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Probabilistic Hazard Curves for Tornadic Winds, Wind Gusts, and Extreme Rainfall Events

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Summary

This paper summarizes a study carried on at the Savannah River Site (SRS) for determining probabilistic hazard curves for tornadic winds, wind gusts, and extreme rainfall events. 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. Also, emergency response exercises often use hypothetical weather data to initiate accident scenarios. The hazard curves in these reports provide a means to use extreme weather events based on models and measurements rather than scenarios that are created ad hoc as is often the case.

I. Background

Emergency response modeling exercises for atmospheric dispersion often involve answering "what if" type questions, and computing the downwind concentration of hazardous materials. The scenarios used for these exercises often begin with meteorological phenomena such as tornadoes, wind gusts, or extreme rainfall events that trigger hypothetical accidents and releases. Dose assessment experts are then asked to run models to calculate the dose consequence of a hypothetical accident with upper limits on the boundary concentration and spatial extent of an affected area. The results of this work can be used to help exercise officials determine credible limits for tornadic wind speeds, wind gusts, and extreme rainfall amounts to make such exercises more realistic.

Also, 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. In 1997, the Structural Engineering Department at the SRS requested that the Atmospheric Technologies Group (ATG) update probabilistic hazard curves for tornadic winds, maximum wind gusts, and extreme rainfall events for the SRS. An extended internal report summarizing those results is available from the Savannah River Site (Weber, et. al.).[1]

II. Tornadoes

A. Databases

1. Selection and Testing. Selecting the database to use for the model was problematic since there was no single official source of data but rather a few "semiofficial" sources that differed substantially from one another. The Storm Prediction Center (SPC) maintains a database on tornadoes by state that is accessible through the Internet. The Storm Prediction Center also will transmit on request a tornado database, which is maintained internally. The SPC's internal database differed from the one available over the Internet and previously published databases by South Carolina and Georgia State Climatologists. The main difference between the SPC's internal database and the others is that tornadoes without liftoff coordinates were omitted from the SPC's internal database.

The Internet accessible database was supplemented with a few tornadoes that occurred within the SRS that were not listed in any of the previously published databases. This database therefore included tornadoes without liftoff points. It was reasoned that the absence of a liftoff point could be dealt with by using a statistical model to assign such for each storm.

One and two-degree squares, centered at the SRS, were statistically compared for the time periods 1951-66 and 1967-96 using a chi-square test statistic to determine differences. No statistically significant difference was found between the one and two-degree squares but there was a difference between the two time periods.

2. Summary of Database Used. The final database used for risk probability determination was a two-degree square centered at the SRS (33.25 N 81.63 W) in which the tornado frequency and the intensity frequency distributions were determined using only the tornado data from 1967-1996. A larger database was used to determine the damage path area versus tornado intensity relationship used in the model. 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.

B. Tornado Model Description

The model used to determine the tornado risk probabilities was based on the Lu-McDonald[2,3] modified IDTR model. 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 using the tornado wind field model obtained from the Super Outbreak of Tornadoes of April 3-4, 1974.

Tornado hazard probability is expressed as the probability of tornado wind speeds exceeding some threshold value per year in a defined local region, . A number of assumptions are required for this model. These are: (1) tornado occurrences are independent; that is, the occurrence of one tornado occurs independently of any other tornado within a specific area and time frame, (2) tornado characteristics (damage path and intensity) are homogeneous in the geographical area and over the time period considered for the modeling process, (3) the tornado intensity variation within the damage path is the same throughout the contiguous United States.

C. Uncertainty Estimates

The hazard probability of occurrence for a tornado wind speed has an uncertainty associated with the estimation process. Confidence limits or bounds can be determined around the estimated hazard probability. These confidence bounds permit an interval estimate for the hazard probability to be made with statistical confidence limits.

Uncertainty estimates were made for two terms in the estimation process. The first was the tornado occurrence rate, and the second was the regression equation used to estimate the predicted damage path areas for each tornado. The occurrence rate is estimated by the number of tornadoes observed in the two-degree square divided by the number of years considered. The sample estimate can be considered to be approximately normally distributed as long as the number of tornadoes over the time period exceeds 20 (which it does for the region considered).

In estimating the expected damage path area for the SRS region by F-class, a logarithmic regression was done. These regression estimates are subject to uncertainty. Both the regression estimates and the uncertainty in the estimates were estimated using SAS®.[4]

The total uncertainty for the probability of observing a wind speed, $V>=V_i$ is obtained using a first-order Taylor's series approximation. Once the variances are estimated for each desired wind speed, then 95% confidence intervals were computed using the standard deviation of the variance estimate multiplied by 1.96. These are given in Table 1 for each F-class wind speed.

D. Results for Tornadoes

Table 1. Tornadic wind speeds with return period and probability.

Torn. winds (mph)	Return period (yrs)	Probability (1/Return Period)	Upper 95% Limit	Lower 95% Limit
45	4,858	2.06 E-04	2.64 E-04	1.48 E-04
79	10,931	9.17 E-05	1.18 E-04	6.51 E-05
118	24,073	4.17 E-05	5.44 E-05	2.89 E-05
162	70,721	1.42 E-05	1.90 E-05	9.42 E-06
210	408,163	2.46 E-06	3.41 E-06	1.51 E-06
262	3,846,154	2.61 E-07	3.72 E-07	1.50 E-07

III. Wind Gusts

A. Wind Gust Data

Wind gust data were obtained from the 1987-1996 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. A daily highest wind speed or 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 of the NWS stations 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 SRS climatological documents to complete the data record through 1971. The combination of databases provided wind gust data for the 1950-1996 period.

B. Wind Gust 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. In order to combine the yearly maximums across stations, the maximum yearly 24-hour wind gusts were standardized using the station mean and standard deviation of the yearly 24-hour maximums. The standardized variables were used to fit a generalized extreme-value distribution. A single form of the three possible types of limiting distributions has been derived by Fisher and Tippett.[5] The form of the three extreme value distributions is given by

and S_j are the jth station mean and standard deviation for the yearly 24-hour maxima. The values of k, are estimated from the standardized variables. The term k is a scale parameter that determines which of the three extreme value distributions is appropriate for the data. If k =0, then a Type I distribution should be used. If k is negative, then a Type II distribution is used. If k is positive, then a Type III distribution is used. Most of the meteorological extreme events can be represented by either a Type I or a Type II extreme value distribution. For the wind gusts, a Type I (k=0) extreme value distribution was used to determine the probability of getting a specific maximum or greater wind speed.

C. Results for Wind Gusts

Table 2. Wind gusts with return period and probability.

Wind gusts (mph)	Return period (yrs)	Probability (1/Return Period)
62.8	5	0.2
69.0	10	0.1
76.9	25	0.04
82.7	50	0.02
88.4	100	0.01
91.8	150	0.0067
94.2	200	0.005
96.0	250	0.004
101.8	500	0.002
107.5	1,000	0.001
110.8	1,500	0.00067
113.2	2,000	0.0005
120.8	5,000	0.0002
126.5	10,000	0.0001
139.8	50,000	0.00002
145.5	100,000	0.00001

IV. Extreme Rainfall

A. 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 cooperative stations, and daily rainfall from four rain gauge stations located on the SRS.

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 15-minute and hourly data for these stations were extracted from compact disks containing NCDC TD-3260 and TD-3240 data sets. 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 co-operative stations and annual maximum one, three, six, and 24-hour rainfall values for each of the eight NWS and co-operative 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 that overlaps the fixed interval, empirical factors are used to convert the fixed interval maxima to an estimated `true' interval value (Miller[6]).

Rainfall data are 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 database. 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[6] to approximate true 24-hour maxima.

B. Model

An extreme value distribution was assumed for each period of yearly maximum rainfall based on the Fisher-Tippett[5] model given in Eqs. (1) and (2). Depending on the time period for the maximum rainfall, each maximum was multiplied by the appropriate factors.[6] After multiplying the rainfall by the appropriate factor, the yearly maximum was obtained for each station. These yearly maximums were standardized by station so that all stations could be used to determine the parameters for the extreme value distribution.

Only the 15 minute and 1-hour rainfall periods have a zero shape parameter (k=0) indicating a Type I extreme value distribution. For all other rainfall periods, the shape parameter (k) is negative indicating a Type II extreme value distribution.

C. Results for Extreme Rainfall

Table 3. Extreme Rainfall Estimates by Accumulation Period

Return Period (yrs)	Frequency (per year)	15-minute	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
1,000	1×10^{-3}	2.7	5.0	7.4	8.3	11.5
2,000	5×10^{-4}	2.9	5.4	8.2	9.2	12.8
5,000	2×10^{-4}	3.2	5.8	9.4	10.7	14.7
10,000	1×10^{-4}	3.3	6.2	10.3	11.8	16.3
50,000	2×10^{-5}	3.7	7.0	12.8	15.1	20.6

100,000	1×10^{-5}	3.9	7.4	14.1	16.7	22.7

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