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SUBJECT: Forwards response to NRC 821018 request for addl info re tornado-protected means of providing steam generator cooling water.Portions of response discussed during 821116 telcon.

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November 19, 1982

Mr. Harold R. Denton, Director
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Attention: Mr. John F. Stolz, Chief
Operating Reactors Branch No. 4

Subject: Oconee Nuclear Station
Docket Nos. 50-269, -270, -287

Dear Sir:

By letter dated October 18, 1982, the NRC requested additional information concerning a tornado protected means of providing steam generator cooling water. The response to this request is attached. Portions of this response were discussed during a telephone conference call with the NRC on November 16, 1982.

Very truly yours,

Hal B. Tucker

Hal B. Tucker

RLG/php
Attachment

cc: Mr. James P. O'Reilly, Regional Administrator
U. S. Nuclear Regulatory Commission
Region II
101 Marietta Street, Suite 3100
Atlanta, Georgia 30303

Mr. Philip C. Wagner
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Mr. W. T. Orders
NRC Resident Inspector
Oconee Nuclear Station

A001

Duke Power Company
Oconee Nuclear Station

Response to NRC Request for Information
Tornado Protected Means of Providing Steam Generator Cooling Water

1. You state that the bounding evaluation of the frequency at which a tornado might be expected to damage the EFWS and the SSF ASWS piping and controls, where they enter the reactor building through the west penetration room, showed that the frequency of occurrence is no higher than approximately 7.5×10^{-5}/yr. for any particular Oconee unit.

   Provide a description of the methodology, assumptions, modeling and error bounds of your analysis.

Response

In order to estimate the frequencies of tornados that could damage both the emergency feedwater system (EFWS) and the Standby Shutdown Facility auxiliary service water system (SSFASWS) the following steps were performed:

1. identification of critical plant areas in which the EFWS and SSFASWS could be exposed to damage due to tornado winds;

2. determination of which minimum sets of these areas must be exposed to tornado winds simultaneously in order to defeat the function of both the EFWS and the SSFASWS;

3. identification of the paths a tornado could follow to damage those areas;

4. determination of the frequencies of tornados following those paths whose velocities exceed the building design criteria; and

5. estimation of the conditional probabilities that, given tornado wind exposure, critical equipment would be damaged.

The following assumptions were made relative to the steps listed above:

1. The west penetration room is vulnerable to tornados that produce wind loadings normal to its west or north walls; this is the only critical area for the SSFASWS.

2. The EFWS is vulnerable to tornados resulting in damage to either the east and west penetration rooms or the Turbine Building.

3. The Turbine Building is subject to damage from any tornado producing winds in excess of 95 mph; damage to the Turbine Building is assumed to result in failure of the EFWS.

4. Because the penetration rooms are relatively small with respect to the area of their exposed walls, EFWS and SSFASWS equipment located in them are assumed to fail when the walls fail.

5. Because the tornados typically rotate counter-clockwise in this region, the west penetration rooms are exposed to tornados originating from compass points S through N; the east penetration rooms are exposed to tornados originating from compass points N through S (see Figure 1).

The tornado frequencies were obtained from data tabulated by the National Severe Storms Forecast Center for the area within 50 nautical miles of Clemson, South Carolina for the thirty-year period, 1950-1980 (copy attached).

In light of the assumptions outlined above, it can be seen that damage to the east penetration room is not relevant, since the EFWS is assumed to fail when the Turbine Building is damaged. Therefore, the frequency at which the EFWS and SSFASWS are damaged for any unit is equivalent to the frequency at which that unit's west penetration room is struck by a tornado. As suggested by Thom (see attachment), the frequency at which a tornado will strike a point can be expressed as the following:

$$P = \frac{zt}{A}$$

where z = tornado path area

A = geographical area for which tornado data are collected

t = frequency of tornados occurring in area A

Because the targets presented by an Oconee unit and by the site are not negligible compared to the width of a tornado, the value of z must be increased to account for these targets. This is done as follows:

$$z = L \cdot W + L \cdot D$$

where L = path length

W = path width

D = equivalent target diameter

For a single Oconee unit, D is taken as the length of a west penetration room wall, approximately 50 feet. For a tornado striking any of the three Oconee units, D is taken as the distance from the north end of the Oconee 1 west penetration room to the south end of the Oconee 3 west penetration room, approximately 470 feet.

The tabulated data indicate that there are no tornados originating from compass points N, NE, E and SE. Thus, direction of origin is not a factor affecting the frequency of tornados of interest. The tornado wind speeds are tabulated according to F-scale. The break point in this scale corresponding most closely to the design value of 95 mph is at $F \geq 2$, wind speeds of $\gtrsim$ 113 mph, and damage indicated as "considerable".

Calculation of mean damage areas:

from the data for tornados with F $\geq$ 2,

$$I = 8.0 \text{ mi}, \overline{L \cdot W} = 0.687 \text{ mi}^2$$

the mean damage area for a single unit is

$$\overline{z} = \overline{L \cdot W} + \overline{L} \cdot D, \; D = 50 \text{ ft}$$

$$\overline{z} = 0.763 \text{ mi}^2$$

the mean damage area for the station, D = 470 ft, is

$$\overline{z} = 1.40 \text{ mi}^2$$

Calculation of mean regional tornado frequency:

there were 33 tornados recorded in 30 yr, $\therefore$

$$\overline{t} = \frac{33}{30} = 1.1 \text{ tornados/yr}$$

Calculation of mean tornado strike frequency:

$$\overline{P} = \frac{\overline{z}\,\overline{t}}{A} \qquad A = \text{area of 50 NM radius circle}$$

for a single Oconee unit,

$$\overline{P} = \frac{(0.763 \text{ mi}^2)(1.1)}{\pi(50 \text{ NM} \cdot 1.15 \text{ mi/NM})^2}$$

$$= 8.1 \times 10^{-5}/\text{yr}$$

for any one or more units,

$$\overline{P} = 1.5 \times 10^{-4}/\text{yr}$$

Uncertainty bounds are estimated by calculating the variances for each of the parameters and combining them using the method of moments. Assuming, as suggested by Thom, that the resultant probability distribution is approximately lognormal in shape, the following bounds are obtained:

$$P_{05} = 1.7 \times 10^{-6}/\text{reactor-year}, \; 4.2 \times 10^{-6}/\text{station-year}$$

$$P_{50} = 2.3 \times 10^{-5}/\text{reactor-year}, \; 4.9 \times 10^{-5}/\text{station-year}$$

$$P_{95} = 3.1 \times 10^{-4}/\text{reactor-year}, \; 5.7 \times 10^{-4}/\text{station-year}$$

$$\overline{P} = 8.1 \times 10^{-5}/\text{reactor-year}, \; 1.5 \times 10^{-4}/\text{station-year}$$

Conservatisms

It was assumed that the capacity of the Auxiliary Building walls is nominally 95 mph. However, this is the design value for a continuous wind loading. The walls could be expected to withstand greater momentary loading under tornado conditions. A higher threshold wind speed would reduce the tornado occurrence frequency.

It was also assumed that damage to the penetration room walls and to the Turbine Building is certain to cause system failures. However, the equipment could escape damage despite wall failures, since the building frames are substantially stronger. In addition, most EFWS equipment is located in the Turbine Building basement, affording substantial protection from tornado wind effects.

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2. [The NRC requests the] results of an analysis which demonstrates that adequate decay heat removal can be continuously maintained through the use of the existing auxiliary service water system, and that such a cool-down method will not result in an accidental overpressurization of the auxiliary service water system or the excessive loss of reactor coolant.

Response

In view of the low likelihood of occurrence of a tornado which would result in damage to the west penetration room, and the multiple sources of steam generator cooling water available, Duke respectfully declines to respond to this item.

TORNADOES WITHIN 50. NM OF CLEMSON SOUTH CAROLINA

YR	MO	DAY	TIME CST	STATE	SEQ	SEG	LAT BEGIN	LON BEGIN	LAT END	LON END	LENGTH 10THS MI	WIDTH FEET	DEATHS	INJURIES	DAMAGE CLASS	F	P	P	AZRAN
52	2	29	1900	GA	7	1	3424	8320	3425	8312	100	230	0	0	4	2	2	2	227./ 22.
52	2	29	1930	GA	8	1	3422	8335	3422	8325	100	900	0	3	5	2	3	3	232./ 43.
52	5	10	1400	SC	1	1	3448	8215	3448	8208	60	250	0	0	1	3	3	2	90./ 22.
52	5	10	1415	SC	1	2	3448	8208	3448	8151	170	250	2	4	1	3			90./ 38.
54	3	31	1515	GA	6	1	3407	8314	3409	8304	100	600	0	5	5	2	3	3	202./ 44.
54	3	31	1525	GA	6	2	3409	8304	3410	8250	80	600	0	20	5	2			197./ 40.
54	7	4	1400	GA	11	1	3426	8307	0	0	1	2400	0	0	3	1	-	4	206./ 25.
55	6	23	1400	SC	4	1	3430	8240	0	0	2	70	0	0	3	0	-	1	147./ 21.
56	4	6	1230	SC	2	1	3408	8223	3412	8220	50	300	0	1	5	2	2	2	147./ 48.
56	8	13	1515	SC	5	1	3435	8237	0	0	3	250	0	0	3	1	0	2	132./ 19.
59	9	6	1345	SC	3	1	3437	8218	0	0			0	0	0	0	-	0	110./ 32.
61	7	16	1530	GA	37	1	3428	8318	0	0	9	130	0	0	4	1	0	1	225./ 28.
61	8	18	1930	SC	10	1	3443	8247	0	0		100	0	0	3	1	0	1	131./ 8.
63	8	13	1720	SC	5	1	3420	8223	0	0	20	30	0	0	3	1	1	0	136./ 38.
64	4	28	1730	SC	5	1	3453	8200	0	0			0	0	1	0	0	1	84./ 45.
64	4	28	1830	SC	6	1	3503	8206	0	0			0	0	1				65./ 42.
64	12	24	2330	SC	21	1	3456	8214	0	0	2	50	0	0	1	0	-	0	71./ 34.
65	1	10	815	NC	1	1	3504	8342	0	0			0	0	3	1	0	0	292./ 42.
66	5	1	1430	GA	8	1	3412	8334	0	0	10	150	0	0	4	2	1	1	223./ 49.
66	12	10	330	GA	21	1	3435	8320	0	0	5	1500	0	0	3	2	0	3	235./ 25.
67	5	15	1230	GA	12	1	3442	8340	0	0	5	100	0	0	4	1	0	1	261./ 38.
67	5	2	1810	SC	4	1	3450	8225	0	0	10	200	0	0	4	2	1	2	85./ 24.
67	7	12	1700	SC	8	1	3450	8222	0	0	1	80	0	0	4	0	-	0	86./ 26.
68	11	17	1616	GA	19	1	3412	8314	0	0	26	150	0	0	4	1	1	1	205./ 40.
68	3	22	1630	SC	2	1	3438	8230	0	0	3	40	0	0	3	1	0	0	117./ 22.
68	3	22	1730	SC	3	1	3501	8158	0	0	5	40	0	0	3	1	0	0	74./ 48.
69	8	15	1419	SC	8	1	3451	8215	0	0			0	0	1	0	0	0	85./ 32.
69	8	15	1419	SC	8	1	3451	8215	0	0			0	0	1	0	0	0	85./ 32.
69	8	15	1426	SC	9	1	3451	8215	0	0			0	0	1	0	0	0	85./ 32.
70	4	2	540	GA	8	1	3418	8256	3421	8252	50	300	0	2	4	2	1	2	183./ 30.
70	4	9	1645	GA	9	1	3418	8308	3419	8306	30	1200	0	0	5	3	1	3	201./ 32.
71	1	30	1635	GA	12	1	3434	8325	0	0	5	80	0	6	4	1	0	1	241./ 29.
71	7	19	1100	GA	44	1	3406	8254	0	0	1	150	0	0	4	1	-	1	180./ 42.
72	3	2	1500	GA	18	1	3400	8247	3407	8246	80	1200	0	0	5	1	2	3	173./ 48.
73	5	27	1730	GA	14	1	3450	8320	0	0		150	0	0	4	1	0	1	275./ 21.
73	5	28	130	GA	18	1	3419	8313	0	0	10	120	0	0	5	1	1	1	208./ 33.
73	11	21	830	GA	24	1	3434	8317	0	0			0	0	4	2	0	2	234./ 24.
73	3	31	1900	SC	1	1	3446	8237	3452	8226	110	300	0	0	4	2	3	2	98./ 14.
73	3	31	1820	SC	2	1	3405	8234	3415	8217	210	600	7	20	6	4	3	3	155./ 46.
73	3	31	1900	SC	2	2	3415	8217	3416	8215	20	600	0	0	6	4			137./ 45.
73	5	27	1720	SC	8	1	3446	8226	3455	8213	150	300	0	17	6	3	3	2	95./ 23.
73	5	27	1730	SC	8	2	3455	8213	3500	8203	130	450	0	16	6	3			71./ 34.
73	5	27	1820	SC	8	3	3500	8203	3510	8146	210	300	0	4	6	3			74./ 44.
73	5	27	1930	SC	9	1	3448	8317	3457	8256	230	600	0	1	5	2	3	3	270./ 19.
73	5	27	2130	SC	10	1	3452	8259	0	0	10	300	0	0	4	2	1	2	314./ 6.
73	5	27	1930	SC	11	1	3418	8231	3424	8221	160	300	0	7	5	2	1	2	148./ 36.
73	5	27	2100	SC	12	1	3453	8247	3459	8223	250	450	0	0	4	2	2	2	45./ 8.
73	5	28	1530	SC	13	1	3448	8225	0	0	5	270	0	0	3	1	0	2	90./ 24.
73	11	21	910	SC	17	1	3429	8235	0	0	3	150	0	0	4	2	0	1	147./ 23.
73	12	13	1410	SC	18	1	3416	8210	3410	8203	70	600	0	2	6	3	3	3	131./ 48.
74	4	3	2000	GA	17	1	3458	8323	0	0	3	60	0	0	5	2	0	0	293./ 26.
74	4	3	1500	NC	5	1	3507	8250	0	0	10	90	0	0	4	1	1	1	10./ 19.
74	12	25	355	NC	22	1	3502	8348	3503	8340	90	50	0	0	4	1	2	1	288./ 46.
74	12	25	420	NC	22	2	3503	8340	3504	8337	40	50	0	0	4	1			292./ 41.
74	4	8	1533	SC	6	1	3425	8245	0	0	10	300	0	0	3	3	1	2	162./ 24.

YR	MO	DAY	TIME CST	STATE	SEQ	SEG	LAT BEGIN	LON BEGIN	LAT END	LON END	LENGTH 10THS MI	WIDTH FEET	DEATHS	INJURIES	DAMAGE CLASS	F	P	P	AZRAN
74	4	8	1600	SC	7	1	3424	8245	0	0	2	270	0	0	3	1	0	2	162./ 25.
75	1	10	2030	NC	1	1	3509	8250	3512	8248	30	60	0	0	4	2	1	1	[illegible]./ 21.
75	3	12	1430	NC	3	1	3522	8309	0	0			0	0	2	0	-	0	240./ 26.
75	10	17	735	NC	31	1	3524	8234	0	0	1	60	0	0	3	1	-	1	24./ 40.
75	3	24	925	SC	2	1	3457	8233	3458	8231	20	600	0	0	1	1	1	3	62./ 19.
75	3	24	930	SC	2	2	3458	8231	3500	8223	100	600	0	5	5	1			62./ 21.
76	5	14	2100	GA	13	1	3415	8334	3415	8333	10	480	0	0	1	2	2	2	225./ 47.
76	5	14	2110	GA	13	2	3415	8333	3420	8330	60	400	0	2	5	2			224./ 46.
76	5	14	2115	GA	14	1	3428	8332	0	0	10	150	0	0	5	2	1	1	237./ 37.
76	2	18	1230	NC	1	1	3530	8315	0	0	20	120	0	0	5	1	0	1	338./ 45.
76	2	18	1305	NC	2	1	3532	8257	0	0	10	150	0	0	5	1	0	1	357./ 44.
76	2	18	1245	NC	3	1	3512	8328	3514	8325	40	150	0	0	5	1	1	1	311./ 37.
76	2	18	1335	NC	5	1	3533	8240	0	0	5	120	0	0	5	1	0	1	14./ 46.
76	2	18	1345	NC	6	1	3518	8223	0	0	60	90	0	0	5	1	1	1	40./ 39.
76	6	28	1830	NC	14	1	3519	8310	0	0	2	30	0	0	5	2	-	0	337./ 34.
76	7	29	1600	NC	17	1	3513	8322	0	0	15		0	0	3	1	1	1	318./ 34.
76	6	19	1630	SC	12	1	3502	8158	0	0	2	150	0	0	2	1	-	1	73./ 48.
77	9	7	1440	GA	16	1	3435	8315	0	0	10	300	0	0	5	1	1	2	238./ 24.
77	11	5	1900	GA	17	1	3435	8319	0	0	2	300	0	0	2	1	0	2	238./ 24.
77	8	17	1120	NC	23	1	3523	8222	3519	8218	100	150	0	0	4	1	3	1	37./ 44.
77	8	17	1136	NC	23	2	3519	8218	3515	8215			0	0	4	1			44./ 43.
77	5	8	1740	SC	4	1	3431	8158	0	0	15	150	0	5	5	1	0	1	110./ 49.
77	9	7	1400	SC	7	1	3505	8207	0	0	3	230	0	0	4	1	0	2	68./ 42.
77	12	5	1020	SC	8	1	3445	8241	0	0	10	150	0	0	5	1	1	2	108./ 11.
79	3	23	1720	GA	2	1	3437	8331	3439	8325	110	180	0	1	5	1	1	2	250./ 32.
79	9	13	1700	GA	17	1	3434	8333	0	0	10	150	0	0	4	0	1	1	246./ 35.
79	3	23	1530	SC	1	1	3451	8224	0	0	1	230	0	2	6	2	-	2	83./ 25.
80	4	13	1645	GA	14	1	3400	8306	3402	8303	250	300	0	0	4	1	3	1	192./ 49.
80	4	13	1655	GA	14	2	3402	8303	3406	8300			0	0	4	1			185./ 47.
80	4	13	1705	GA	14	3	3406	8300	3415	8245			0	1	4	1			187./ 42.
80	6	16	1905	GA	29	1	3418	8338	0	0	1	80	0	0	2	1	-	1	231./ 47.
80	7	24	1830	GA	31	1	3406	8252	0	0	1	60	0	0	3	1	-	1	178./ 42.
80	4	13	1750	SC	2	1	3423	8245	3434	8225	200	600	0	5	6	2	2	3	164./ 26.
80	4	13	1758	SC	2	2	3434	8225	3443	8222			0	0	6	2			120./ 28.

NATIONAL SEVERE STORMS FORECAST CENTER
TORNADO DATA

The enclosed tornado listing provides information on all reported tornadoes in the area indicated from 1950 through 1980. The
various entries and tables are explained below. If you have additional questions, please write or call the National Severe
Storms Forecast Center, Room 1728, 601 E. 12th St., Kansas City, Mo. 64106, phone (816) 374-3427.

The item-by-item listing shows they year, month, date and time of occurrence of each tornado in Central Standard Time.

The column labeled SEQ and SEG indicate the sequence number and segment number of each tornado. Sequence numbers are assigned
chronologically within each state. The first tornado in 1973 in Ohio is given sequence number 1 for the state of Ohio that
year. Many tornadoes have more than one touchdown point, that is they may touchdown again. These tornadoes are broken down
into segments and the segments are indicated by segment numbers. For a tornado with 3 segments the sequence number stays the
same but the segment number is different for each separate touchdown. The statistics in the tables are based only on the
initial touchdown points.

The Latitude and Longitude of the beginning and ending points of each tornado are shown followed by the overall length and
width. Deaths and injuries for each segment are listed, followed by Damage Class. Damage Class numbers range from 1 to 9 and
provide an estimate of the damage according to the table (#1) below.

The columns labeled FPP provide the Fujita-Pearson scale estimates of Force, Path Length and Path Width. All three scales are
logarithmetic with values ranging from -1 for the smallest category to +5 for the largest.

the following table (#2) shows the range in each scale. The Path Length and the Path Width values represent estimates as to
the actual amount of ground contact for each tornado. For instance, if a tornado had an overall length of 45 miles but made
actual ground contact only 60 percent of the time the Path Length scale value would be a 3.

The AZRAN column indicates the azimuth and range from the center point. 129/83 indicates the tornado touchdown was 129 degrees
(southeast) at 83 nautical miles from the center point.

A circular plot of tornado touchdown points is enclosed. The city of interest is at the center of the plot, north is at the top,
east at the right hand side, etc. Each digit represents the number of touchdowns in a small square area, about 2 miles on a
side. Thus, what might be plotted as 21 actually represents 2 touchdowns in one square and 1 touchdown in the adjacent square.

The four frequency tables provide detailed information about the time of day, time of year and length and width characteristics
of tornadoes in the area of interest.

The Path Width vs Path Length table is computed from the Pl and Pw data. Also, the mean path length and mean path areas are
computed from the Pl and Pw data. When the length and width scale values are converted back to length and width figures the
minimum values in each range are used. For example, a Pl value of 3 is converted to a length of 10 miles in the calculation.

The monthly and hourly distribution tables indicate the favored times of day and year for tornadoes in each area. Monthly and
hourly percentages are shown on the hourly distribution table. Mean times are shown for each month and for the entire year.
These times should be interpreted and used in conjunction with the hourly percentages in examining the diurnal trend of
tornadoes. All times in these tables are Central Standard Time.

The latitude and longitude of the center point of the search program is listed at the upper right hand side of the Hourly
Distribution Table. Thes figures are in degrees and hundredths. The map scale used in the circular plot is compatible with
the WSR 57 radar map, 125 nautical range.

Table #1 (DAMAGE CLASS)

1	Less than $50
2	$50 to $500
3	$500 to $5,000
4	$5,000 to $50,000
5	$50,000 to $500,000
6	$500,000 to $5 million
7	$5 Million to $50 Million
8	$50 Million to $500 Million

table #2 (FPP SCALE)

SCALE	F (mph)	DAMAGE	Pl (miles)	Pw (width)
-1	Less than 40	(little or no damage)	Less than .3	Less than 6
0	40-72	Light	0.3-1.0	6-17 yards
1	73-112	Moderate	1.0-3.1	18-55 yards
2	113-157	Considerable	3.2-9.9	56-175 yards
3	158-206	Severe	10-31	176-556 yards
4	207-260	Devastating	32-99	0.3-0.9 miles
5	261-318	Incredible	100-315	1.0-3.1 miles

TORNADO PROBABILITIES

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ABSTRACT

The frequency distributions of tornado path width and length are developed using data series from Iowa and Kansas. From these, the distribution of path area is derived. Direction of path and annual frequency are discussed. It is found that all but about 1 percent of Iowa tornadoes had path directions toward the northeast and southeast quadrants. The annual frequency for a group of Iowa counties is found to have a negative binomial distribution indicating that the climatological series is formed from a Polya stochastic process. This resembles the situation for other types of storms where the events tend to cluster. A new map of annual frequency for the United States is presented for the period 1953–62, during which it is believed tornado observation was fairly stable. The expected value of tornado area is derived from the area distribution. From this and the annual frequency, the probability of a tornado striking a point is found.

1. INTRODUCTION

There have been a large number of studies of tornado climatology, most of which have been simply counts of tornadoes for various areas and time periods. Asp [1] lists 78 references, a few of which are not climatological in nature; not all references have been listed. Many of these studies have recognized the possible incompleteness of the frequency series and the difficulties of observation, but little could be done to correct this deficiency. So far as is known, none of these studies made a direct attack on the problem of tornado probability, which is the object of the present study.

In 1945, William F. Kuffel, then of the Dubuque Fire Marine Insurance Company, asked the writer to develop a system of limiting the loss from a single tornado in a given region for the purpose of preventing liabilities from exceeding reserve funds. This resulted in a limited study for several Iowa counties [2] in which the direction frequency and path length and width distributions were discussed. From this, a directed standard path was devised within whose bounds the insured liability could be totaled. If this exceeded a certain limit related to the reserves of the company, the excess could be reinsured with other companies. It should be noted that the occurrence of more than one tornado in the region is still to be taken care of by the ordinary risk of the business which is not well defined in this type of insurance coverage.

By 1957, these ideas had developed further [3], and after mathematical distributions were fitted to the path length and width it was possible to determine the probability of a tornado striking a point. There still remained a bothersome correlation between path length and width which was not easily taken into account in the area distribution. This prevented obtaining a complete solution to the distribution problem. In 1958, Battan [4] presented a simple frequency diagram of path length, but his objective was to study the duration of a tornado, not its probability of occurrence.

In the present study, we introduce distribution theory which provides a better fit to the basic data and makes possible a more satisfactory solution to the area distribution problem. The distribution of annual frequency is also discussed and several comparisons of data are made, together with a number of statistical tests for homogeneity.

2. PATH LENGTH AND WIDTH DISTRIBUTIONS

Since path width and length cannot be negative, zero must be the lower bound of any distribution assumed, although this need not be a greatest lower bound. As with a number of other physical variables, where the true bound is certainly near zero, but cannot be established to be different from zero, it has proven convenient to assume that the distribution has a zero lower bound. Also, in this instance, it would appear that both variables should have a probability density of zero at the origin, for as the path length and width approach their greatest lower bounds, the probability density should approach zero.

In previous studies [3], a gamma distribution was assumed. While it has a zero bound, it need not have a zero probability density at the origin. When fitted to length and width data, both variables gave shape parameter estimates which indicated non-zero densities at the origin. Furthermore, with this function the distribution of area becomes intractable, and above all, the distribution did not fit the data series particularly well.

listribution meets all the above theo-
s: It may have a zero bound, its
is zero at the origin, and the distribu-
of area is simply a convolution of the logarithmic
ibutions of path length and width, the correlation
een them entering quite naturally.

t x be the path length in miles, and w be the path
h in yards; then, transforming to logarithms, we have

$$y=\ln x, \tag{1}$$

$$u=\ln w. \tag{2}$$

inversely

$$x=e^{y}, \tag{3}$$

$$w=e^{u}. \tag{4}$$

$\alpha_1(\ )$ and $\sigma^2(\ )$ be the mean and variance operators
ectively. Then, if y is normally distributed, the
ibution of x is log-normal, i.e.,

$$L(x)=\frac{1}{x\sigma(y)\sqrt{2\pi}}\exp\left\{-\frac{1}{2\sigma^2(y)}[\ln x-\alpha_1(y)]^2\right\}dx \tag{5}$$

e $L(x)$ is the distribution function or cumulative
ibution. Similarly, for w

$$f(w)=\frac{1}{w\sigma(u)\sqrt{2\pi}}\exp\left\{-\frac{1}{2\sigma^2(u)}[\ln w-\alpha_1(u)]^2\right\}dw. \tag{6}$$

is well known that the mean and variance estimated
he usual fashion are jointly sufficient statistics for
ating $\alpha_1(y)$, $\alpha_1(u)$, $\sigma^2(y)$, and $\sigma^2(u)$. Since functions
fficient statistics are also sufficient, the optimum
erty holds for the transformed sample given by equa-
(3) and (4). Hence, we may work in the logarithms
forming back after estimation is completed.

ree sets of data were analyzed with distributions
nd (6): Iowa tornadoes for the period 1937–56, Iowa
does for the period 1953–62, a kind of standard
d to be discussed later, and Kansas tornadoes for
standard period. Tornadoes with paths longer than
mi. and paths wider than 1000 yd. were rejected as
tful observations. The relative frequency of these
all and, if included, would have little effect on the
ibutions considering the accuracy of the observations.
fits to the path length are all excellent, none of the
distributions having an absolute departure signifi-
at the 0.05 level on the Kolmogorov-Smirnov distri-
n. The fits to the path width are also good, there
no absolute departure significant at the 0.01 level.
somewhat greater precision of the path length obser-
ns was to be expected since the path width is more
ult to estimate.

e sample means and standard deviations are shown in
1. Since all of the distribution fits were very good,
s decided to show only those for the Iowa 1953–62

Table 1.—*Path statistics (logarithms)*

	Path Length		Path Width	
	$\bar{y}$	$s(y)$	$\bar{u}$	$s(u)$
Iowa 1937-56	1.99	1.25	5.41	1.01
Iowa 1953-62	1.42	1.43	5.15	0.91
Kansas 1953-62	1.32	1.44	4.92	1.12
Means 1953-62	1.37	1.43	5.04	1.02

record which consisted of 106 observations of path length and 103 observations of path width. These samples were large enough to confuse the plotting, so only the middle point of each series of repeated values was plotted on figures 1 and 2. While this might seem to make the fit appear better, this criticism can not be important because the fits were shown to be good by the significance test. The theoretical lines on the graphs were obtained from the statistics for Iowa 1953–62 in table 1.

The variance of the three records of table 1 were compared by Bartlett's test and no significant difference at the 0.05 level was found for either path length or width. However, an analysis of variance on the three records showed significant differences in the means for both path length and width. Since this could be due to poorer observing during the 1937–52 period, it was decided to discard the earlier record for present purposes. t–tests on the Iowa and Kansas means for the 1953–62 record then showed no significant difference at the 0.05 level for either path length or width. An F–test on the variances for path length showed no significant difference at the 0.05 level as the variances are nearly identical. The variances for path width, however, tested significantly different. Inasmuch as the difference is small and the number of degrees of freedom large (103 and 125), and considering the accuracy of the observations, it was decided to average the variances as if they, like the means, were from the same population. The resulting means and standard deviations of path length and width are shown at the foot of table 1.

Although expected superiority of path width and length observations over frequency observations was the basis for the study, it was a surprise to the writer to find an apparently crude observational technique producing such a remarkable agreement between data for Iowa and Kansas. It should not be forgotten, however, that the observational technique still may be biased and methods should be devised for testing this. Data from other areas should also be analyzed to determine whether the tornado characteristics presented here are invariant over larger areas or possibly physically invariant.

3. THE DISTRIBUTION OF PATH AREA

The convolution of the distributions of the logarithms is the transformed distribution of the product. Thus, the distribution of $y+u=v$ is the transformed distribution of

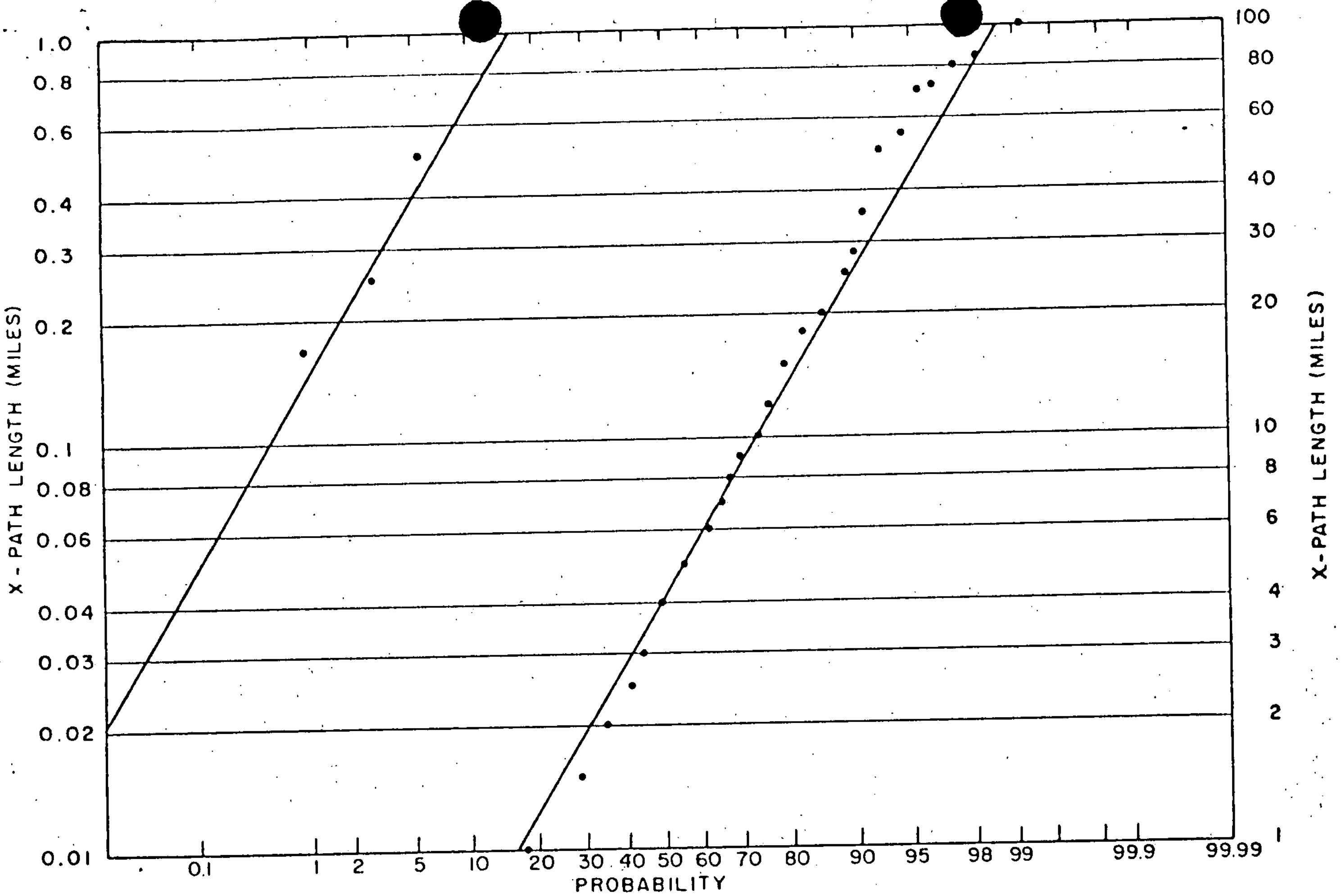

FIGURE 1.—Distribution of path length for Iowa tornadoes during 1953–62.

$xw=z$, the path length times the path width, or the tornado path area in yard-miles. The equations of transformation are similar to those of path length and width, i.e.,

$$v=\ln z \tag{7}$$

and

$$z=e^v.$$

Since y and u are normally distributed, their sum v is also normally distributed, and z has the log-normal distribution

$$dQ(z)=\frac{1}{z\sigma(v)\sqrt{2\pi}}\exp\left\{-\frac{1}{2\sigma^2(v)}[\log v-\alpha_1(v)]^2\right\}dz. \tag{8}$$

The value of $\alpha_1(v)$ is given easily by the sum of the means of y and u or

$$\alpha_1(v)=\alpha_1(y)+\alpha_1(u) \tag{9}$$

The variance of v is more complicated because the path length and path width are positively correlated. This introduces a covariance term and the variance is then

$$\sigma^2(v)=\sigma^2(y)+\sigma^2(u)+2\rho(y,u)\sigma(y)\sigma(u), \tag{10}$$

where $\rho(y, u)$ is the correlation between the logarithm of path length and width. The correlation coefficient between 96 pairs of path lengths and widths for Iowa was found to be 0.39. Inasmuch as the correlation would be expected to vary less areally than the variances, we use this correlation coefficient with the average path length and width variances of table 1. This gives a sample path area variance of $s^2(v)=4.233$ and standard deviation $s(v)=2.057$. Substituting the sample means from table 1 in equation (9) gives $\bar{v}=6.41$.

We shall need to know the mean value of z. This is given by the expectation operator

$$E(z)=E[e^v] = \int_{-\infty}^{\infty} e^v dN(v) \tag{11}$$

where $N(v)$ is a normal distribution. By the moment generating properties of the normal distribution, (11) gives

$$E(z)=\exp\{\alpha_1(v)+1/2\sigma^2(v)\} \tag{12}$$

It is interesting to note that although the expected value

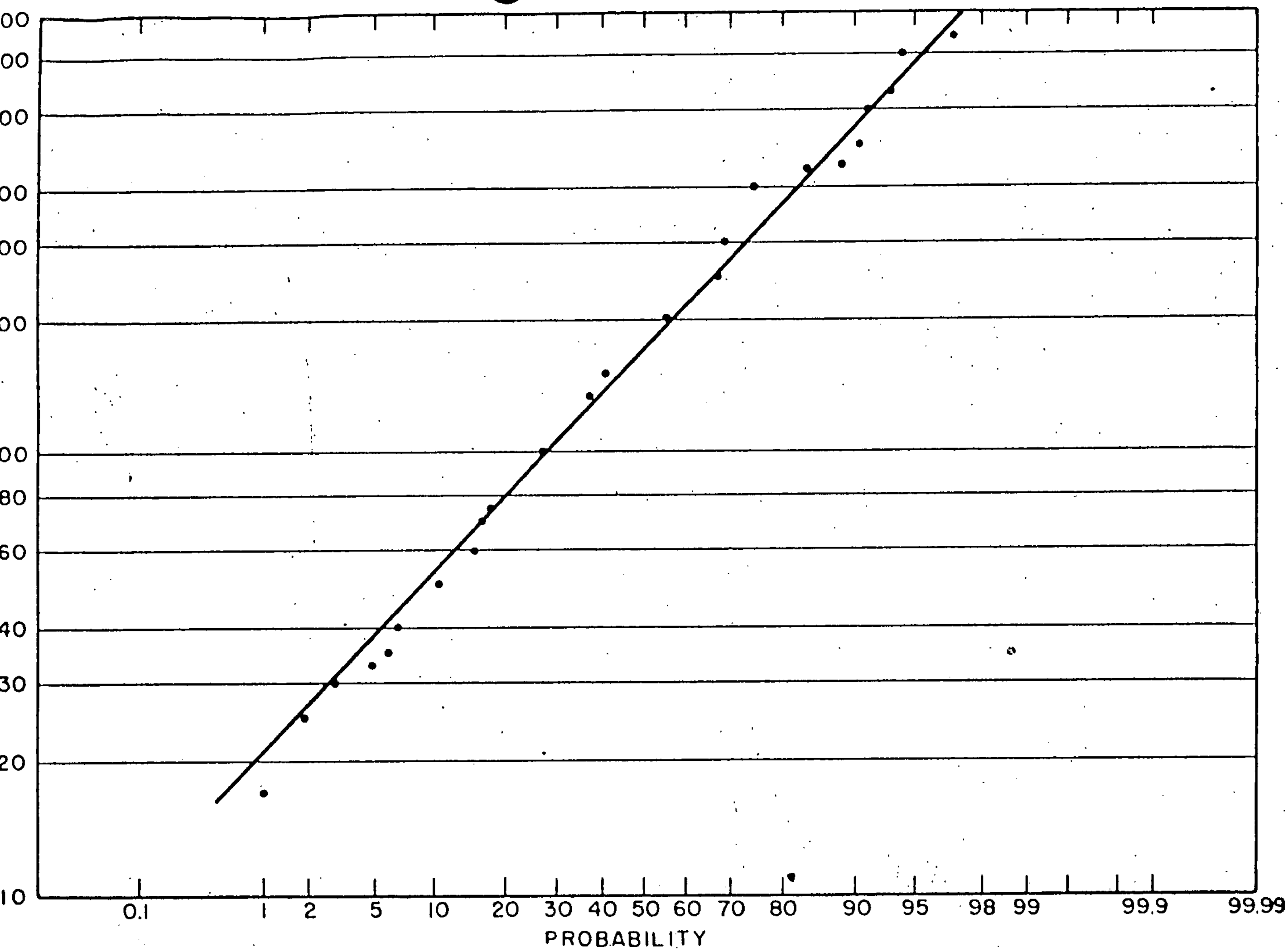

FIGURE 2.—Distribution of path width of Iowa tornadoes, 1953–62.

a product is not the product of the expectations when … factors are correlated, in case the factors have log-…mal distributions the adjustment for the correlation is … covariance term of equation (10) which defines the …ance term in (12).

…Substituting sample values $\bar{v}$ and $s^2(v)$ into equation …) gives a mean path area of 4964.8 mi. yd. Dividing …1760 gives 2.8209 mi.^{2}

4. DIRECTION AND ANNUAL FREQUENCY

It is well known that the preponderant direction of …nado movement is toward the northeast. Our findings …m a tabulation of 230 tornadoes in Iowa are in agree…nt with this. Table 2 shows the distribution by direc…s. It is seen in the table that about 63 percent of the …nadoes tabulated have path directions toward the …theast, while about 90 percent of them have an easterly …ponent in their paths. For practical purposes, it …ht be useful to assume that almost all tornadoes have …hs with a component toward the east.

We now consider the annual frequency of tornadoes for a central section of Iowa where it is believed that the population mean annual frequency was constant during the period 1916–56. This series consists of the data for Boone, Story, Marshall, Dallas, Polk, and Jasper Counties. To demonstrate the stability of annual frequency, we made a run test on the annual series. The number of runs of years with frequency of one and zero and those with frequency greater than one was 18, which is approximately at the median frequency. This value has a probability of 0.37 of being exceeded on the run distribution, and is therefore clearly not significant at the 0.05 level. The

TABLE 2.—*Tornado path direction-frequency*

Toward	NW	N	NE	E	SE	S	Total
Number	3	13	145	35	32	2	230
Percent	1.3	5.6	63.1	15.0	13.8	1.2	100

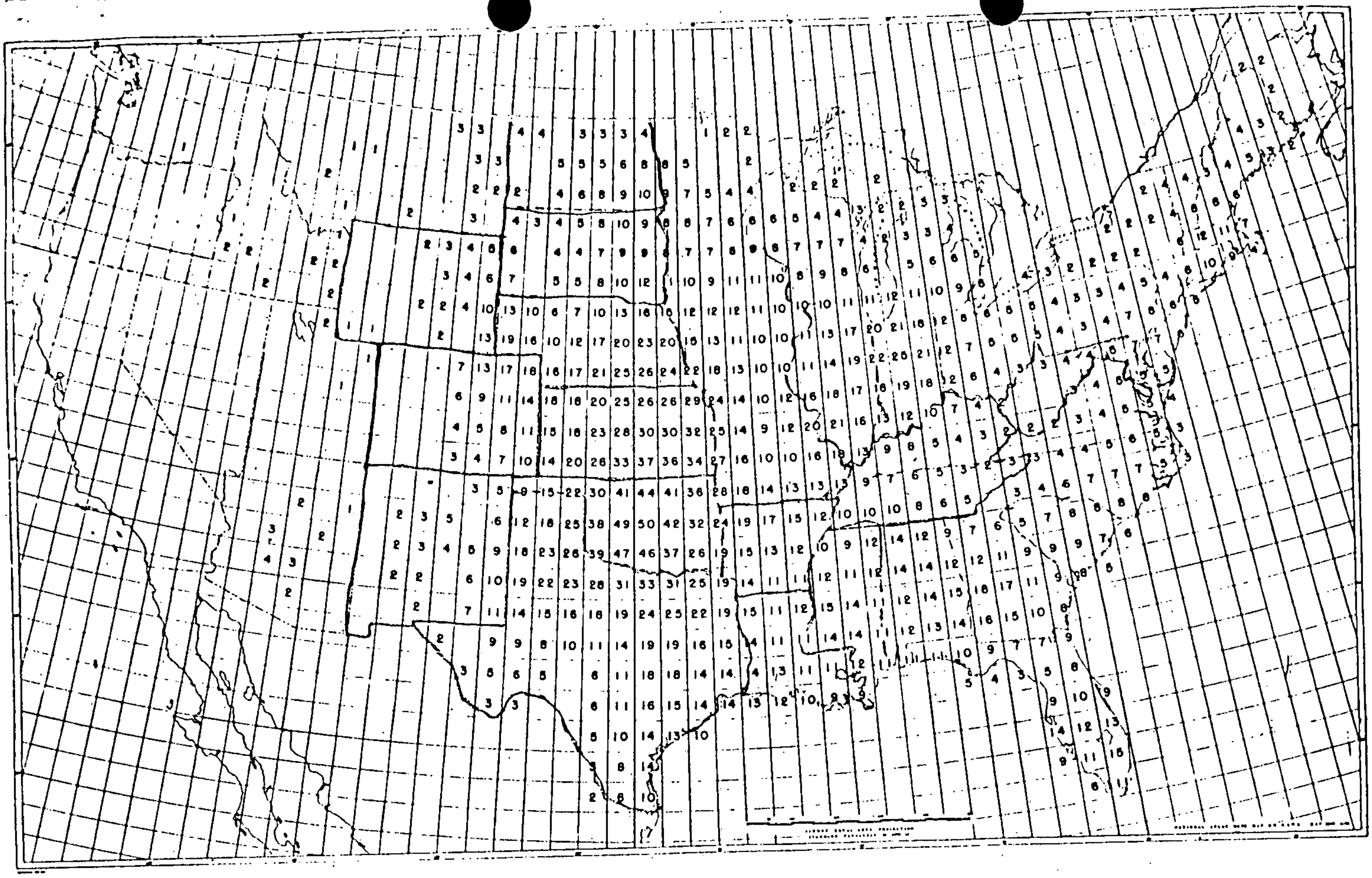

FIGURE 3.—Total frequency of tornadoes, 1953–62

annual frequency series for central Iowa may therefore be treated as a random series.

Since the annual tornado series is discrete, it would appear that some distribution such as that of the Poisson stochastic process would fit the annual frequencies. Poisson-related distributions and their criteria were discussed in [5] and [6]. As described in [6], Sukatme's test was applied to the central Iowa series and showed a probability of less than 0.0005, indicating a significant departure of the series from a Poisson distribution in the direction of a time clustering of tornado occurrences in the annual totals. Hence, the series is of the Polya type having a negative binomial distribution. The probabilities of this distribution are given by

$$f(t)=\frac{\Gamma(t+k)p^t}{\Gamma(t+1)\Gamma(k)(1+p)^{k+t}} \tag{13}$$

where p and k are parameters.

Application of Fisher's criterion as in [5] showed that the method of moments would not produce efficient estimates of p and k; hence, the method of maximum likelihood [6] had to be used. This produced estimates $\hat{p}=1.30$, $\hat{k}=1.06$, using $\bar{t}=1.37$. When these were substituted in equation (13) for various annual occurrences, probabilities at each t were obtained. When these in turn were multiplied by the total number of occurrences for the record, 41, the estimated annual frequency $\hat{g}$ for each t was obtained. This is shown in the comparative table, table 3. Here the observed value g_0 is compared to the estimated value $\hat{g}$. A χ^2-test showed the fit of the negative binomial distribution to be excellent, as is also clear from a comparison of g_0 and $\hat{g}$. As might have been expected, like other convectional storms [7], tornadoes tend to cluster within years and follow a Polya process rather than a Poisson process in areas where frequency of occurrence is high.

TABLE 3.—*Annual tornado frequencies—central Iowa*

t	g_0	$\hat{g}$
0	17	17.0
1	10	10.2
2	6	5.0
3	4	3.4
4	2	2.0
5	0	1.2
6	1	0.7
7	0	0.4
8	1	0.2

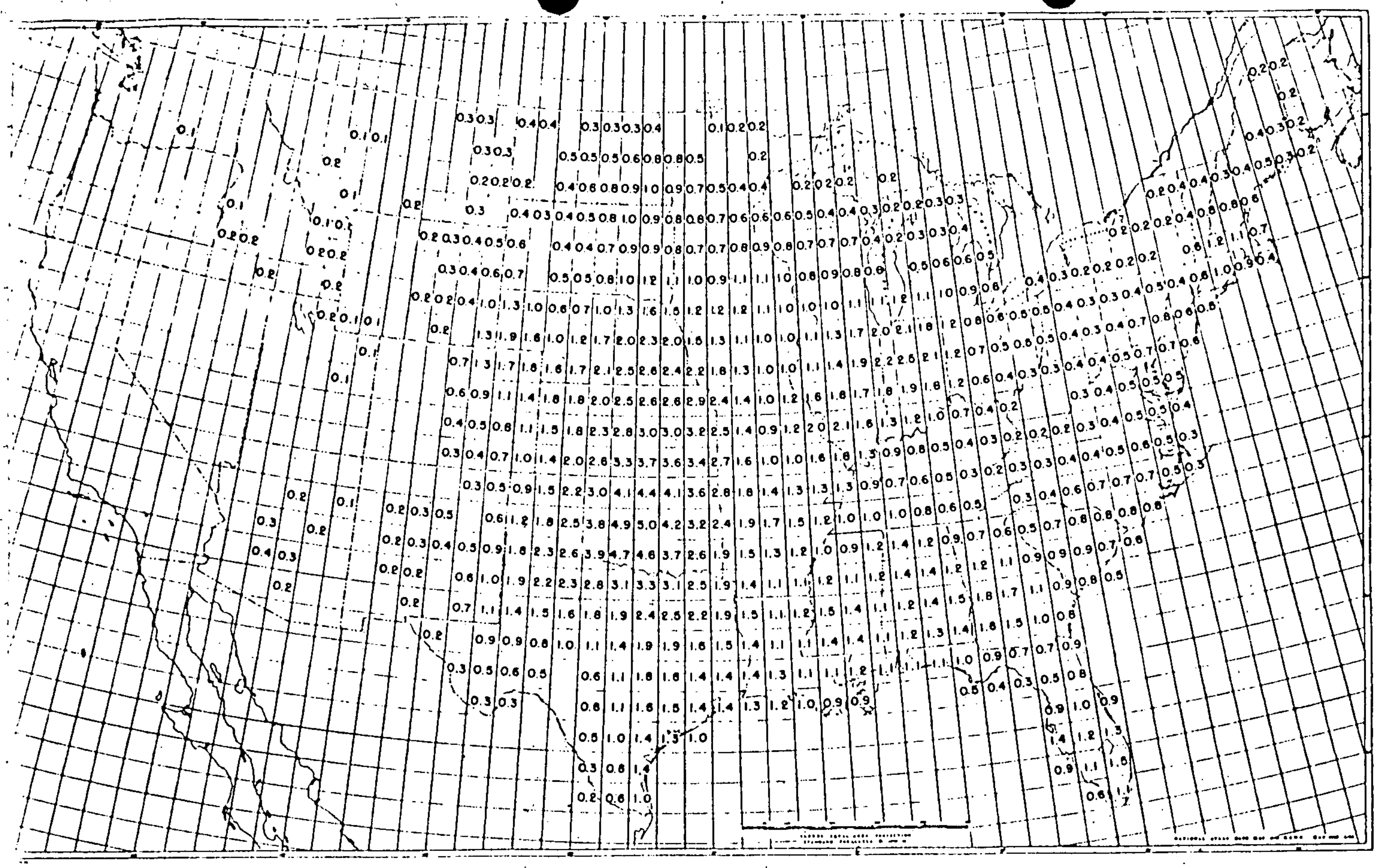

FIGURE 4.—Mean annual frequency of tornadoes, 1953–62.

5. TORNADO FREQUENCY IN THE UNITED STATES

When the interest in local severe storms in the Weather Bureau was heightened by the development of forecasting methods in the late 1940's, it was already fully realized that tornado observations were incomplete in many areas. Beginning in the early 1950's, efforts were made to make the observation of frequency more complete, and by 1953 it was thought that a large proportion of the tornadoes in the areas of high frequency was being reported.

The run test on the central Iowa Counties discussed above did not show a significant lack of runs in the 1916–36 period. This could be accounted for either by the fact that observing was already nearly exhaustive in this area, which appears to be a good possibility, or that not enough of the period after 1952 was included to show in the test.

We shall not go into this further at present, but rather make a test on the annual frequencies for the whole State of Iowa. The mean frequency for the period 1916–52 is 3.8 and the mean frequency for 1953–62 is 16.6. Since the samples are fairly large and the distributions not widely different from normal, the *t*-test may be used to test the difference in the means. There is one difficulty, however, which must be taken care of first. This is caused by the fact that an F-test showed the variances of the two periods to be different. Hence, it was necessary to correct for this, using Geary's method which resulted in a reduction of the degrees of freedom from the original $36+9=45$ to 24. Even this severe reduction in the degrees of freedom did not alter the test result; the difference between the mean frequencies of the two periods was not significant at the 0.10 level. This indicates that for the Iowa record the mean does not appear to have changed, but the variance has. Hence, in all probability there has been a change in the shape of the distribution.

It appears likely therefore that since there was a change in the Iowa record there was all the more change in other areas. Consequently, it seems desirable to prepare a United States map for the shorter more complete record for the period 1953–62 and thus, it is hoped, to avoid large biases at the expense of more moderate increases in standard errors.

Figure 3 shows a map of the total number of tornadoes occurring in 1° squares smoothed by Hann areal smoothing, i.e., smoothing in both the north–south and west–east directions with the Hann weights 0.25, 0.50, 0.25. Figure 4 shows the mean annual frequency of occurrence of tornadoes. This is needed in estimating probability of a tornado striking a point.

6. POINT PROBABILITY

For a number of applications the place where a tornado might strike may be approximated by a geometrical point, therefore the probability of a tornado striking a point is of interest. By the principles of geometrical probability the probability of a tornado striking a point is the ratio of the mean area covered by tornadoes per year to the area over which the tornadoes may occur. If we take the mean path area of a tornado to be $\bar{z}$ in square miles and the mean number of tornadoes per year to be $\bar{t}$, then the average area covered by tornadoes per year will be $\bar{t}\bar{z}$. If $\bar{z}$ and $\bar{t}$ are defined for 1° squares as $\bar{t}$ is in figure 4, then the mean probability P of a tornado striking a point in any year in a 1° square with $\bar{z}$, $\bar{t}$, and area A is

$$P=\frac{\bar{z}\bar{t}}{A} \tag{14}$$

If it is assumed further that $\bar{z}$ is invariant, we may substitute the value for $\bar{z}$ previously obtained and equation (14) becomes

$$P=\frac{2.8209\bar{t}}{A} \tag{15}$$

A may be found from geographical tables but for convenience we give in table 4 its value for each 5° for the range of latitude of the United States. Linear interpolation will suffice between the values.

For the square below Des Moines, Iowa, at latitude 40°30′, $\bar{t}=1.3$ and $A=3634$; hence $P=0.0010$. The mean recurrence interval for a tornado striking a point is $R=1/P$ or 1000 yr. for a point in this square.

TABLE 4.—*Areas of 1° squares (sq. mi.)*

	Latitude of middle of square					
	25°30′	30°30′	35°30′	40°30′	45°30′	50°30′
Area	4300	4109	3887	3634	3354	2983

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