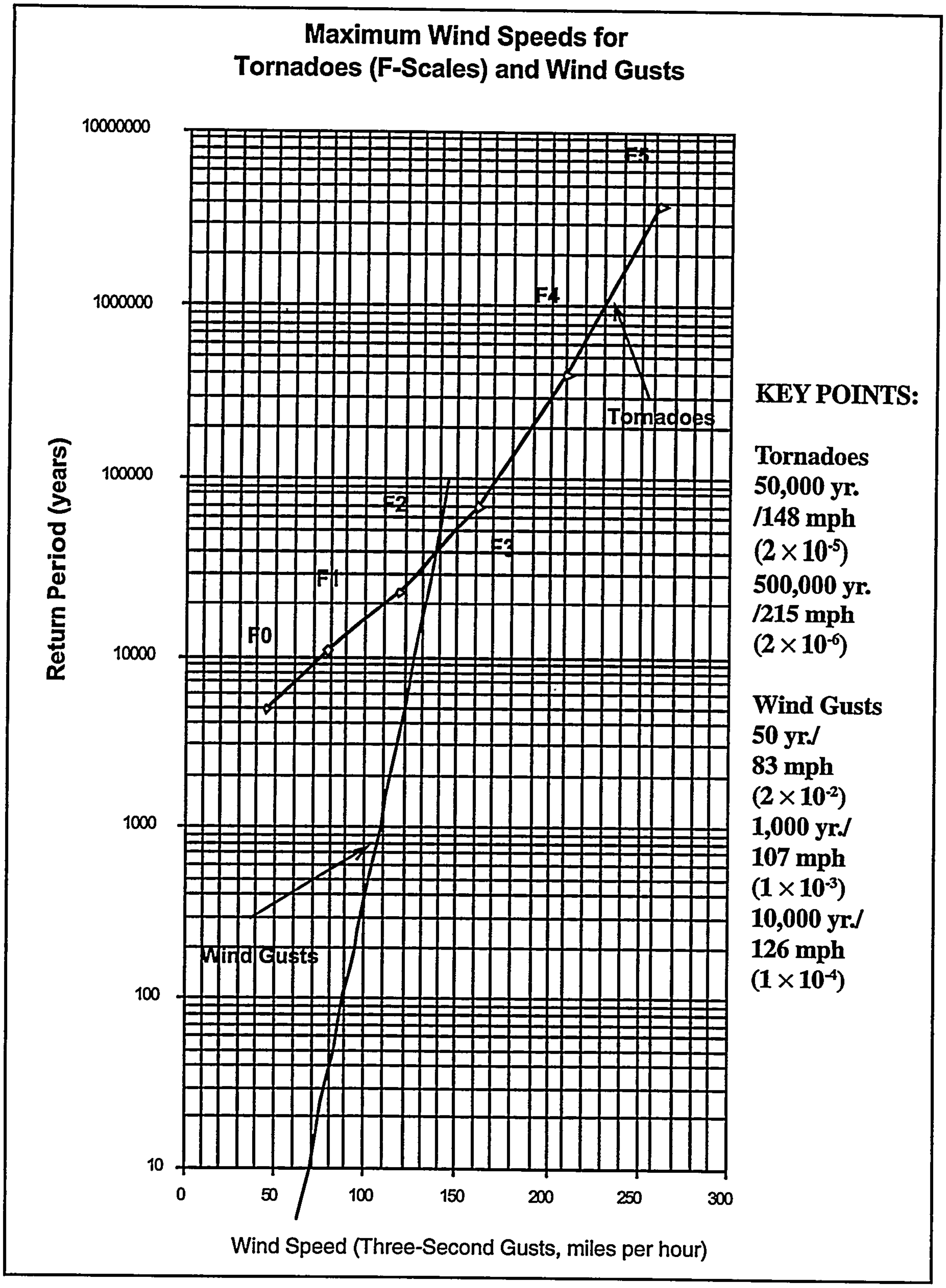


Figure 2. Maximum Wind Speeds (Three-Second Gusts) for Tornadoes (F-Scales) and Wind Gusts

Table XIV. Stations with Daily Precipitation Data

Station	Location (Latitude, Longitude)	Elevation (m)	Period of Record (mo/yr)	Years
Augusta, GA NWS	33:22:00N, 81:58:00W	45	1/49 thru 12/95	47
Macon, GA NWS	32:42:00N, 83:39:00W	108	1/49 thru 12/95	47
Athens, GA NWS	33:57:00N, 83:19:00W	244	1/58 thru 12/95	38
Sylvania, GA 2SSE *	32:44:00N, 81:37:00W	76	1/49 thru 12/95 *1/71 thru 12/95*	47 *25*
Louisville, GA 1E *	33:01:00N, 82:24:00W	98	1/49 thru 12/95 *1/71 thru 12/95*	47 *25*

* Co-operative stations providing 15-minute rainfall. Period of record for the 15-minute data are italicized.

Table XV. Stations with Hourly Precipitation Data

Station	Location (Latitude, Longitude)	Elevation (m)	Period of Record (mo/yr)	Years
SRTC	33:21:00N, 81:44:00W	107	1/68 thru 12/97	30
Barricade 3	33:21:00N, 81:30:00W	91	1/64 thru 12/97	34
Barricade 5	33:07:00N, 81:36:00W	50	1/70 thru 12/97	28
200-F	33:17:00N, 81:40:00W	90	1/61 thru 12/97	37

these stations were extracted from compact disks containing NCDC TD-3260 and TD-3240 data sets, respectively (EarthInfo, 1995). The hourly data were used to determine 3, 6, and 24-hour rainfall for overlapping intervals beginning with each hour in the station's record. The results were used to create files of annual maximum 15-minute rainfall values for the three cooperative stations and annual maximum 1, 3, 6, and 24-hour rainfall values for each of the eight NWS and cooperative stations.

The NCDC rainfall data were recorded over a fixed hourly interval that begins on the hour. Since the true maximum rainfall in a given year may occur over a period which overlaps the fixed interval, empirical factors are used to convert the fixed interval maxima to an estimated 'true' interval value (Miller, 1982). These adjustment factors are summarized in Table XVI.

Rainfall data is collected at SRS from a network of eight rain gauges. These gauges are read once daily, usually around 6 a.m.. The daily rainfall measurements are reported to ATG and entered into an electronic data base. Rain gauge stations used in this study are summarized in Table XV and Figure 3. Files of annual maxima rainfall for each of the four stations were used in the statistical model. The annual maxima of daily rainfall were adjusted by the conversion factor in Table XVI to approximate true 24-hour maxima.

Model

An extreme-value distribution was assumed for each period of yearly maximum rainfall. Depending on the time period for the maximum rainfall, each maximum was multiplied by the appropriate factors found in Table XVI. After multiplying the rainfall by the appropriate factor, the maximum was obtained for each station and year. The average, standard deviation, and coefficient of variation of the yearly maximum rainfall were calculated. The individual maximum rainfall amounts for each station were standardized and used to fit a generalized extreme-value distribution.

Let X_{ij} be the i^{th} yearly maximum rainfall for the appropriate time period for station-j, then the mean, standard deviation, coefficient of variation (divided by 100%), and standardized ij^{th} value are given by:

$$\overline{X}_j = \sum_{i=1}^{n_j} X_{ij} / n_j \tag{33}$$

$$S_j = \sqrt{\sum_{i=1}^{n_j}\left(X_{ij}-\overline{X}_j\right)^2 \Big/ \left(n_j - 1\right)} \tag{34}$$

$$\tau_{ij} = \frac{X_{ij} - \overline{X}_j}{S_j} \tag{35}$$

$$CV_j = S_j / \overline{X}_j \tag{36}$$

Table XVII gives the average, the standard deviation, and the coefficient of variation divided by 100% for each time period and station. Also included for the rainfall time peri-

Table XVI. Multiplication Factors for Yearly Maximum by Rainfall Periods

Rainfall Period	Multiplication Factor	Comments
24-hour	1.01	except SRS datasets which used a fixed 24-hour period
	1.13	SRS data (Barricades 3 and 5, F200 area, and SRTC)
12-hour	1.01	
6-hour	1.02	
3-hour	1.03	
1-hour	1.13	
15 min.	1.13	

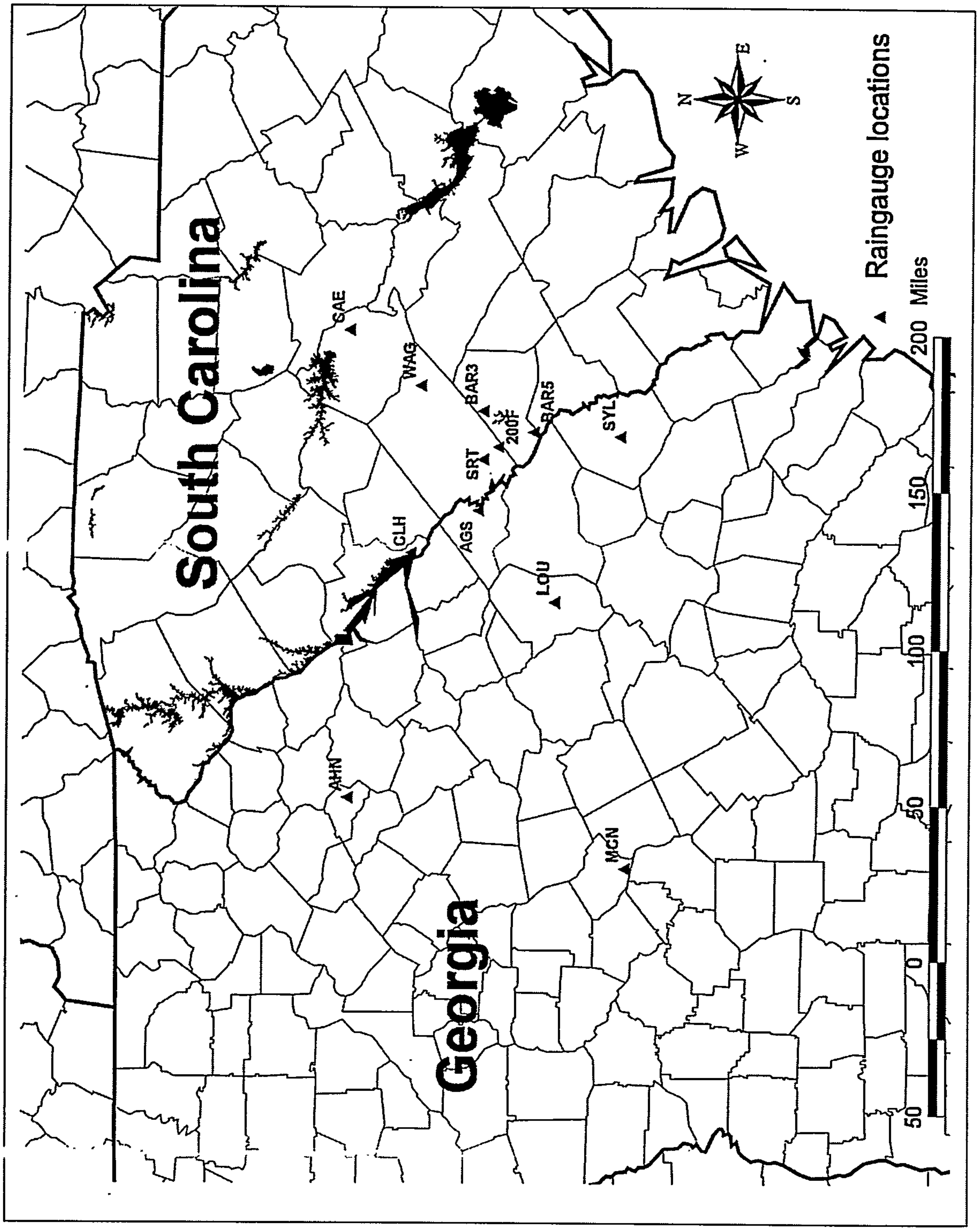


Figure 3. Rain Gauge Locations

Table XVII. Station Average, Standard Deviation, and Coefficient of Variation for Maximum Yearly Rainfall by Rainfall Periods

Station	No. Years	Station Average (in.)	Standard Deviation (in.)	Coefficient Variation (/100%)
Time Period = 24-hour				
Augusta	48	3.44031	1.18761	0.345204
Athens	38	3.98817	1.57366	0.394583
Barricade 3	35	3.43585	1.04429	0.303941
Barricade 5	29	3.77732	1.47263	0.389862
Clarks Hill	42	3.74854	1.57028	0.418905
Columbia	46	3.76752	1.17674	0.312338
F200 Area	38	3.72246	1.13109	0.303856
Louisville	48	3.52700	1.12546	0.319099
Macon	47	3.66802	1.41511	0.385797
SRTC	31	3.84273	1.22965	0.319994
Sylvania	48	3.50596	1.04634	0.298445
Wagner	47	3.51459	1.30400	0.371025

Average wt. coefficient of variation (/100%) = 0.34636
Shape Parameter: khat = -0.12149
Z-Test: kratio = -3.60874

Station	No. Years	Station Average (in.)	Standard Deviation (in.)	Coefficient Variation (/100%)
Time Period = 12-hour				
Augusta	48	3.09691	1.07108	0.345854
Athens	38	3.34788	1.47808	0.441498
Clarks Hill	42	3.19665	1.49854	0.468786
Columbia	46	3.23661	1.05927	0.327278
Louisville	47	3.05020	1.17514	0.385266
Macon	47	3.20342	1.11145	0.346957
Sylvania	46	3.12419	0.88503	0.283282
Wagner	45	3.11888	1.10452	0.354141

Average wt. coefficient of variation (/100%) = 0.366241
Shape Parameter: khat = -0.15685
Z-Test: kratio = -3.95960

Table XVII. Station Average, Standard Deviation, and Coefficient of Variation for Maximum Yearly Rainfall by Rainfall Periods (contd)

Station	No. Years	Station Average (in.)	Standard Deviation (in.)	Coefficient Variation (/100%)
Time Period = 6-hour				
Augusta	48	2.62969	0.78791	0.299620
Athens	38	2.72582	1.09917	0.403243
Clarks Hill	40	2.64869	1.19490	0.451130
Columbia	46	2.78017	0.95047	0.341875
Louisville	46	2.67151	1.06892	0.400117
Macon	47	2.85622	0.96548	0.338028
Sylvania	41	2.69529	0.65149	0.241716
Wagner	43	1.75020	0.99645	0.362317

Average wt. coefficient of variation (/100%) = 0.35314
Shape Parameter: khat = -0.13380
Z- Test: kratio = -3.33043

Station	No. Years	Station Average (in.)	Standard Deviation (in.)	Coefficient Variation (/100%)
Time Period = 3-hour				
Augusta	46	2.31616	0.80537	0.347718
Athens	38	2.25733	0.80819	0.358032
Clarks Hill	39	2.26732	0.92495	0.407949
Columbia	42	2.48034	0.82606	0.333043
Louisville	46	2.26175	0.87645	0.387512
Macon	46	2.40080	0.78833	0.328362
Sylvania	40	2.36514	0.64097	0.271006
Wagner	43	2.43415	0.89049	0.365833

Average wt. coefficient of variation (/100%) = 0.3500
Shape Parameter: khat = -0.10950
Z-Test: kratio = -2.69009

Table XVII. Station Average, Standard Deviation, and Coefficient of Variation for Maximum Yearly Rainfall by Rainfall Periods (contd)

Station	No. Years	Station Average (in.)	Standard Deviation (in.)	Coefficient Variation (/100%)
Time Period = 1-hour				
Augusta	46	1.80038	0.65007	0.361073
Athens	35	1.57328	0.37792	0.240213
Clarks Hill	36	1.75746	0.61179	0.348110
Columbia	42	1.92181	0.57630	0.299877
Florence	16	1.87863	1.09706	0.583971
Louisville	40	1.92015	0.72830	0.379295
Macon	46	1.76722	0.65436	0.370277
Sylvania	34	1.80468	0.52970	0.293515
Wagner	39	1.95867	0.75274	0.384314

Average wt. coefficient of variation (/100%) = 0.348919
Shape Parameter: khat = -0.015450
Z-Test: kratio=-0.37622

Station	No. Years	Station Average (in.)	Standard Deviation (in.)	Coefficient Variation (/100%)
Time Period = 15 min.				
Louisville	25	0.97180	0.24411	0.251191
Sylvania	25	1.14356	0.36952	0.323129
Wagner	25	1.05768	0.29337	0.277367

Average wt. coefficient of variation (/100%) = 0.28390
Shape Parameter: khat = 0.15823
Z-Test: kratio = 1.82577

ods is the generalized extreme value shape parameter and the Z-test (to determine if the shape parameter is statistically different from zero).

The standardized variables, τ_{ij}, were used to fit a generalized extreme-value distribution to determine which extreme type distribution was appropriate. A single form of the three possible types of limiting distributions for extreme values has been derived by Fisher and Tippett (1928) and can be modeled by

$$F(\tau) = \exp[-\{1 - k(\tau-\xi)/\alpha\}^{1/k}],\ k\neq 0, \quad (37)$$

$$F(\tau) = \exp[-\exp\{-(\tau-\xi)/\alpha\}],\ k=0. \quad (38)$$

τ is bounded by $\xi+\alpha/k$ from above if $k>0$ and from below if $k<0$. Here ξ and α are location and scale parameters, respectively. The shape parameter, k, determines which extreme-value distribution is best represented by the data. Fisher-Tippett Types I, II, and III correspond to $k=0$, $k<0$, and $k>0$, respectively. In practice the shape parameter usually lies in the range $-(1/2) < k < (1/2)$. When this is the case, the following can be used to estimate the parameters, ξ, α, and k (Hosking, et al., 1985):

$$\hat{k} = 7.8590c + 2.9554c^2, \text{ where}$$
$$c = \frac{2b_1 - b_o}{3b_2 - b_o} - \frac{\log 2}{\log 3} \quad (39)$$

The error in estimating k using Eq. (39) is less than 0.0009 through the range $-(1/2) < k < (1/2)$.

Given $\hat{k}$ the scale and location parameters can be estimated successively by

$$\hat{\alpha} = \frac{(2b_1 - b_o)\hat{k}}{\Gamma(1+\hat{k})(1-2^{-k})} \quad (40)$$

$$\hat{\xi} = b_o + \hat{\alpha}\{\Gamma(1+\hat{k}) - 1\}\hat{k} \quad (41)$$

The Type I extreme-value distribution, or Gumbel distribution, is a particularly simple special case of the generalized extreme-value (GEV) distribution and is often useful to test whether a given set of data is generated by a Gumbel rather than a GEV distribution. This process is equivalent to testing whether the shape parameter, k, is zero in the GEV distribution. Assuming the null hypothesis H_o: $k=0$, the estimator $\hat{k}$ is asymptotically distributed as $N(0,0.5633/n)$. The test may be performed by comparing the statistic $Z = \hat{k}(n/0.5633)^{1/2}$ with the critical values of a standard normal distribution. Significant positive values of Z imply rejection of H_o in favor of the alternative $k>0$, and significant negative values of Z imply rejection in favor of $k<0$. Values of Z (k-ratio) between -1.96 and +1.96 indicate that k is not significantly different from zero with 95% confidence.

The estimates of $\hat{k}$ and the Z-statistic ratio (kratio) are given in Table XVIII for all rainfall periods analyzed. Only the 15-minute and 1-hour rainfall periods have a zero shape parameter indicating a Type I extreme value distribution. For all other rainfall periods, the shape parameter is negative indicating a Type II extreme value distribution.

For the Type I or Gumbel distribution, the scale and location parameters can be estimated using the Method of Moments (Eliasson, 1997). These estimates are given by

$$\hat{\alpha} = 1/1.28255$$
$$\hat{\xi}/\hat{\alpha} = \hat{\beta} = 0.57722. \quad (42)$$

The estimates of scale and location parameters for the Type II extreme value distribution are given in Eqs. (40) and (41), where the values b_o, b_1, and b_2 are estimated from the data using Eqs. (43) through (45). τ_{ij} are the standardized variables ordered from smallest to largest and ij is the rank.

Table XVIII. Scale and Location Parameters for Type II GEV by Rainfall Periods

24-hour rainfall	Estimate for ξ =	-0.46546	Estimate for α =	0.65303
12-hour rainfall	Estimate for ξ =	-0.46949	Estimate for α =	0.61844
6-hour rainfall	Estimate for ξ =	-0.47165	Estimate for α =	0.64742
3-hour rainfall	Estimate for ξ =	-0.46758	Estimate for α =	0.67004

$$b_0 = \sum_{ij=1}^{N} \tau_{ij} \div N. \quad (43)$$

$$b_1 = \frac{1}{N(N-1)} \sum_{ij=1}^{N} (ij-1)\tau_{ij} \quad (44)$$

$$b_2 = \frac{1}{N(N-1)(N-2)} \sum_{ij=1}^{N} (ij-1)(ij-2)\tau_{ij} \quad (45)$$

In order to determine the rainfall amount, τ in Eqs. (37) for the Type II distribution and Eq. (38) for the Type I distribution must be solved for each return period of interest. Each station will have a separate rainfall amount for each return period.

For the Type I distributions, rainfall for the 15-minute and 1-hour periods, Eq. (38) is used.

Let P be the return period of interest. Then (1-1/P) is the probability corresponding to a rainfall amount ≥ $Inch_p$ or

$$Prob(Inch \geq Inch_p) = (1-1/P) = \exp[-\{\exp[-(1.28255(\tau_p) + 0.5772)]\}], \quad (46)$$

where

$$\tau_p = (X_p - \overline{X}_j) / S_j. \quad (47)$$

The station average, $\overline{X}_j$, and the station standard deviation, S_j, are computed from Eqs. (32) and (33). The return period is then given by Eq. (47).

$$X_p = S_j(\log[-\log\{-(1-1/P)\}] - 0.57722)(1/1.28255) + \overline{X}_j. \quad (48)$$

Eliasson (1997) indicates that often a smoother fit can be obtained by using the coefficient of variation averaged over all stations. Eliasson also gives an alternate method to Eq. (48) using the 5-year-return rainfall, which should always be within the data. Both Eq. (48) and Eq. (49) in which the individual station's CV_j and the 5-year return rainfall, denoted by $M5_j$, can be used to obtain the rainfall for station j and return period P.

$$X_p = M5_j[1 + C_i(y - 1.5]. \quad (49)$$

where y = log(-log(1(1-1/P))),

$$M5_j = S_j\{(0.8 - 0.57722)/1.28255\} + X_j, \quad (50)$$

and

$$C_i = 0.78 / \{(1/CV_j) + 0.72\}. \quad (51)$$

If the coefficient of variation is averaged over all stations, C_a replaces C_a in Eqs. (49) and (51), where CV_a is the average coefficient of variation and C_a is computed by

$$C_a = 0.78 / \{(1/CV_a) + 0.72\}. \quad (52)$$

The 24-hour, 12-hour, 6-hour, and 3-hour yearly maximum rainfall fit a Type-II extreme value distribution. The shape parameter, k, was given in Table XVII. The scale and location parameters are given in Table XVIII.

To get the rainfall amounts for each return period of interest, Eq. (37) must be solved for the station's standardized value, τ_p, and then converted to actual inches. Eq. (53) is used to get the rainfall in inches for each station for a return period of P years.

$$X_{p-j} = \overline{X}_p + S_j\left\{\hat{\xi} + \left(\frac{\hat{\alpha}}{\hat{k}}\right)\left(1 - \left[-\log\left(1 - \frac{1}{P}\right)\right]^{\hat{k}}\right)\right\}. \quad (53)$$

Results for Extreme Rainfall

Extreme rainfall estimates for return periods from 10 to 100,000 years are summarized in Table XIX and plotted in Figure 4.

Table XIX. Extreme Rainfall Estimates by Accumulation Period

Return Period (yrs)	Frequency (per year)	Accumulation Period				
		15-min	1-hour	3-hours	6 hours	24-hours
10	1×10^{-1}	1.5	2.7	3.3	3.7	5.0
25	4×10^{-2}	1.8	3.2	4.0	4.4	6.1
50	2×10^{-2}	2.0	3.5	4.6	5.0	6.9
100	1×10^{-2}	2.1	3.9	5.1	5.7	7.8
200	5×10^{-3}	2.3	4.2	5.8	6.4	8.8
500	2×10^{-3}	2.6	4.7	6.7	7.4	10.3
1000	1×10^{-3}	2.7	5.0	7.4	8.3	11.5
2000	5×10^{-4}	2.9	5.4	8.2	9.2	12.8
5000	2×10^{-4}	3.2	5.8	9.4	10.7	14.7
10000	1×10^{-4}	3.3	6.2	10.3	11.8	16.3
50000	2×10^{-5}	3.7	7.0	12.8	15.1	20.6
100000	1×10^{-5}	3.9	7.4	14.1	16.7	22.7

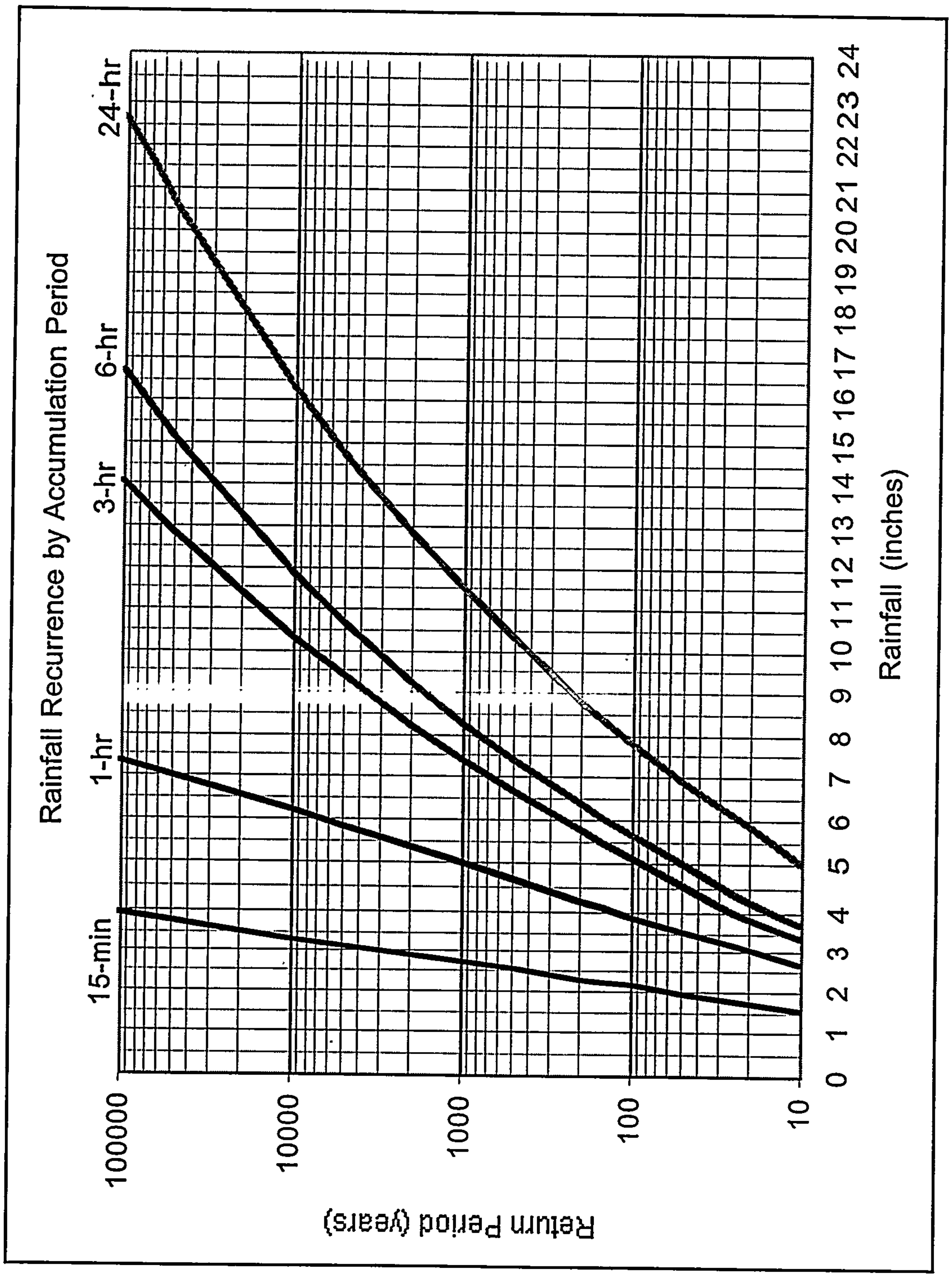


Figure 4. Rainfall Recurrences by Accumulation Periods

Acknowledgments

The work performed for this project was funded by the U. S. Department of Energy under Contract DE-AC09-89SR18035.

References

EarthInfo, Inc., NCDC Hourly and 15 Minute Precipitation, Boulder, CO (1995).

Eliasson, J., 1997: A Statistical Model for Extreme Precipitation, *Water Resources Research*, Vol. 33, No. 3, pp 449-455.

Fisher, R. A., and Tippett, L. H. C., 1928, "Limiting Forms of the Frequency Distribution of the Largest or Smallest Number of a Sample," *Proc. Cambridge Phil. Soc.*; 24, pp. 180-190.

Fujita, T. T., 1971: Proposed Characterization of Tornadoes and Hurricanes by Area and Intensity. Satellite and Mesometeorology Research Project Research Paper 91, Department of Geophysical Sciences, The University of Chicago, Chicago, IL. 44 pp.

Fujita, T. T., 1973: Experimental Classification of Tornadoes in FPP Scale. Satellite and Mesometeorology Research Project Research Paper 98, Department of Geophysical Sciences, The University of Chicago, Chicago, IL. 15 pp.

Fujita, T. T., 1980: Tornado and High-Wind Hazards at Savannah River Plant. Task No. 1. Site-Specific Evaluation Performed for Lawrence Livermore Laboratory under P.O. No. 7249609.

Fujita, T. T., and Pearson, A. D., 1973: "Results of FPP Classification of 1971 and 1972 Tornadoes," *Preprints* of the Eighth Conference on Severe Local Storms, Denver, Co, published by the American Meteorological Society, Boston, MA.

Garrett, A. J., 1983: April 23, 1983 Tornado at the Savannah River Plant. DP-1667. E. I. Du Pont de Nemours and Company, Savannah River Laboratory, Aiken, SC 29808.

Hosking, J. R. M., J. R. Wallis, E. F. Wood, 1985: "Estimation of the Generalized Extreme-Value Distribution by the Method of Probability-Weighted Moments", *Technometrics*, August 1985, Vol. 27, No. pages 251-261.

Hunter, C. H., 1989: A Climatological Description of the Savannah River Site (U). WSRC-RP-89-313. Westinghouse Savannah River Company, Aiken, SC 29808.

Lu, D., 1995: A Statistically Rigorous Model For Tornado Hazard Assessment, Institute for Disaster Research, Master Thesis Texas Tech University.

Mehta, K. C., Minor, J. E., McDonald, J. R., Manning, B. R., Abernathy, J. J. and Koehler, U. W., 1975: "Engineering Aspects of the Tornadoes of April 3-4, 1974," report published by the National Academy of Sciences, Washington, DC.

McDonald, J. R., 1981: A Methodology for Tornado Hazard Probability Assessment, Prepared for Division of Health, Siting and Waste Management Office of Nuclear Regulatory Research, U. S. Nuclear Regulatory Commission, Washington, DC.

McDonald, J. R., 1985: Evaluation of SRP Buildings or Facilities for Effects of Tornadoes. McDonald, Mehta and Minor, Consulting Engineers, Lubbock, TX, 79409.

McDonald, J. R., 1997: Tornado Hazard Assessment of Facilities at the Savannah River Site. McDonald-Mehta Engineers, Lubbock, TX, 79409.

Miller, J. F., *Engineering Meteorology*, Elsevier Scientific Publishing Co., New York (1982).

Parker, M. J. and R. J. Kurzeja, 1990: October 1, 1989 Tornado at the SavannahRiver Site (U). WSRC-RP-89-1288. Westinghouse Savannah RiverCompany, Aiken, SC 29808.

Parker, M. J., 1991: Savannah River Site Tornado Damage of March 1991 (U). WSRC-RP-91-439. Westinghouse Savannah River Company, Aiken,SC 29808.

Pepper, D. W. and J. F. Schubert, 1978: Tornado Activity at SRP During 1976. DP-1451. E. I. Du Pont de Nemours and Company, Savannah River Laboratory, Aiken, SC 29808.

Plummer, G. and J. Purvis, 1991: Tornadoes in Georgia 1950-1989; Technical Paper #110191, Southeast Regional Climate Center, Columbia, SC 29201; 28 pp.

Purvis, J. C., S. Sidlow, D. J. Smith, I. Turner, W. Tyler, 1990: South Carolina Tornado Statistics 1912-1989; Research Report #121590, Southeast Regional Climate Center, Columbia, SC 29201; 59 pp.

Weber, J. H., 1998: Tornado, Maximum Wind Gust, and Extreme Rainfall Event Recurrence Frequencies Calculation Note, SRT-SCS-98-050.

Appendix I. Tornado Database

Used for Inten-Freq	Use/ State	F-Scale	Touchdown Lattitude	Touchdown Longitude	Liftoff Lattitude	Liftoff Longitude	Path Width	Predicted Path Width	Path Length	Predicted Area (sq.mi.)	Area (sq.mi.)	Date
No	1	0	34.02	81	34.02	80.99	15	.015616	8	.01249	.02273	11JUN55:11:30
No	1	0	33.45	82.52	33.44	82.5	15	.016015	10	.01602	.02841	24MAY55:20:30
No	1	0	33.67	81.12	33.67	81.11	11	.015018	5	.00751	.01042	24FEB61:20:00
No	1	0	33.2	80.92	33.22	80.89	17	.018409	22	.0405	.07083	23NOV61:12:00
No	1	0	33.38	81.38	33.42	81.29	9	.025591	58	.14843	.09886	08APR64:08:00
No	1	0	34.18	80.97	34.18	80.96	4	.01422	1	.00142	.00076	26MAR65:10:15
No	1	0	33.62	81.1	33.62	81.1	82	.015018	5	.00751	.07765	24MAY65:14:00
Yes	1	0	33.03	82.32	33.03	82.32	3	.01422	1	.00142	.00057	22JUL70:16:15
Yes	1	0	32.67	81.63	32.67	81.63	15	.015018	5	.00751	.0142	13JAN72:18:45
Yes	1	0	32.75	81.63	32.75	81.63	6	.01422	1	.00142	.00114	03FEB72:10:00
Yes	1	0	32.82	81.23	32.81	81.23	10	.014619	3	.00439	.00568	30NOV74:02:23
Yes	1	0	32.38	82.6	32.43	82.53	15	.024394	52	.12685	.14773	01FEB76:16:30
Yes	1	0	33.35	81	33.35	81	6	.01422	1	.00142	.00114	13JUL82:14:00
Yes	1	0	33.25	81.97	33.28	81.97	30	.01801	20	.03602	.11364	23APR83:18:17
Yes	1	0	33.03	82	33.04	82	6	.015018	5	.00751	.00568	23APR83:19:42
Yes	1	0	32.88	82.47	32.87	82.45	9	.016015	10	.01602	.01705	04DEC83:01:15
Yes	1	0	34.22	80.87	34.22	80.86	6	.015018	5	.00751	.00568	16JUN89:15:00
Yes	1	0	34.17	81.92	34.17	81.92	6	.01422	1	.00142	.00114	29APR91:18:15
Yes	1	0	33.57	81.3	33.58	81.29	15	.016015	10	.01602	.02841	25FEB92:20:15
Yes	1	0	33.5	82.05	33.5	82.05	6	.014619	3	.00439	.00341	19MAY93:11:25
Yes	1	0	33.82	80.97	33.82	80.97	2	.01422	1	.00142	.00038	06JUN94:14:15
Yes	1	0	32.47	80.73	32.47	80.73	3	.01422	1	.00142	.00057	30JUN94:13:00
Yes	1	0	33.07	80.85	33.07	80.85	7	.01422	1	.00142	.00133	01AUG94:17:40
Yes	1	0	33.87	81.2	33.87	81.19	9	.015018	5	.00751	.00852	16AUG94:11:16
Yes	1	0	33.9	80.78	33.92	80.76	15	.01801	20	.03602	.05682	16AUG94:12:30
Yes	1	0	33.9	81.17	33.9	81.17	30	.01422	1	.00142	.00568	16AUG94:11:53
Yes	1	0	34.18	81.5	34.18	81.5	12	.01422	1	.00142	.00227	14JAN95:07:14
Yes	1	0	33.52	81.05	33.52	81.05	6	.01422	1	.00142	.00114	14JAN95:08:25
Yes	1	0	34.05	81.03	34.05	81.03	15	.01422	1	.00142	.00284	27OCT95:17:45
Yes	1	0	33.97	81.05	33.97	81.05	15	.01422	1	.00142	.00284	07NOV95:15:15
Yes	1	0	33.57	81.3	33.57	81.29	15	.015018	5	.00751	.0142	07NOV95:15:16
Yes	1	0	33.98	81.02	33.98	81.02	15	.01422	1	.00142	.00284	07NOV95:15:21
Yes	1	0	33.9	81.12	33.9	81.12	15	.01422	1	.00142	.00284	07NOV95:15:23
Yes	1	0	33.65	81.1	33.65	81.1	15	.01422	1	.00142	.00284	07NOV95:15:33
Yes	1	0	32.9	80.75	32.9	80.73	9	.016015	10	.01602	.01705	07NOV95:16:47

Appendix I. Tornado Database (contd)

Used for Inten-Freq	Use/ State	F-Scale	Touchdown Lattitude	Touchdown Longitude	Liftoff Lattitude	Liftoff Longitude	Path Width	Predicted Path Width	Path Length	Predicted Area (sq.mi.)	Area (sq.mi.)	Date
Yes	1	0	33.98	82.3	34.02	82.18	30	.027985	70	.1959	.39773	07NOV95:14:00
Yes	1	0	32.88	82.47	32.88	82.47	20	.01422	1	.00142	.00379	15JUN96:18:49
Yes	1	0	32.57	81.48	32.58	81.47	20	.01422	1	.00142	.00379	21NOV96:21:06
Yes	1	0	33.5	80.87	33.5	80.87	50	.01422	1	.00142	.00947	02JAN96:09:10
Yes	1	0	33.5	80.85	33.5	80.85	50	.01422	1	.00142	.00947	02JAN96:09:19
Yes	1	0	33.38	81	33.38	81	30	.01422	1	.00142	.00568	07MAR96:01:30
Yes	1	0	33.83	81.62	33.83	81.62	30	.01422	1	.00142	.00568	07MAY96:08:45
No	1	1	33.32	81.13	33.32	81.1	40	.059598	23	.13708	.17424	24JUN51:15:00
No	1	1	33.42	81.42	33.39	81.41	50	.05889	20	.11778	.18939	12JUN52:20:00
No	1	1	32.58	82.33	32.58	82.33	10	.054406	1	.00544	.00189	28JAN52:08:30
No	1	1	33.5	81.03	33.52	80.98	20	.06125	30	.18375	.11364	01JUN53:16:30
No	1	1	33.47	82	33.48	81.99	10	.05653	10	.05653	.01894	17AUG54:15:30
No	1	1	32.33	81.55	32.33	81.56	10	.054878	3	.01646	.00568	04SEP56:13:44
No	1	1	32.3	82	32.3	81.99	10	.05535	5	.02768	.00947	25SEP56:14:00
No	1	1	32.75	81.22	32.78	81.05	15	.078006	101	.78786	.28693	03MAY56:17:00
No	1	1	34.2	81.53	34.22	81.48	30	.061958	33	.20446	.1875	05APR57:08:14
No	1	1	34.17	82.03	34.16	82	11	.05889	20	.11778	.04167	22APR58:13:30
No	1	1	32.87	80.73	32.87	80.73	30	.054878	3	.01646	.01705	06MAY58:15:20
No	1	1	33.32	81.78	33.32	81.78	18	.05535	5	.02768	.01705	24FEB61:18:30
No	1	1	33.42	81.68	33.42	81.67	15	.05535	5	.02768	.0142	24FEB61:19:00
No	1	1	33.25	80.82	33.25	80.81	4	.054878	3	.01646	.00227	23NOV61:12:45
No	1	1	33	80.65	33	80.64	18	.05511	4	.02205	.01364	23NOV61:13:00
No	1	1	33.25	81.95	33.26	81.94	30	.05653	10	.05653	.05682	24FEB61:18:30
No	1	1	33.85	82.25	33.86	82.24	30	.05653	10	.05653	.05682	06JAN62:08:15
No	1	1	33.23	81.37	33.24	81.35	15	.05653	10	.05653	.02841	30APR63:18:30
No	1	1	33.73	81.1	33.74	81.07	30	.05889	20	.11778	.11364	28SEP63:19:00
No	1	1	33.82	81.88	33.82	81.88	30	.05464	2	.01093	.01136	07APR64:13:08
No	1	1	32.87	81.12	32.86	81.11	8	.05535	5	.02768	.00758	08APR64:10:45
No	1	1	33	81.3	33.06	81.28	22	.06408	42	.26914	.175	24APR65:17:30
No	1	1	32.47	80.98	32.46	80.97	30	.05606	8	.04485	.04545	19MAY65:19:00
No	1	1	33.53	81.68	33.53	81.67	62	.05535	5	.02768	.05871	25AUG65:18:00
No	1	1	33.43	80.68	33.43	80.67	11	.05535	5	.02768	.01042	07OCT65:03:10
Yes	1	1	33.92	80.82	33.91	80.8	12	.05653	10	.05653	.02273	24NOV67:19:10
Yes	1	1	33.83	80.83	33.84	80.82	18	.05653	10	.05653	.03409	12SEP71:15:30

Appendix I. Tornado Database (contd)

Used for Inten-Freq	Use/ State	F-Scale	Touchdown Lattitude	Touchdown Longitude	Liftoff Lattitude	Liftoff Longitude	Path Width	Predicted Path Width	Path Length	Predicted Area (sq.mi.)	Area (sq.mi.)	Date
Yes	1	1	32.22	82.42	32.25	82.35	71	.06432	43	.27657	.57822	15JAN71:13:20
Yes	1	1	32.82	82.3	32.82	82.28	23	.05771	15	.08657	.06534	23APR71:15:30
Yes	1	1	32.8	81.95	32.8	81.94	15	.05535	5	.02768	.0142	12MAY71:15:15
Yes	1	1	33.2	82.38	33.2	82.38	9	.05441	1	.00544	.0017	19JUL71:19:30
Yes	1	1	33.62	80.8	33.72	80.63	24	.08225	119	.97882	.54091	22FEB71:16:20
Yes	1	1	33.48	80.88	33.55	80.83	12	.06739	56	.37736	.12727	03MAR71:11:40
Yes	1	1	32.87	81.7	32.92	81.62	23	.06857	61	.41825	.26572	23APR71:13:30
Yes	1	1	33.92	82.25	33.9	82.22	30	.05889	20	.11778	.11364	10JAN72:03:30
Yes	1	1	32.85	82.02	32.87	81.99	30	.05889	20	.11778	.11364	11JAN72:15:00
Yes	1	1	34.05	81.22	34.08	81.12	23	.06833	60	.40998	.26136	10JAN72:15:05
Yes	1	1	33.28	81.45	33.35	81.3	30	.07753	99	.76759	.5625	13JAN72:17:10
Yes	1	1	33.5	82.47	33.5	82.45	15	.05653	10	.05653	.02841	02FEB73:03:30
Yes	1	1	33.38	81.25	33.48	80.78	10	.11978	278	3.32983	.52652	24MAY73:18:00
Yes	1	1	33.9	81.55	33.91	81.54	9	.05653	10	.05653	.01705	22FEB74:05:00
Yes	1	1	33.78	81.72	33.79	81.7	15	.05653	10	.05653	.02841	21MAR74:06:55
Yes	1	1	33.65	80.8	33.65	80.79	23	.05535	5	.02768	.02178	21MAR74:07:40
Yes	1	1	32.3	81.23	32.32	81.21	15	.05889	20	.11778	.05682	12MAY74:05:30
Yes	1	1	32.28	81.72	32.28	81.71	15	.05535	5	.02768	.0142	12MAY74:04:30
Yes	1	1	32.68	82.52	32.69	82.5	15	.05653	10	.05653	.02841	07JUN74:19:15
Yes	1	1	33.87	82.33	33.9	82.27	30	.06526	47	.30673	.26705	21MAR74:06:15
Yes	1	1	32.28	81.72	32.28	81.67	30	.06196	33	.20446	.1875	30NOV74:23:00
Yes	1	1	32.45	81.78	32.46	81.78	9	.05535	5	.02768	.00852	27APR75:16:45
Yes	1	1	33.43	80.93	33.43	80.93	9	.05441	1	.00544	.0017	16MAR76:10:00
Yes	1	1	33.23	81.65	33.28	81.68	30	.06597	50	.32985	.28409	28MAY76:15:30
Yes	1	1	33.33	81.52	33.33	81.53	40	.05535	5	.02768	.03788	28MAY76:20:43
Yes	1	1	33.32	81.77	33.37	81.65	30	.07187	75	.53903	.42614	02JUL76:18:00
Yes	1	1	32.85	81.08	32.9	81.05	10	.06432	43	.27657	.08144	28MAY76:13:30
Yes	1	1	32.33	81.38	32.4	81.27	30	.07399	84	.62155	.47727	01FEB76:18:15
Yes	1	1	33.55	81.73	33.55	81.73	20	.05441	1	.00544	.00379	24FEB77:06:00
Yes	1	1	33.85	80.67	33.85	80.67	9	.05488	3	.01646	.00511	19JUN77:21:00
Yes	1	1	33.33	80.83	33.35	80.67	39	.0773	98	.75752	.72386	05DEC77:18:55
Yes	1	1	33.67	81.1	33.67	81.1	7	.05464	2	.01093	.00265	25JUN78:17:30
Yes	1	1	33.65	80.85	33.65	80.87	6	.05653	10	.05653	.01136	25JUL78:16:00
Yes	1	1	32.63	81.6	32.65	81.59	15	.05653	10	.05653	.02841	24JUN78:17:00
Yes	1	1	33.53	82.02	33.68	81.5	30	.12851	315	4.04807	1.78977	08MAY78:20:23
Yes	1	1	33.52	82.13	33.53	82.02	30	.07093	71	.50357	.40341	08MAY78:20:15
Yes	1	1	33.33	80.83	33.36	80.79	5	.06078	28	.17018	.02652	13APR79:16:07

Appendix I. Tornado Database (contd)

Used for Inten-Freq	Use/ State	F-Scale	Touchdown Lattitude	Touchdown Longitude	Liftoff Lattitude	Liftoff Longitude	Path Width	Predicted Path Width	Path Length	Predicted Area (sq.mi.)	Area (sq.mi.)	Date
Yes	1	1	32.75	81.25	32.75	81.23	9	.05653	10	.05653	.01705	08MAR80:14:20
Yes	1	1	32.68	82.52	32.68	82.48	25	.05889	20	.11778	.0947	17MAR80:19:45
Yes	1	1	33.87	80.88	33.88	80.78	18	.06762	57	.38545	.19432	20MAY80:11:10
Yes	1	1	33.95	80.85	33.96	80.84	10	.05606	8	.04485	.01515	11FEB81:01:00
Yes	1	1	33.98	81.25	33.98	81.22	15	.05889	20	.11778	.05682	11FEB81:01:15
Yes	1	1	33.58	80.82	33.59	80.81	6	.05488	3	.01646	.00341	20APR81:16:00
Yes	1	1	33.85	80.77	33.85	80.77	6	.05488	3	.0165	.00341	20APR81:16:05
Yes	1	1	33.53	81.12	33.53	81.11	9	.05488	3	.0165	.00511	26JUL81:18:00
Yes	1	1	32.87	81.12	32.87	81.11	30	.05488	3	.0165	.01705	07AUG81:16:00
Yes	1	1	32.87	82.4	32.88	82.37	9	.05889	20	.1178	.03409	18MAR81:14:25
Yes	1	1	33.12	82.38	33.12	82.38	4	.05535	5	.0277	.00379	25JUL81:15:15
Yes	1	1	32.88	81.12	32.92	81.07	5	.06597	50	.3299	.04735	03NOV82:16:45
Yes	1	1	33.5	80.85	33.5	80.84	9	.05535	5	.0277	.00852	03JUL83:18:30
Yes	1	1	33.02	80.98	33.02	80.98	15	.05464	2	.0109	.00568	25JUL83:16:35
Yes	1	1	33.68	81.12	33.72	81.03	5	.0655	48	.3144	.04545	08APR83:14:00
Yes	1	1	33.33	81.8	33.35	81.7	30	.06833	60	.41	.34091	23APR83:20:15
Yes	1	1	34.25	82.3	34.25	82.27	30	.05889	20	.1178	.11364	03MAY84:15:45
Yes	1	1	32.28	81	32.28	80.97	9	.05771	15	.0866	.02557	03MAY84:16:00
Yes	1	1	32.23	80.95	32.25	80.92	15	.05889	20	.1178	.05682	03MAY84:16:00
Yes	1	1	32.32	81.97	32.32	81.95	12	.05653	10	.0565	.02273	03MAY84:13:30
Yes	1	1	33.22	82.02	33.22	81.97	1	.06361	40	.2544	.00758	14APR84:17:40
Yes	1	1	32.52	81.4	32.55	81.33	30	.06597	50	.3299	.28409	03MAY84:15:00
Yes	1	1	32.75	81.82	32.75	81.81	15	.05535	5	.0277	.0142	09JUN86:15:30
Yes	1	1	32.7	81.63	32.7	81.63	16	.05535	5	.0277	.01515	25JUL86:15:20
Yes	1	1	33.98	81.13	33.98	81.14	3	.05464	2	.0109	.00114	21FEB89:08:00
Yes	1	1	32.88	82.47	32.88	82.46	15	.05464	2	.0109	.00568	01OCT89:16:35
Yes	1	1	32.52	81.53	32.52	81.52	15	.05653	10	.0565	.02841	15NOV89:15:45
Yes	1	1	32.38	82.52	32.38	82.52	7	.05441	1	.0054	.00133	27APR91:14:00
Yes	1	1	33.95	82.17	33.83	81.78	30	.10609	220	2.334	1.25	21JUN92:14:00
Yes	1	1	33.95	81.47	33.95	81.46	135	.05511	4	.022	.10227	22FEB93:00:15
Yes	1	1	34.05	82.25	34.38	81.92	90	.13441	340	4.5699	5.79545	15APR93:14:26
Yes	1	1	33.53	81.13	33.53	81.13	15	.05441	1	.0054	.00284	16AUG94:10:20
Yes	1	1	34.13	81.23	34.14	81.25	22	.05653	10	.0565	.04167	16AUG94:12:18
Yes	1	1	34.23	81.32	34.24	81.31	15	.05535	5	.0277	.0142	16AUG94:12:32
Yes	1	1	33.38	81	33.38	81	9	.05441	1	.0054	.0017	18SEP94:12:15

Appendix I. Tornado Database (contd)

Used for Inten-Freq	Use/ State	F- Scale	Touchdown Lattitude	Touchdown Longitude	Liftoff Lattitude	Liftoff Longitude	Path Width	Predicted Path Width	Path Length	Predicted Area (sq.mi.)	Area (sq.mi.)	Date
Yes	1	1	33.13	81.15	33.23	81.18	22	.06597	50	.3299	.20833	16AUG94:09:09
Yes	1	1	34.22	82.38	34.27	82.35	22	.06125	30	.1838	.125	04DEC94:19:30
Yes	1	1	33.77	81.33	33.78	81.32	22	.05653	10	.0565	.04167	14JAN95:10:56
Yes	1	1	34.13	82.22	34.14	82.2	9	.05653	10	.0565	.01705	08MAR95:11:35
Yes	1	1	34.13	81.23	34.13	81.2	30	.06125	30	.1838	.17045	06JAN95:21:10
Yes	1	1	32.38	80.63	32.3	80.53	39	.07069	70	.4948	.51705	12JUN95:18:10
Yes	1	1	33.97	81.23	33.95	81.18	75	.06125	30	.1838	.42614	07NOV95:15:30
Yes	1	1	33.55	80.87	33.52	80.82	75	.06125	30	.1838	.42614	07NOV95:15:37
Yes	1	1	33.23	82.38	33.25	82.32	200	.05488	3	.0165	.11364	07MAR96:01:30
No	1	2	33.85	81.67	33.88	81.5	40	.12729	99	1.2602	.75	13MAR55:22:00
No	1	2	34.13	82.38	34.2	82.33	30	.1148	54	.6199	.30682	06APR56:13:30
No	1	2	33.83	81.53	34.03	81.25	12	.15893	213	3.3852	.48409	05APR57:07:45
No	1	2	33.47	82.5	33.5	82.37	120	.16448	233	3.8323	5.29545	05APR57:07:00
No	1	2	33.58	80.65	33.62	80.35	30	.14894	177	2.6362	1.00568	22APR58:14:20
No	1	2	34.25	81.45	34.27	81.35	17	.11619	59	.6855	.18996	30MAR60:20:06
No	1	2	33.5	81.28	33.5	81.29	30	.10121	5	.0506	.02841	28SEP63:18:30
No	1	2	32.6	82.37	33.05	81.67	30	.24634	528	13.0068	3	28SEP63:16:00
No	1	2	34.13	81.2	34.14	81.19	20	.10259	10	.1026	.03788	29AUG64:16:15
Yes	1	2	33.92	80.83	33.92	80.83	6	.10121	5	.0506	.00568	29MAY67:19:00
Yes	1	2	32.75	81.63	32.75	81.63	10	.10121	5	.0506	.00947	07JUL67:17:45
Yes	1	2	32.9	81.73	32.9	81.74	3	.10065	3	.0302	.0017	06AUG68:16:30
Yes	1	2	32.8	82.4	32.8	82.37	90	.10537	20	.2107	.34091	22JUL70:15:00
Yes	1	2	32.23	82.12	32.27	81.98	16	.12368	86	1.0637	.26061	15JAN71:13:40
Yes	1	2	32.37	81.32	32.37	81.33	120	.10259	10	.1026	.22727	27OCT72:21:45
Yes	1	2	34.2	81.53	34.2	81	24	.18446	305	5.626	1.38636	13DEC73:17:16
Yes	1	2	34.17	81.4	34.17	81.33	6	.11036	38	.4194	.04318	13DEC73:17:45
Yes	1	2	33.28	81.82	33.29	81.8	11	.10259	10	.1026	.02083	17SEP75:15:30
Yes	1	2	34	81.02	34.02	81	15	.10537	20	.2107	.0568	12NOV75:20:15
Yes	1	2	33.37	81.42	33.37	81.37	20	.10898	33	.3596	.125	18FEB75:17:20
Yes	1	2	32.48	81.27	32.53	81.2	15	.1148	54	.6199	.1534	03MAY75:16:25
Yes	1	2	32.7	82.05	32.71	82.04	120	.10204	8	.0816	.1818	16MAR76:11:30
Yes	1	2	32.8	81.97	32.8	81.96	30	.10065	3	.0302	.017	16MAR76:11:30
Yes	1	2	33.47	81.03	33.52	81.05	12	.11036	38	.4194	.0864	15MAY76:01:20
Yes	1	2	34.03	81	34.08	80.98	12	.11036	38	.4194	.0864	15MAY76:02:30
Yes	1	2	33.57	81.13	33.57	81.13	3	.1001	1	.01	.0006	25JUL78:16:00

Appendix I. Tornado Database (contd)

Used for Inten-Freq	Use/ State	F-Scale	Touchdown Lattitude	Touchdown Longitude	Liftoff Lattitude	Liftoff Longitude	Path Width	Predicted Path Width	Path Length	Predicted Area (sq.mi.)	Area (sq.mi.)	Date
Yes	1	2	34.23	81.75	34.45	81.47	300	.16364	230	3.7638	13.0682	28MAR84:17:20
Yes	1	2	32.37	81.88	32.52	81.63	60	.15532	200	3.1064	2.2727	03MAY84:14:00
Yes	1	2	33.93	80.85	33.94	80.85	3	.10037	2	.0201	.0011	31AUG87:15:15
Yes	1	2	34.22	82.12	34.22	82.1	80	.10176	7	.0712	.1061	15NOV89:14:34
Yes	1	2	33.1	81.67	33.22	81.45	528	.14422	160	2.3075	16	01OCT89:19:30
Yes	1	2	33.4	81.43	33.5	81.37	15	.11092	40	.4437	.1136	01MAY89:16:25
Yes	1	2	32.83	82.62	32.88	82.67	30	.11092	40	.4437	.2273	01OCT89:15:15
Yes	1	2	33.58	80.78	33.58	80.78	6	.1001	1	.01	.0011	22OCT90:16:50
Yes	1	2	33.33	82.18	33.34	82.17	30	.10232	9	.0921	.0511	29JAN90:15:43
Yes	1	2	33.35	81.68	33.37	81.67	45	.10259	10	.1026	.0852	01MAR91:22:15
Yes	1	2	33.3	81.63	33.38	81.57	60	.12063	75	.9047	.8523	03MAR91:15:00
Yes	1	2	33.3	81.67	33.38	81.58	60	.11924	70	.8347	.7955	03MAR91:15:00
Yes	1	2	33.23	81.72	33.23	81.73	45	.10121	5	.0506	.0426	29MAR91:14:15
Yes	1	2	33.88	81.83	34.12	81.53	165	.18307	300	5.4921	9.375	22NOV92:18:00
Yes	1	2	33.68	82.48	33.82	82.28	15	.11369	50	.5685	.142	22NOV92:18:00
Yes	1	2	33.88	81.33	33.88	81.33	15	.1001	1	.01	.0028	16AUG94:11:00
Yes	1	2	33.9	81.25	33.9	81.28	7	.10537	20	.2107	.0265	16AUG94:11:27
Yes	1	2	33.82	80.92	33.81	80.9	60	.10259	10	.1026	.1136	02NOV95:16:02
Yes	1	2	33.85	81.62	33.84	81.59	75	.10398	15	.156	.2131	07NOV95:14:53
Yes	1	2	33.57	80.68	33.57	80.66	75	.10398	15	.156	.2131	07NOV95:16:00
No	2	3	34.8	82.25	34.8	81.85	25	.22385	227	5.0815	1.0748	10MAY52:15:00
No	2	3	32.8	83.68	32.78	83.62	120	.16433	43	.7066	.9773	03MAR52:21:11
No	2	3	31.37	83.25	31.4	83.2	60	.16433	43	.7066	.4886	11MAY52:07:20
No	2	3	32.7	83.35	32.69	83.32	3	.15689	20	.3138	.0114	30APR53:17:30
No	2	3	32.5	85	32.48	84.92	120	.16692	51	.8513	1.1591	18APR53:18:50
No	2	3	32.35	85.02	32.37	84.93	180	.16692	51	.8513	1.7386	13MAR54:21:45
No	2	3	32.53	84.37	32.87	83.62	90	.31055	495	15.3723	8.4375	13MAR54:22:20
No	2	3	32.67	85.08	32.87	84.6	60	.25265	316	7.9836	3.5909	05DEC54:13:30
No	2	3	31.85	83.08	31.85	82.83	120	.19797	147	2.9102	3.3409	08APR57:16:30
No	2	3	32.78	79.83	32.8	79.98	30	.17889	88	1.5742	.5	11SEP60:14:00
No	2	3	32.25	83.73	32.26	83.72	30	.15366	10	.1537	.0568	31MAR61:08:20
No	2	3	32.45	84.98	32.52	84.93	10	.16724	52	.8697	.0985	31MAR61:14:10
No	2	3	34.17	84.42	34.16	84.24	10	.18277	100	1.8277	.1894	21MAR62:03:20
No	2	3	33.73	85.33	33.73	85.15	10	.18471	106	1.9579	.2008	28APR64:15:15

Appendix I. Tornado Database (contd)

Used for Inten-Freq	Use/ State	F-Scale	Touchdown Lattitude	Touchdown Longitude	Liftoff Lattitude	Liftoff Longitude	Path Width	Predicted Path Width	Path Length	Predicted Area (sq.mi.)	Area (sq.mi.)	Date
No	2	3	33.5	84.92	33.48	83.83	120	.39434	754	29.7332	17.1364	24DEC64:22:00
No	2	3	32.72	84	33.13	83.1	180	.34387	598	20.5636	20.3864	26DEC64:00:35
No	2	3	33.83	78.67	33.83	78.66	15	.15139	3	.0454	.0085	17AUG65:18:10
No	2	3	33.93	79.22	33.95	79.17	30	.1611	33	.5316	.1875	24NOV67:21:30
No	2	3	31.35	83.93	31.35	83.9	30	.15689	20	.3138	.1136	11NOV68:04:00
No	2	3	31.17	82.3	31.17	82.29	10	.15204	5	.076	.0095	18NOV68:14:20
No	2	3	30.75	84.63	30.75	84.63	30	.15204	5	.076	.0284	28DEC68:04:44
No	2	3	34.42	80.13	34.67	79.5	30	.2795	399	11.1519	2.267	18APR69:15:00
No	2	3	33.33	84.8	33.33	84.8	30	.15139	3	.0454	.017	02APR70:03:25
No	2	3	34.23	84.18	34.32	84.13	15	.17145	65	1.1144	.1847	02APR70:05:00
No	2	3	31.77	84.63	31.92	84.48	150	.16304	39	.6358	1.108	23APR71:15:55
No	2	3	32.02	84	32.03	83.8	45	.19409	135	2.6202	1.1506	23APR71:19:25
No	2	3	33.67	84.4	33.7	84.3	60	.1708	63	1.076	.7159	10JAN72:11:25
Yes	1	3	32.87	82.38	33.08	81.87	120	.25912	336	8.7063	7.6364	13JAN72:15:30
No	2	3	33.72	84.5	33.72	84.49	30	.15204	5	.076	.0284	28MAY73:00:30
No	2	3	34.77	82.43	35.17	81.77	30	.30214	469	14.17	2.6648	27MAY73:18:20
No	2	3	34.27	82.17	34.28	81.98	60	.18503	107	1.98	1.2159	13DEC73:15:10
Yes	1	3	34.13	82.17	34.18	81.87	45	.20768	177	3.676	1.5085	13DEC73:15:25
Yes	1	3	34.2	81.72	34.23	81.42	60	.20639	173	3.57	1.9659	13DEC73:16:03
No	2	3	33.87	83.63	33.97	83.33	60	.21091	187	3.944	2.125	28MAY73:16:00
No	2	3	34.3	83.87	34.3	83.7	60	.18115	95	1.721	1.0795	13DEC73:12:20
No	2	3	34.42	82.75	34.43	82.74	30	.15366	10	.154	.0568	08APR74:16:33
No	2	3	32.55	83.93	32.55	83.77	90	.1818	97	1.763	1.6534	18FEB75:16:08
No	2	3	33.77	84.53	33.9	84.33	150	.1983	148	2.935	4.2045	24MAR75:06:28
No	2	3	34.17	85.2	34.25	85.08	120	.17889	88	1.574	2	04APR77:16:15
No	2	3	34.37	79.55	34.4	79.37	155	.18503	107	1.98	3.1411	20MAY80:13:45
Yes	1	3	33.17	81.45	33.33	80.87	60	.25718	330	8.487	3.75	23APR83:20:20
No	2	3	34.32	81.42	34.35	81.08	261	.21189	190	4.026	9.392	28MAR84:17:45
No	2	3	33.28	84.83	33.42	84.68	36	.19571	140	2.74	.9545	05MAR89:21:12
No	2	3	34.62	83.6	34.7	83.5	528	.1763	80	1.41	8	15NOV89:19:30
No	2	3	33.83	84.65	33.9	84.58	396	.1666	50	.833	3.75	29MAR91:07:30
Yes	1	3	33.82	82.28	34.27	81.35	120	.35099	620	21.761	14.0909	22NOV92:18:15
No	2	3	34.57	83.93	34.68	83.8	260	.18277	100	1.828	4.9242	22NOV92:12:10
No	2	3	33.95	85.38	34.02	85.25	264	.17954	90	1.616	4.5	21FEB93:19:00

Appendix I. Tornado Database (contd)

Used for Inten-Freq	Use/ State	F-Scale	Touchdown Lattitude	Touchdown Longitude	Liftoff Lattitude	Liftoff Longitude	Path Width	Predicted Path Width	Path Length	Predicted Area (sq.mi.)	Area (sq.mi.)	Date
No	2	3	33.93	84.7	33.9	84.5	264	.1763	80	1.41	4	21FEB93:20:15
Yes	1	3	33.92	81.25	33.91	81.25	22	.15139	3	.045	.0125	16AUG94:12:35
No	2	3	34.75	83.32	34.85	83.02	528	.21512	200	4.302	20	27MAR94:15:12
Yes	1	3	33.93	81.23	34.07	81.28	132	.1763	80	1.41	2	16AUG94:12:35
No	2	3	34.63	81.52	34.98	81.82	75	.24747	300	7.424	4.2614	16AUG94:13:50
No	2	3	34.5	84.22	34.72	83.47	784	.29276	440	12.881	65.3333	27MAR94:13:17
No	2	3	34.3	84.95	34.5	84.37	784	.27982	400	11.193	59.3939	27MAR94:14:01
No	2	3	34.7	83.42	34.75	83.32	528	.1763	80	1.41	8	27MAR94:15:04
No	2	3	34.57	84.03	34.7	83.63	396	0.22483	230	5.171	17.25	27MAR94:14:23
No	2	3	34.08	85.33	34.15	85.07	264	0.21836	210	4.585	10.5	27MAR94:18:01
Yes	1	3	33.82	81.1	33.83	81.08	75	0.15527	15	0.233	0.2131	02NOV95:15:45
No	2	4	32.6	83.6	32.61	83.59	100	0.20916	10	0.209	0.1894	30APR53:17:13
No (AL)	3	4	33.22	85.93	33.3	85.75	132	0.25061	121	3.032	3.025	01MAY53:20:05
No (AL)	3	4	34.35	87.05	34.37	86.9	60	0.23754	86	2.043	0.9773	24APR55:06:04
No (AL)	3	4	33.5	86.97	33.63	86.63	60	0.28498	213	6.07	2.4205	15APR56:16:04
No	2	4	34.63	80.58	34.73	79.62	40	0.41271	555	22.906	4.2045	08APR57:17:00
No (AL)	3	4	33.9	87.18	33.93	87.3	60	0.23231	72	1.673	0.8182	17NOV57:16:11
No (AL)	3	4	33.37	86.97	33.48	86.75	200	0.26107	149	3.89	5.6439	05MAR63:16:03
No (AL)	3	4	33.9	86.9	34.18	86.55	264	0.31	280	8.68	14	11MAR63:15:03
No (AL)	3	4	33.32	86.43	33.33	86.38	30	0.21775	33	0.719	0.1875	24JAN64:20:01
No (AL)	3	4	33.7	87.17	33.78	86.82	132	0.28348	209	5.925	5.225	06MAR67:16:03
No (AL)	3	4	31.83	86.63	32.22	85.88	150	0.40113	524	21.019	14.886	18APR69:03:04
No (AL)	3	4	31.5	87.3	31.77	87	90	0.30029	254	7.627	4.3295	23APR71:12:04
Yes	1	4	34.18	82.02	34.19	82.01	15	0.20916	10	0.209	0.0284	13DEC73:15:30
Yes	1	4	34.08	82.57	34.27	82.25	60	0.28983	226	6.55	2.5682	31MAR73:19:20
No (AL)	3	4	34.47	85.75	34.5	85.67	120	0.22559	54	1.218	1.2273	19MAY73:19:05
No (AL)	3	4	32.53	87.8	33.53	85.75	240	0.72496	1391	100.842	63.227	27MAY73:18:05
No	2	4	34.5	85.05	34.8	84.7	45	0.3156	295	9.31	2.5142	03APR74:17:40
No	2	4	34.37	84.33	34.53	84.12	60	0.27153	177	4.806	2.0114	03APR74:19:30
No	2	4	34.95	84.3	34.97	84.22	120	0.22447	51	1.145	1.1591	03APR74:20:20
No (AL)	3	4	33.27	88.2	34.27	86.7	150	0.61851	1106	68.407	31.421	03APR74:18:04

Appendix I. Tornado Database (contd)

Used for Inten-Freq	Use/ State	F-Scale	Touchdown Lattitude	Touchdown Longitude	Liftoff Lattitude	Liftoff Longitude	Path Width	Predicted Path Width	Path Length	Predicted Area (sq.mi.)	Area (sq.mi.)	Date
No (AL)	3	4	33.08	87.6	33.25	87.45	150	0.2592	144	3.733	4.0909	23FEB75:14:02
No	2	4	34.37	81.32	34.42	80.92	300	0.28386	210	5.961	11.932	28MAR84:18:00
No	2	4	34.53	80.63	34.6	80.58	159	0.22036	40	0.881	1.2045	28MAR84:18:20
No	2	4	34.58	79.92	34.62	79.82	210	0.23157	70	1.621	2.7841	28MAR84:18:45
No	2	4	34.65	79.75	34.67	79.5	210	0.25771	140	3.608	5.5682	28MAR84:19:10
No	2	4	34.63	79.6	34.67	79.5	780	0.2241	50	1.1205	7.3864	28MAR84:19:20
No	2	4	35.08	81.93	35.18	81.8	210	0.23904	90	2.1513	3.5795	05MAY89:17:20
No (AL)	3	4	34.65	86.65	34.78	86.37	264	0.27452	185	5.0786	9.25	15NOV89:17:11
No	2	4	33.92	84.67	34.17	84.43	260	0.28012	200	5.6024	9.8485	22NOV92:10:44
No	2	4	33.18	83.45	33.47	83.03	260	0.32494	320	10.3981	15.758	22NOV92:15:45
No	2	4	34.13	85.03	34.43	84.3	528	0.38844	490	19.0333	49	27MAR94:12:14
No (AL)	3	4	33.72	86.15	34.02	85.42	264	0.39217	500	19.6085	25	27MAR94:11:03
No	2	4	34.08	79.28	34.09	79.27	12	0.20803	7	0.1456	0.0159	07NOV95:17:05
No (AL)	3	4	34.83	87.03	34.8	86.25	390	0.35109	390	13.6923	28.807	18MAY95:17:05
No (AL)	3	5	32.82	88.35	33.2	87.82	45	0.43957	407	17.8903	3.4688	03MAR66:20:03
No (AL)	3	5	34.47	87.48	34.83	86.7	150	0.48793	520	25.3724	14.773	03APR74:18:04
No (AL)	3	5	34.8	86.77	34.83	86.7	150	0.28549	47	1.3418	1.3352	03APR74:19:04
No (AL)	3	5	34.7	87.05	34.83	86.78	150	0.34113	177	6.0379	5.0284	03APR74:19:04
No (AL)	3	5	33.83	88.13	34.5	87	150	0.60563	795	48.1476	22.585	03APR74:20:04
No (AL)	3	5	33.52	86.93	33.6	86.7	165	0.32829	147	4.8258	4.5938	04APR77:16:04

* The use/state code is "1" if within the 2-degree square centered at SRS, latitude 33.25 degrees and longitude 81.63 degrees
The use/state code is "2" if the tornado occurred anywhere else in the state of Georgia or South Carolina.
The use/state code is "3" if the tornado occurred in Alabama.
The tornadoes used to determine the tornado frequency and the intensity frequency (proportion of tornados by F-scale are limited to those with use/state code = 1 and which occurred between 1967 and 1996.
Predicted Width = -0.05363+0.00138*length(mi)+0.0011(F-j median windspeed)+0.00001*length*median windspeed
Predicted Area (sq mi) = Predicted Width * length/10.
Area (sq mi) = width*length/5280.

Appendix II. Breakdown of Tornado Data

Number of Tornadoes in two-degree square centered at SRS (33.25°N, 81.63°W)

			F-Scale				
Year	**F-0**	**F-1**	**F-2**	**F-3**	**F-4**	**F-5**	**Total**
1951	0	1	0	0	0	0	1
1952	0	2	0	0	0	0	2
1953	0	1	0	0	0	0	1
1954	0	1	0	0	0	0	1
1955	2	0	1	0	0	0	3
1956	0	3	1	0	0	0	4
1957	0	1	2	0	0	0	3
1958	0	2	1	0	0	0	3
1959	0	0	0	0	0	0	0
1960	0	0	1	0	0	0	1
1961	2	5	0	0	0	0	7
1962	0	1	0	0	0	0	1
1963	0	2	2	0	0	0	4
1964	1	2	1	0	0	0	4
1965	2	4	0	0	0	0	6
1966	0	0	0	0	0	0	0
1967	0	1	2	0	0	0	3
1968	0	0	1	0	0	0	1
1969	0	0	0	0	0	0	0
1970	1	0	1	0	0	0	2
1971	0	8	1	0	0	0	9
1972	2	4	1	1	0	0	8
1973	0	2	2	2	2	0	8
1974	1	8	0	0	0	0	9
1975	0	1	4	0	0	0	5
1976	1	6	4	0	0	0	11
1977	0	3	0	0	0	0	3
1978	0	5	1	0	0	0	6
1979	0	1	0	0	0	0	1
1980	0	3	0	0	0	0	3
1981	0	8	0	0	0	0	8
1982	1	1	0	0	0	0	2
1983	3	4	0	1	0	0	8
1984	0	6	2	0	0	0	8
1985	0	0	0	0	0	0	0
1986	0	2	0	0	0	0	2
1987	0	0	1	0	0	0	1
1988	0	0	0	0	0	0	0
1989	1	3	4	0	0	0	8
1990	0	0	2	0	0	0	2
1991	1	1	4	0	0	0	6
1992	1	1	2	1	0	0	5
1993	1	2	0	0	0	0	3
1994	6	6	2	2	0	0	16
1995	10	6	3	1	0	0	20
1996	6	1	0	0	0	0	7
Totals	**42**	**108**	**46**	**8**	**2**	**0**	**206**
1967-1996 Totals	**35**	**83**	**37**	**8**	**2**	**0**	**165**

Appendix III. Frequency of Tornadoes within F-Scales (0 to 5) for the Georgia-South Carolina Region

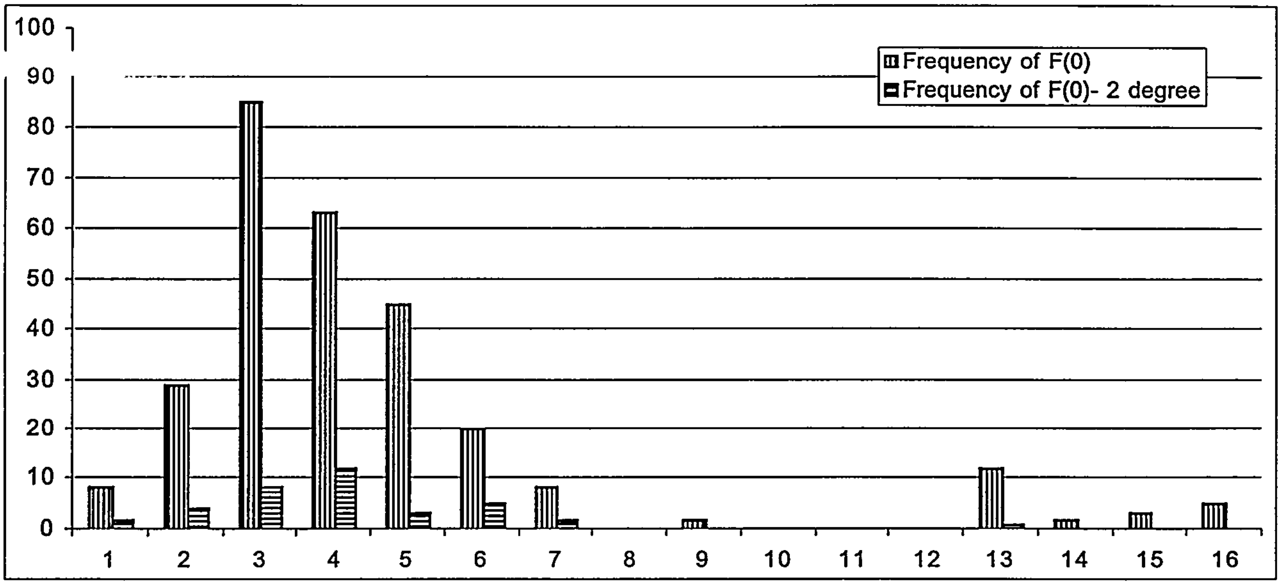
Frequency of tornadoes within F-Scales (0 to 5) for the Georgia-South Carolina region and for for two-degree square centered over the SRS. Totals for F-Scales 4 to 5 also include observations from Alabama (1951-1996).

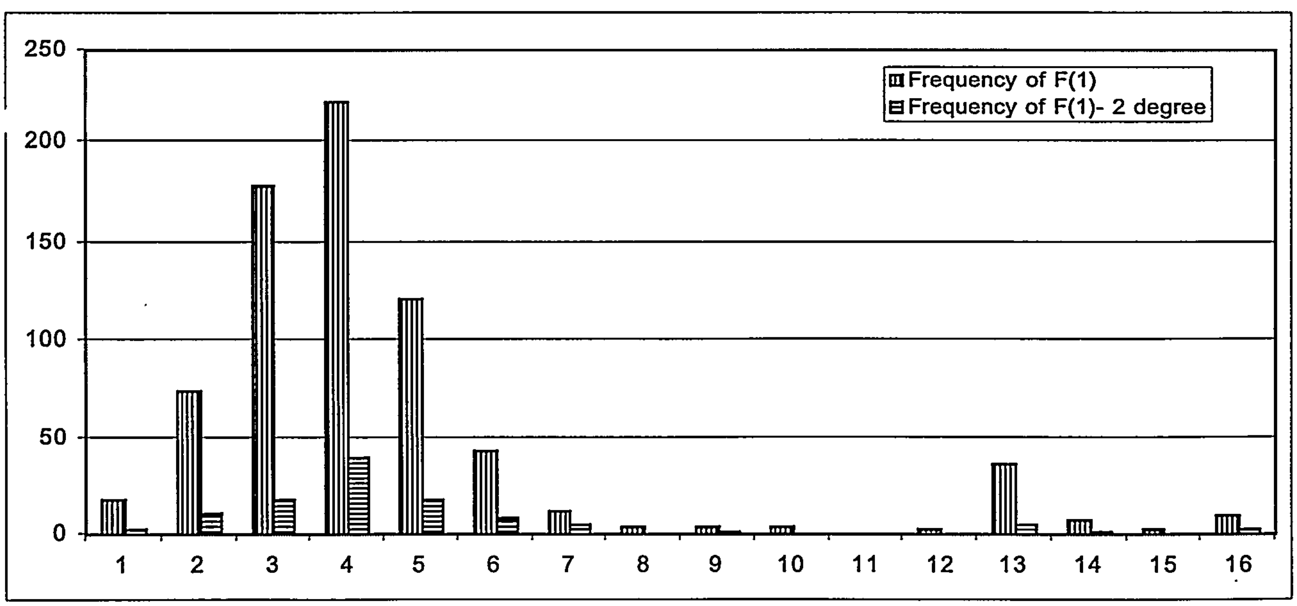
F-Scale	Georgia-South Carolina*	Two-Degree Square Centered Over the SRS
F(0)	282	42
F(1)	730	108
F(2)	323	46
F(3)	59	8
F(4)	34*	19*
F(5)	6*	6*

*Including Alabama

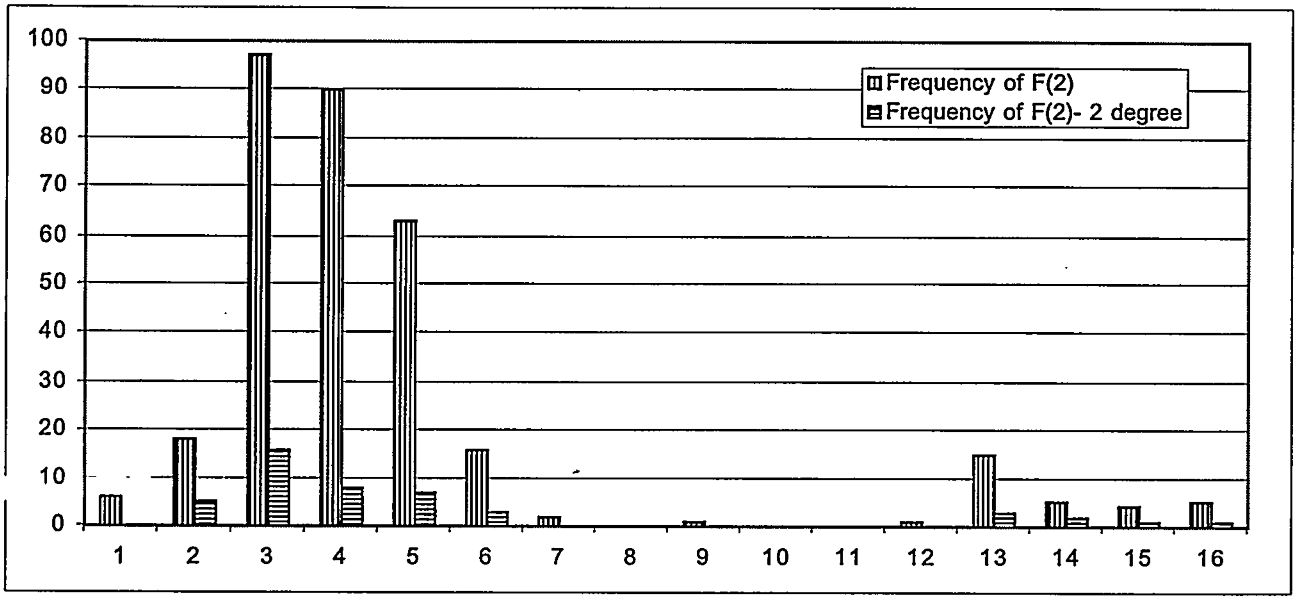
Appendix IV. Frequency of Occurrences for Tornadoes by 22.5 Degree Sector and F-Scale Classes

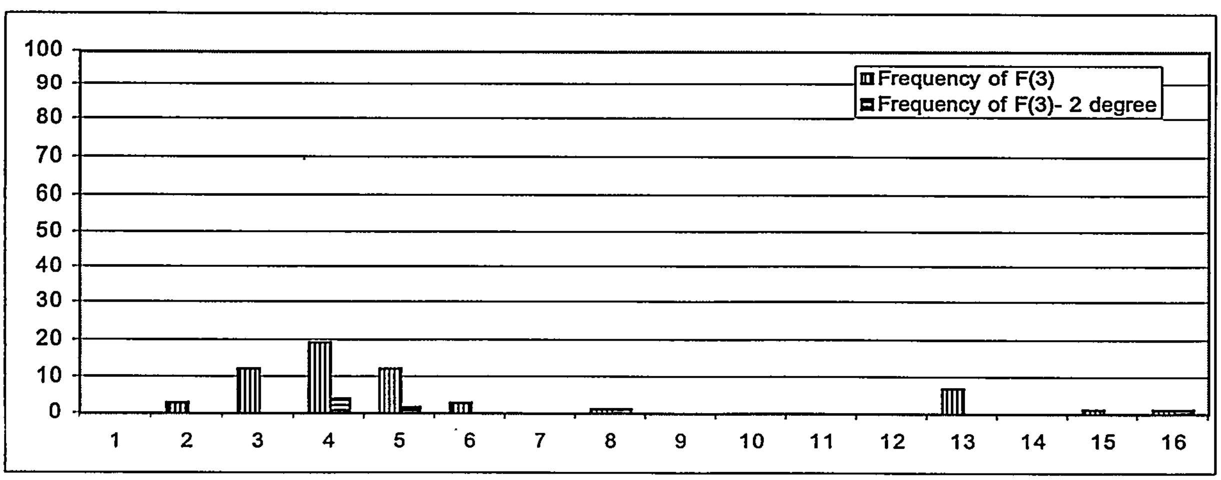
Comparison of frequency of occurrences for tornadoes by 22.5 degree sector and F-scale classes. Each F-scale class is compared against the entire study area and the two-degree area centered on the SRS.



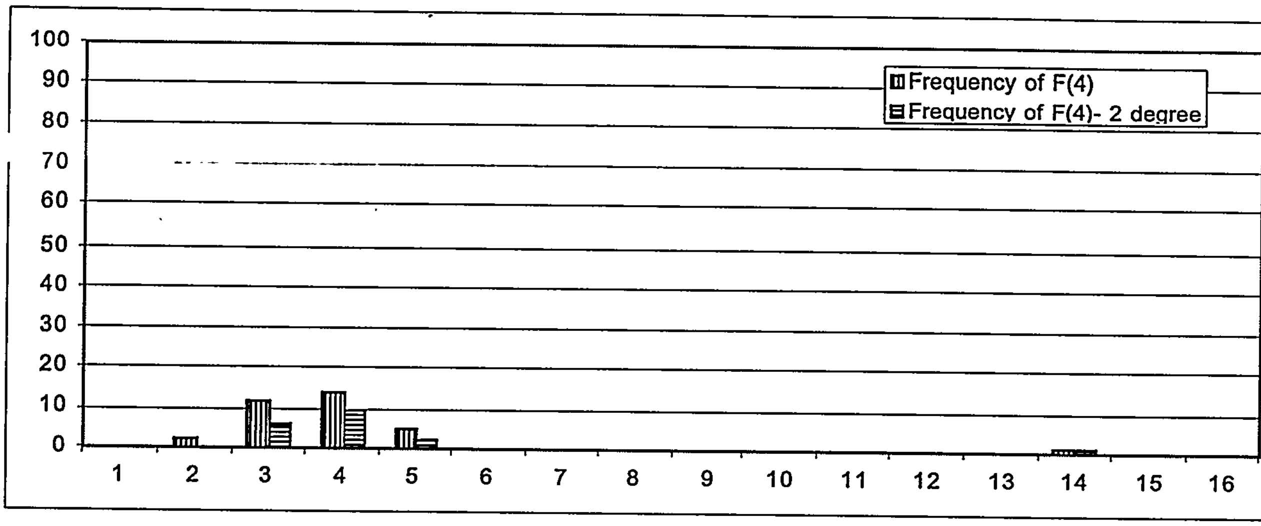


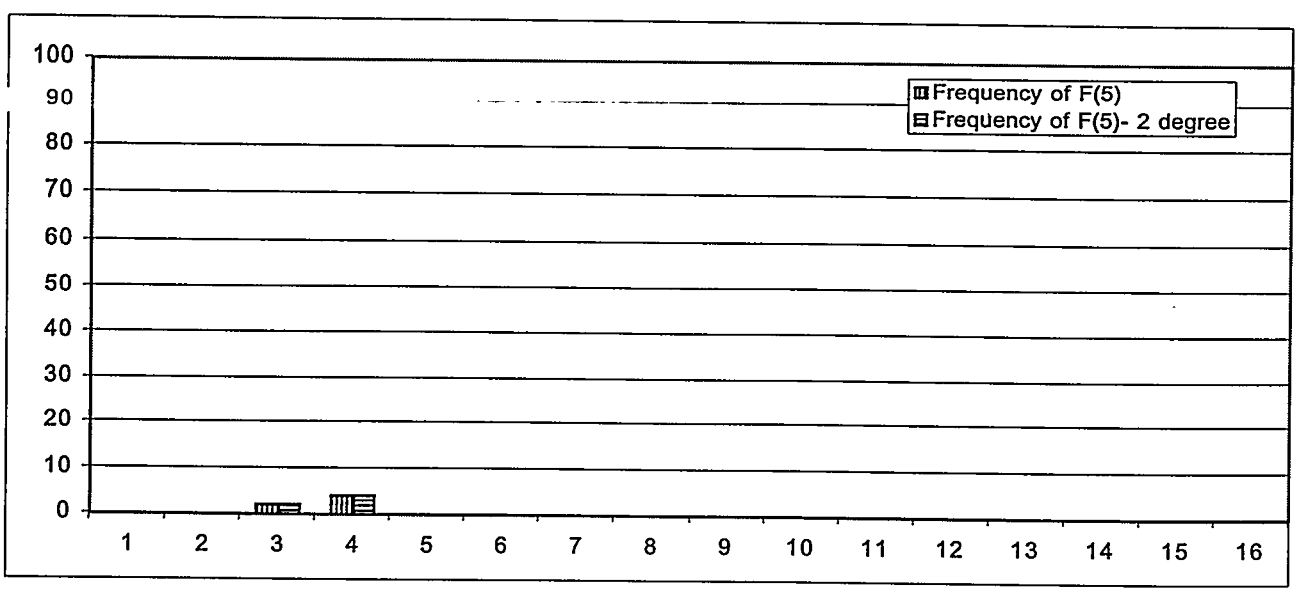
Appendix IV. Frequency of Occurrences for Tornadoes by 22.5 Degree Sector and F-Scale Classes (contd)





Appendix IV. Frequency of Occurrences for Tornadoes by 22.5 Degree Sector and F-Scale Classes (contd)





Distribution List:

R. P. Addis, 773-A, Rm.A-1011
C. H. Hunter, 773-A, Rm.A-1009
M. J. Parker, 773-A, RM.A-1005
C. O. Minyard, 773-A, Rm. A-1005
R. J. Kurzeja, 773-A, Rm. A-1020
A. H. Weber, 773-A, Rm. A-1012
K. Chen, 773-A, Rm. 1118
A. L. Boni, 773-A, Rm. A-202
P. T. Deason, 773-A, A-235
R. C. Tuckfeld, 773-42A
J. H. Weber, 773-42A
G. P. Shine, 773-42A
G. R. Peterson 703-F, Rm 57
D. C. Hanna, 703-46A
G. R. Whitney, 703A, B222
C. T. Edwards, 703-47A
J. L. Merrick, 703-47A
W. N. Kennedy, 730-1B/314
F. Loceff, 730-1B/319
G. B. Rawls, 730-1B/313
J. R. Joshi, 730-1B/3068
G. E. Mertz, 730-1B/3080
G. R. Baldwin, 730-1B/3081
J. P. Kelley, 730-1B/3070
L. A. Salomone, 730-2B/130
M. W. Lewis, 730-2B/116
M. E. Maryak, 730-2B/115
B. J. Gutierrez, 703-47A/220
D. P. Matthews, 706-8C
ETG files (15 copies)