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Frequency and Areal Distributions of Tropical Storm Rainfall in the United States Coastal Region on the Gulf of Mexico

SILVER SPRING, MARYLAND
JULY 1968

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ESSA TECHNICAL REPORT WB-7

Frequency and Areal Distributions of Tropical Storm Rainfall in the United States Coastal Region on the Gulf of Mexico

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SILVER SPRING, MARYLAND
JULY 1968

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ABSTRACT

The frequency and areal distributions of rainfall from tropical storms entering the Gulf Coast between Apalachicola, Fla., and Brownsville, Tex., were investigated. Forty-six well-developed storms during the 26-year period 1940–65 provided the basic data. The rainfall investigated was for the 48-hour period from 24 hours before landfall to 24 hours after.

The results of the investigation are presented on a series of charts showing the spatial distribution of 12-, 24-, and 48-hour rainfall up to 100 miles inland and within 150 miles on either side of the storm track. Another series shows distributions of 6- and 12-hour point rainfalls for the 2-, 10-, 25-, and 50-percent frequency levels in five 25-mile zones parallel to the coast and extending 125 miles on each side of the storm track.

Average rainfalls for 12-, 24-, and 48-hour periods show maximum values 25 to 50 miles to the right of the storm track. The first 24-hour period of rainfall indicates an offshore maximum, but the second shows a maximum 25–50 miles inland. The four 12-hour periods show a gradual inland movement of the center of maximum rainfall from offshore to 50–75 miles inland for the fourth period.

Irrespective of location, the most probable time of the maximum 6-hour point rainfall (29-percent probability) is during the 6 hours before landfall, and there is a 50-percent probability that it will occur within the 12-hour period from 6 hours before landfall to 6 hours after. Irrespective of time, there is a 7-percent probability that the maximum 6-hour rainfall will occur 25 to 50 miles to the right of the storm track and 25 to 50 miles inland. Combining probabilities of both time and space, there is a 21-percent probability that the maximum 6-hour point value will occur within the 12-hour period from 6 hours before to 6 hours after landfall and in a 75-mile square immediately to the right of and landward from point of landfall.

An area-point relation is provided for adjusting point rainfall values to average depths for areas up to 1,000 square miles.

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1. INTRODUCTION

1.1. *Purpose*

The principal purpose of this report is to provide basic rainfall data for the design and operation of public works for protection from tropical storms entering the United States from the Gulf of Mexico. The report presents data on the frequency and areal distribution of rainfall in tropical storms as they cross the coastline. These data are for the area within 125 to 150 miles of the storm track and cover rainfall distribution during the 48-hour period from 24 hours before to 24 hours after landfall. Subsection 1.2 gives more information on the aspects covered.

Cline (1926), among the first to map the distribution of hurricane rainfall, said that in a moving hurricane the rainfall is asymmetrically distributed, the heaviest amounts being in front (60 to 80 miles) and to the right of the storm center. Relatively little rain falls to the rear, and the pattern is more symmetrical if forward motion ceases. More recently, Schoner (1968) investigated the areal distribution of rainfall around centers of tropical storms moving inland into Texas and found the greatest amounts generally to the right of the point of entry.

An investigation of tropical storms entering Florida gave only a slightly different picture. Miller (1958) reported that in 11 storms the highest hourly rate of rainfall was near and ahead of the center. The rainfall was heavier to the right than to the left of the storm path, but not to the extent suggested by Schoner.

In summary, there appears to be little doubt that tropical storms entering the coastal regions give more rain to the right than to the left of the storm track, and near the coast rather than far inland. Is it possible, however, to specify more closely how far inland and to the right the heaviest rains fall? How do they decrease from this optimum location? Is there a difference between the pattern and rates of rainfall between the time the storm is about to move inland and the first 6 or 12 hours after it is inland? More directly, what is the space-time distribution of rain close to the track of a tropical storm as it approaches and enters the coast?

The answers to the above questions are of practical significance to the engineer for at least two reasons: (1) In the design of levees to control flooding from heavy hurricane rains near coastal sections, the probable rainfall amounts and their distribution must be known; and (2) where seawalls and dikes are designed to prevent flooding by the hurricane tidal surge, rainfall on the interior side must be taken into account. If these are gated structures with pumping facilities, the operational plans for opening or closing such gates and for pumping schedules are subject to the combination of simultaneous rainfall and surge heights, which establish the volume of water to be pumped and the head to pump against. To keep impounded waters at a safe level, pumping may have to be initiated hours before the heaviest rains are expected.

1.2. *Scope*

The area chosen for the investigation extends from Apalachicola, Fla., to Brownsville, Tex. These limits coincide with geographic zones B and C of a planning document on extreme hurricane winds by Graham and Nunn (1959, fig. 11). The data were obtained from 46 well-developed storms during the 26-year period 1940–65. Only those tropical storms and hurricanes that entered the coast between the above limits were used.

The time intervals of rain used were from 6 hours to 48 hours, covering the period from 24 hours before to 24 hours after the storm entered the coast. The area of interest extended to 150 nautical miles on each side of the storm track and to 100 miles inland. (All references to *miles* in this report imply *nautical miles.*) Further detail on all the above is furnished in section 2.

Section 3 discusses the average rainfall during 48 hours and its distribution in time and space, by 12- and 24-hour increments. Section 4 presents the frequency and space distribution of the maximum 6-hour point rainfalls in the 46 storms analyzed. Section 5 deals with the frequency and areal distribution of 6- and 12-hour point rainfalls, and section 6 shows the frequency distribution of the maximum 6- and 12-hour point rainfalls at every station in the 46 storms. Section 7 provides means of estimating areal rainfall averages at different frequency levels, and section 8 summarizes the findings.

2. BASIC DATA

2.1. *Sources*

Most of the 6-hour rainfall amounts used in this study are from hourly data published in *Climatological Data* and *Hourly Precipitation Data.*[1] The rest are from rainfall mass curves which are part of the *Storm Studies Part I*, prepared mostly by the U.S. Corps of Engineers (1945 and continuing) for "Storm Rainfall in the United States." Rainfall data from nonrecording as well as recording gages were used. The time distribution of the nonrecording gage data was determined from the data of nearby recording gages.

Storm tracks through 1963 are mostly from *Weather Bureau Technical Paper No. 55* (Cry, 1965, p. 2) and for 1964 and 1965 from the *Monthly Weather Review.* A few storm tracks previously analyzed by the author or his colleagues for other purposes were also used.

2.2. *Selection of Storms*

Cry's definitions for tropical storms and hurricanes (1965) were used as criteria in selecting the storms used. Weak tropical depressions were excluded. The rainfall in the storms was not a criterion in their selection. The storm survey for the 26-year period 1940–65 yielded 46 storms (table 1) that could be classified as either fully developed hurricanes or tropical storms at time of landfall. All storms entered the Gulf Coast between 84° W. and Brownsville, Tex.

The word *landfall* is used to mean both the point on the coast and the time at which the pressure center of the storm entered the land. Figure 1 shows the points of landfall and the direction of motion at time of entry of the 46 storms. Points of entry appear to be fairly well distributed along the coast, none being significantly more vulnerable to a "hit" than another.

TABLE 1.—*Tropical storms entering the Gulf Coast from 84° W. to Brownsville, Tex., 1940–65*

Storm No. and class[1]	Name	Landfall		Storm duration
		Time (e.s.t.)	Date	
1(H)	....	1900	8/7/40	8/2–10
2(S)	....	0600	9/24/40	9/12–24
3(S)	....	0200	9/15/41	9/11–16
4(H)	....	1800	9/23/41	9/16–25
5(H)	....	0500	10/7/41	10/3–14
6(H)	....	1100	8/21/42	8/17–22
7(H)	....	0300	8/30/42	8/21–31
8(H)	....	1600	7/27/43	7/25–29
9(S)	....	2000	9/19/43	9/15–19
10(S)	....	1000	9/10/44	9/8–10
11(H)	....	1300	8/27/45	8/24–29
12(S)	....	0400	6/16/46	6/13–16
13(S)	....	2000	8/1/47	7/31–8/2
14(H)	....	1500	8/24/47	8/18–27
15(H)	....	0600	9/19/47	9/4–21
16(S)	....	0900	9/8/47	9/7–8
17(S)	....	0300	7/9/48	7/7–11
18(H)	....	0300	9/4/48	9/1–6
19(S)	....	0700	9/4/49	9/3–5
20(H)	....	0000	10/4/49	9/27–10/6
21(H)	Baker........	2300	8/30/50	8/20–9/1
22(S)	Alice........	0800	6/6/53	5/25–6/6
23(H)	Florence........	1200	9/26/53	9/23–28
24(S)	Barbara........	0400	7/29/54	7/27–30
25(S)	Brenda........	1300	8/1/55	7/31–8/2
26(S)	....	0000	8/27/55	8/23–29
27(S)	....	1400	6/13/56	6/11–14
28(H)	Flossy........	1800	9/24/56	9/21–30
29(S)	....	1900	6/8/57	6/8–14
30(H)	Audrey........	0900	6/27/57	6/25–28
31(S)	Bertha........	2000	8/27/57	8/8–11
32(S)	Debbie........	1000	9/8/57	9/7–8
33(S)	Esther........	0700	9/18/57	9/16–19
34(S)	Ella........	0400	9/6/58	8/30–9/6
35(S)	Arlene........	1900	5/30/59	5/28–6/2
36(H)	Debra........	0300	7/25/59	7/22–27
37(S)	Irene........	0800	10/8/59	10/6–8
38(S)	....	0100	6/25/60	6/22–28
39(H)	Ethel........	1700	9/15/60	9/14–17
40(H)	Carla........	1600	9/11/61	9/3–15
41(H)	Cindy........	0900	9/17/63	9/16–19
42(S)	Abby........	1700	8/7/64	8/5–8
43(H)	Hilda........	1900	10/3/64	9/28–10/5
44(S)	....	a.m.	6/15/65	6/11–18
45(S)	Debbie........	0000	10/1/65	9/24–30
46(H)	Betsy........	2300	9/9/65	9/8–11

[1] H, hurricane; S, tropical storm.

[1] *Climatological Data* and *Hourly Precipitation Data* are publications issued by the Weather Bureau up to July 1965, then by ESSA's Environmental Data Service.

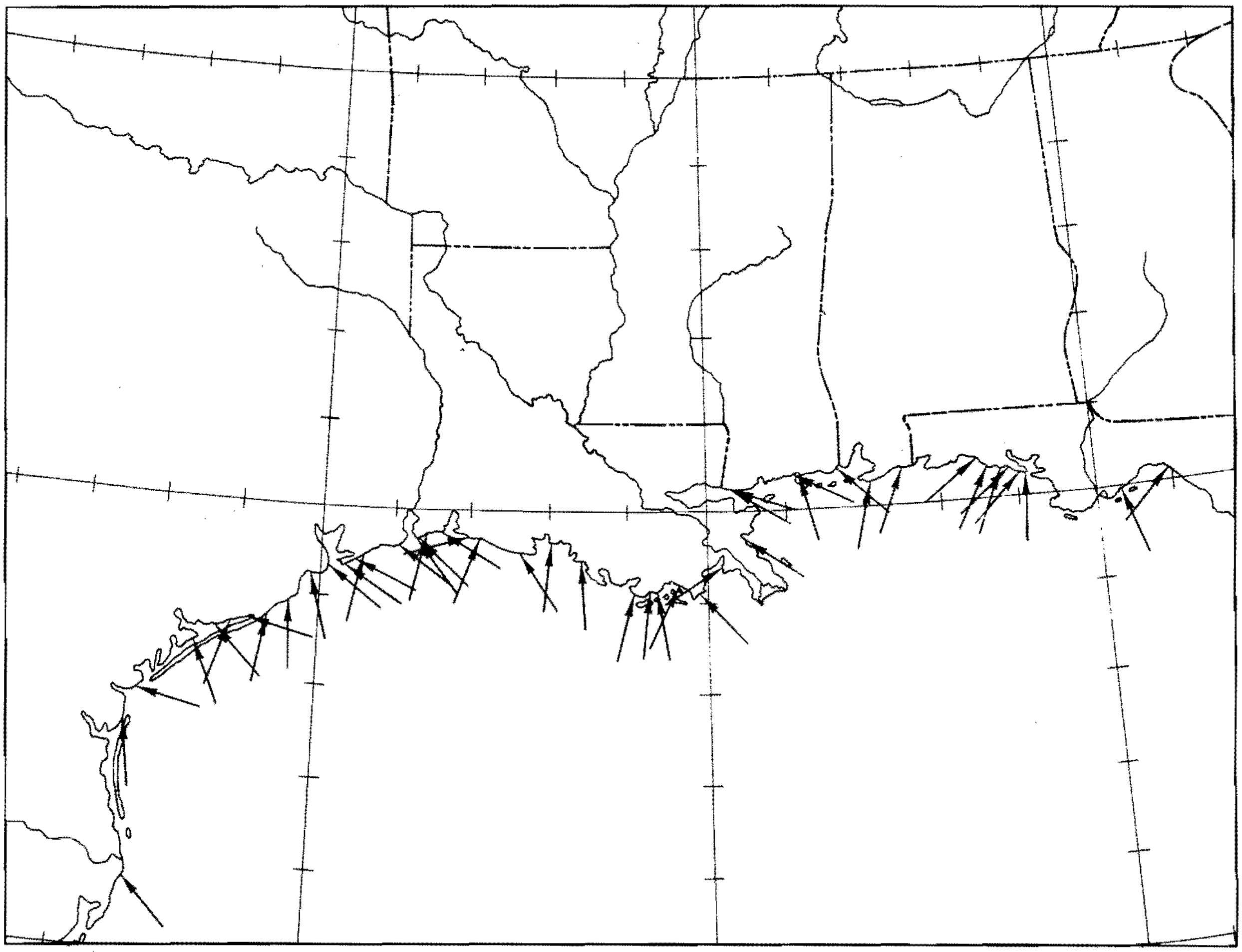

FIGURE 1.—Direction of motion and point of landfall of 46 selected tropical storms, 1940–65

2.3. *Grid Used in Extraction and Tabulation*

The grid used for locating stations with respect to the storm track and point of landfall, and later as the format for tabulating the data, is shown in figure 2. It is 300 miles long and 125 miles wide and divided into 25-mile squares, each covering an area of 625 square miles. The five zones of 12 squares running the length of the grid were labeled E, A, B, C, and D, starting from the bottom. Zone E lies on the seaward side of a straight line tangent to the coast at the point of landfall; the other zones are inland as shown.

In using the grid, a line was first drawn tangent to the coastline at the point of landfall. The grid line separating zones E and A was then superimposed on this tangent with the centerline of the grid through the point of landfall. Figure 2*A* shows the grid positioned for a storm moving inland normal to the coastline. Note that although zone E is essentially over water in most cases, some land areas are usually found toward the lateral edges of the grid because the Gulf Coast from Florida westward is concave.

On both sides of the storm track, rainfall recorder stations that were operating when the storm occurred were located, and a notation was made of the zone (E, A, B, C, or D) and the square to the right or left of the storm track.

When the track was not exactly normal to the coastline, by far the most common case, each zone of the grid was moved right or left, parallel to the coastline, until the midpoint of the zone centerline lay on the storm track (fig. 2*B*). Essentially, this is the same as if for every case the grid were redrawn (sliding the zones relative to each other) so that the storm track would be in the center of each zone. This insured that the two distances that define the position of the station relative to the coastline and to the storm track are orthogonal. Point P is at the same geographical location in figures 2*A* and 2*B*, but although landfall is the same in both cases, P is two squares farther to the right in figure 2*B* than in 2*A*.

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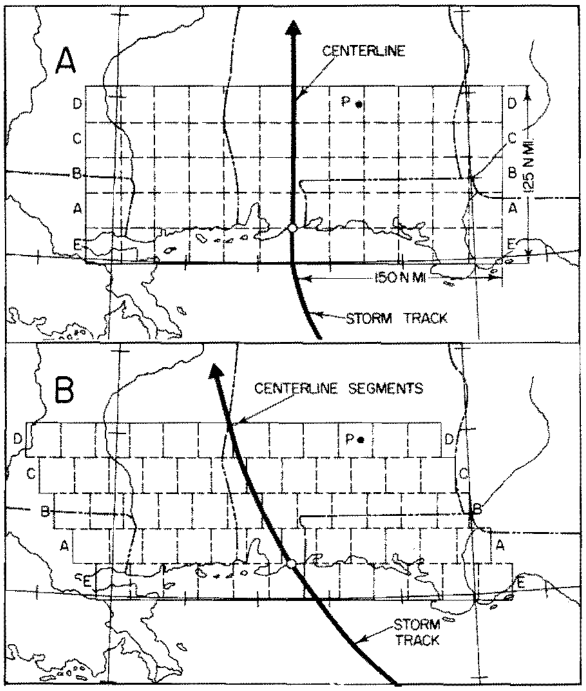

FIGURE 2.—Reference grid: *A*, For storm path normal to coastline; *B*, for storm path not normal to coastline

2.4. *Tabulation*

For every storm studied the track was laid out, and a transparent overlay of the grid positioned as shown in figure 2. Increments of 6-hour and 12-hour rain for the observing station were tabulated in the grid square for that station. For example, table 2 shows the point rainfall amounts for all storms for the 6 hours before landfall in zone B in the two squares immediately to the right and left of the storm path. The total tabulation of the 6-hour increments of rain contains more than 7,000 entries, from an average of about 20 stations per storm for eight time periods.

TABLE 2.—*Sample tabulation of station rainfall amounts (inches) for 6-hour period before landfall, zone B, in grid squares adjacent to storm path*

Left of path		Right of path	
.54	.00	1.84	.29
.83	1.36	.03	.74
1.39	.90	.06	.81
.00	.97	1.88	.51
.20	.80	.00	.01
1.41	1.35	.13	1.80
.80	2.20	4.60	1.32
.00	.00	.18	.00
.02	.16	.23	.18
1.48	.00		
.45	.49		
1.25	.02		
.02	.90		
.00	.00		
1.81	.00		

2.5. *Time Intervals*

All time intervals used in this study, unless otherwise noted, refer to the time of landfall to the nearest clock hour. For example, if a storm makes landfall at 0400 e.s.t., the 6-hour increments of rainfall extracted from the observations of a particular recorder station are the sums of the six hourly observations from 0400 to 1000 e.s.t., 1000 to 1600 e.s.t., etc., of the day before landfall, through 2200 to 0400 e.s.t. on the day after. The total time covered is from 24 hours before landfall to 24 hours after, in intervals of 6 hours. These incremental amounts are called *storm-referenced* rainfall values.

The frequency distributions of the *maximum unreferenced* 6- and 12-hour rainfall amounts that occurred at every station were also investigated. These values are for the 6 and 12 consecutive hours yielding maximum amounts during the 48-hour observation period. These 6- and 12-hour increments are independent of time of landfall.

2.6. *Storm Frequency and Motion*

Excluding indentations, the distance along the coast from 84° W. to Brownsville, Tex., is about 1,090 nautical miles. If only those storms within the category discussed in 2.2 are considered, there are 46 storms per 26 years per 1,090 miles, or *one storm per 5-year period per 123 miles of coastline.*

For later comparisons with rainfall distributions, it is interesting to note the rate at which the storms move inland after landfall (fig. 3). The distances inland (perpendicular distance from the zone A-E boundary to storm centers) of all storms were noted at the end of 6, 12, 18, and 24 hours after landfall. Averages were then obtained of 6-, 12-, 18-, and 24-hour positions of the upper quartile, the median half, and the lower quartile. A few storms dissipated shortly after landfall; therefore not all 46 storms are represented in figure 3.

Results show that the centers of the faster storms have, on the average, moved inland and outside the area covered by the grid in a little more than 6 hours after landfall. The moderately fast storms moved out of the grid by the 12th hour, and the slower storms had barely moved out of the grid by the 24th hour. This considerable range in forward motion is further demonstrated by the inclusion in figure 3 of the positions, by 6-hour increments, of the fastest and the slowest storms.

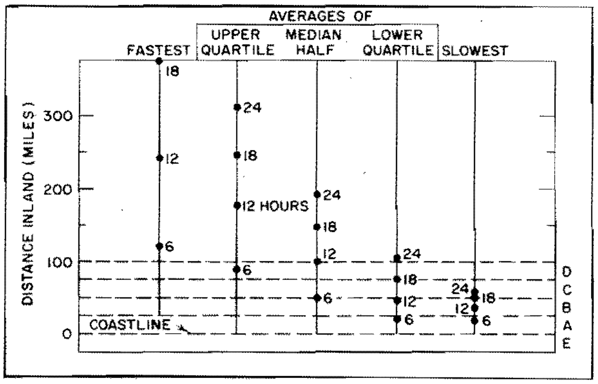

FIGURE 3.—Distance inland (nautical miles) of storm center 6 to 24 hours after landfall

3. AVERAGE POINT RAINFALL

Whereas the main goal of this report is to establish frequency distributions of rainfall, average distributions are in themselves interesting and lend perspective on the storms analyzed. The average rainfall of the 46 storms should show a distinct pattern with significant spatial and time variations. The average rainfall of the 46 storms was computed for the full 48-hour period, the two 24-hour periods, and the four 12-hour periods.

3.1. *48-Hour Rainfall*

Figure 4 shows the average 48-hour rainfall in inches for the 46 storms. The profiles were prepared by first averaging the observations in each square, weighting the square averages by the number of observations, and combining the squares horizontally and vertically. The upper profile is formed by the average for each column of squares, and the curve on the right by the average for each of the five zones.

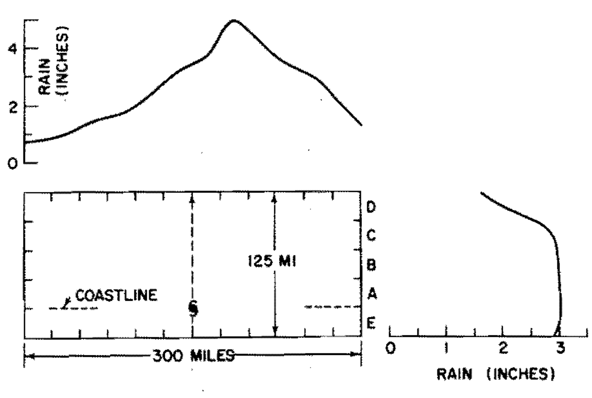

FIGURE 4.—Average profiles of 48-hour storm rainfall (24 hr. before landfall to 24 hr. after)

Figure 4 shows clearly that the highest average rainfall for the 48 hours was to the right of the storm path (25 to 50 miles). In fact, over half the rain volume fell within the four columns of squares to the right of the path. Similarly, the curve on the right indicates a sharp dropoff of rain about 75 miles inland from the coast.

Figure 5 shows the smoothed mean isohyetal pattern derived from the profiles of figure 4. The heaviest amount, almost 6 inches, appears in zones A and B, about 35 miles to the right of the storm path. Figure 5 is constructed from figure 4 as follows:

Let S_x = average value for "x" strip normal to coast, read from top profile of figure 4. x = 1, 2, 3 . . . 12.

V_y = average value for "y" zone, read from right-hand profile of figure 4. y = A, B, C, D, E.

$\overline{P}$ = average precipitation over grid

$\overline{P} = \Sigma S_x/12$

P_{xy} = average rain in square intercepted by strip x and zone y

Then $P_{xy} = \dfrac{S_x V_y}{\overline{P}} = \dfrac{S_x V_y}{\Sigma S_x/12}$

For example, find the average rain for $P_{8,\,B}$. From figure 4, $S_8 = 4.97$, $V_B = 3.05$, $\overline{P} = 31.61/12 = 2.63$. Then $P_{8,\,B} = 5.75$ inches.

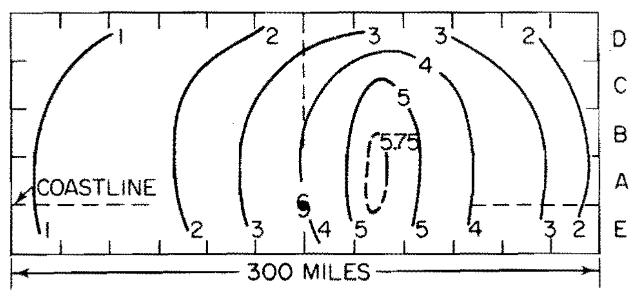

FIGURE 5.—Average 48-hour storm rainfall (in.) as computed from profiles of figure 4

3.2. *24-Hour Rainfall*

The average precipitation during the first and second 24-hour periods is shown in figure 6. The top curves show again that maximum rain falls to the right of the storm for both periods, and that slightly more rain falls after landfall than before. However, the zone-to-zone variation differs from that of the total 48 hours. As might be expected, during the first 24 hours, while the storm is approaching the coast, the rainfall decreases from the coast inland. The rainfall variation is most likely a function of both the coastal effect and distance from the center of the storm. During the second 24-hour

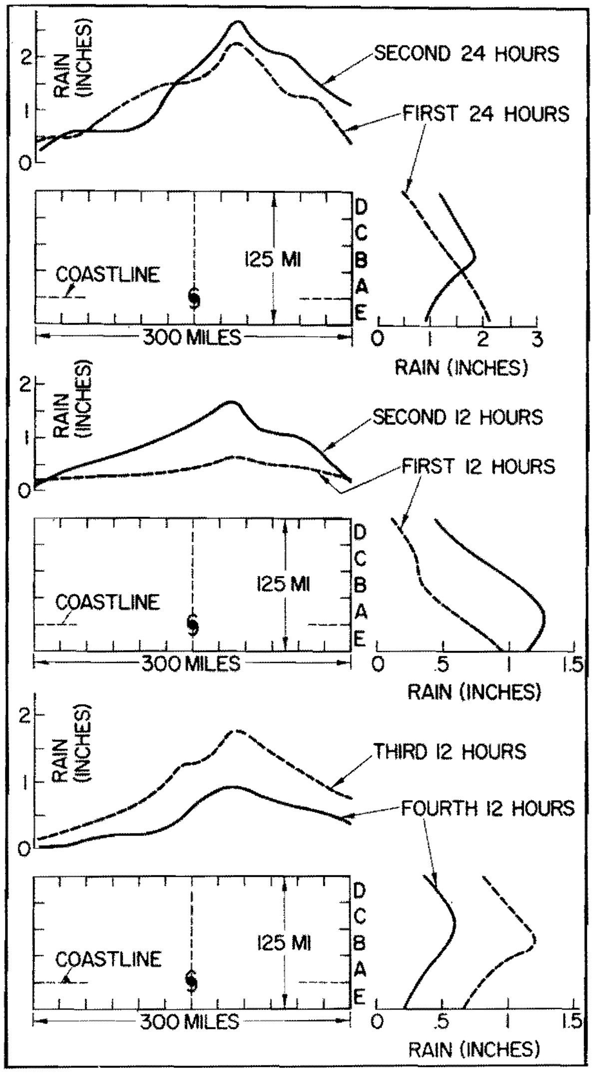

FIGURE 6.—Average profiles of 12- and 24-hour rainfall increments in 48-hour period

period, while the storm is moving inland from the coast, and on the average is a little more than 100 miles inland by the 13th hour (fig. 3), a definite maximum appears in zone B. The coastal effect is apparently much more pronounced than distance from the center of the storm after the center has moved inland.

3.3. *12-Hour Rainfall*

Distribution of 12-hour rainfall (fig. 6) is much the same except that the dropoff of rain from the coast inland in the first 24 hours is concentrated in the first 12. The second 12-hour period shows the rainfall increasing before landfall. During the last two 12-hour periods the rainfall progressed to maxima in zones B–C. In all periods, the maximum rainfall remains somewhere between 25 and 50 miles to the right of the storm path.

Of the total volume of rain falling within the grid in the 48-hour period, 14 percent fell in the first 12-hour period, 34 percent in the second, 35 percent in the third, and 17 percent in the fourth.

4. DISTRIBUTION OF STORM-REFERENCED MAXIMUM 6-HOUR POINT RAINFALL

The heaviest 6- or 12-hour point rainfall that is likely to occur during the passage of a storm is of prime interest, particularly since it is highly correlated with rainstorm volume over the surrounding area. It is useful to know not only the magnitude of the heaviest rainfall but also where and when to expect it.

Table 3 shows the maximum 6- and 12-hour point rainfall values for all 46 storms. Values range from 11.00 inches to less than 1 inch for the 6-hour maxima, and from 15.55 to 1.47 inches for the 12-hour. These are maxima within the storm-referenced time periods defined in section 2.5. A study of the frequency distribution of the maximum 6- and 12-hour unreferenced rainfalls is discussed in section 6.

4.1. *Location of Maximum 6-Hour Amount*

For the maximum 6-hour value in each storm, a notation was made of the grid square and the particular 6-hour period (of the eight periods in the 48 hours) in which it fell.

First neglecting time, the frequency of occurrence of the maxima within grid squares was

TABLE 3.—*Maximum point rainfalls (inches) for 6- and 12-hour intervals referenced to time of landfall, 46 storms*

6-hour		12-hour	
11.00	3.73	15.55	5.24
8.92	3.66	12.62	5.13
8.30	3.64	10.66	5.00
7.58	3.64	10.42	4.93
6.81	3.60	9.43	4.82
6.62	3.55	8.41	4.73
6.05	3.54	8.27	4.70
5.46	3.46	8.14	4.64
5.29	3.40	8.11	4.55
4.98	3.36	7.84	4.50
4.94	3.29	7.79	4.29
4.81	3.00	7.62	4.25
4.41	2.90	7.22	4.22
4.31	2.83	6.93	4.22
4.28	2.66	6.19	4.02
4.27	2.64	6.02	3.83
4.20	2.54	5.83	3.42
4.19	2.39	5.70	3.22
4.14	2.38	5.66	3.04
4.08	1.55	5.58	1.68
3.97	1.35	5.42	1.62
3.94	1.34	5.30	1.55
3.85	.95	5.30	1.47

determined (fig. 7). There is a 7-percent probability that the maximum 6-hour rainfall in any storm will occur in zone C and 25 to 50 miles to the right of the storm path. Frequencies decrease from this square in all directions to less than one-half of 1 percent toward the lateral edges. There is about a 42-percent probability that the highest 6-hour amount will fall within the 75 × 75 mile area bounded by the coastline on one side and the storm track line on the left, an area which is only 15 percent of the total grid area.

Figure 7 agrees rather well with figures 4 and 5, which depict the average rainfall for 48 hours, except that the highest probability appears to be displaced slightly closer to the coast in figure 5.

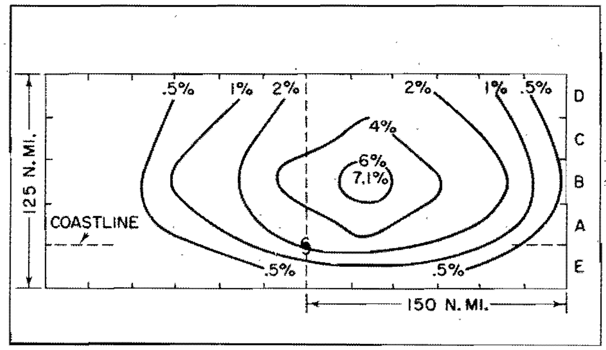

FIGURE 7.—Probability of largest 6-hour rainfall point value falling in any particular grid square

4.2. *Combined Time and Space Distribution of Maximum 6-Hour Values*

Figure 8 shows probabilities of maximum 6-hour rain occurring in specific squares and specific 6-hour periods. Figures 8 *A, B, F* substantiate the expected low probabilities of maximum 6-hour rainfall early or late in the 48-hour period. For example, the chance of maximum 6-hour rainfall in the period 24 to 18 hours before landfall in zone B, 25–50 miles to the right of the storm path is only 0.15 percent (fig. 8*A*). The 6-hour maximum rainfall has the highest probability of occurrence in the 6 hours before landfall (fig. 8*C*).

Figures 8 *C* and *D* indicate about 21-percent probability that the maximum 6-hour rain will

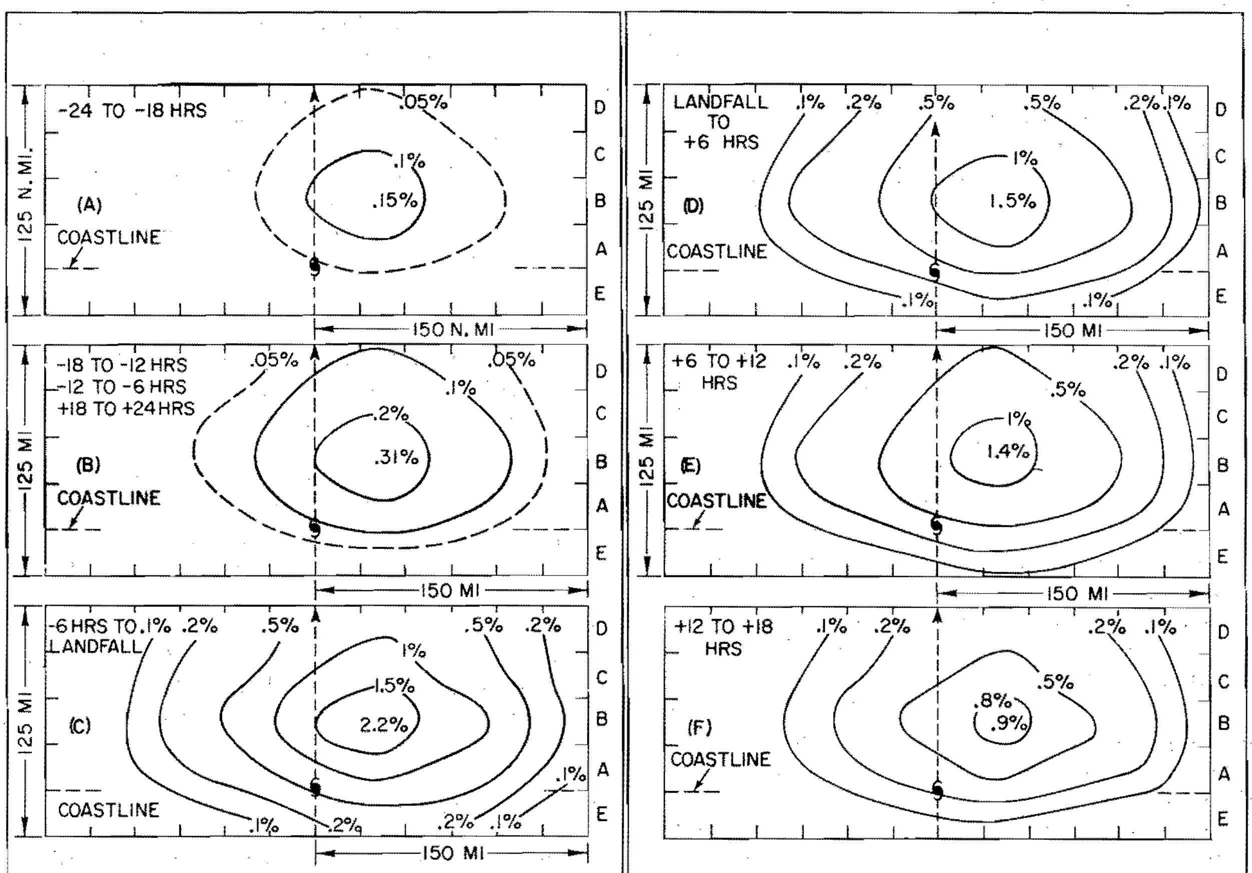

FIGURE 8.—Probability of largest point value falling within a specified 6-hour period and a particular grid square (minus sign indicates time prior to landfall)

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occur between 6 hours before and 6 hours after landfall and in the 75 × 75-mile area bounded by the coastline, the upper boundary of zone C, the storm path, and a line parallel to the path and 75 miles to the right.

5. FREQUENCY DISTRIBUTION OF POINT RAINFALL OBSERVATIONS

5.1. *Discussion*

Typical questions toward which this report is directed are:

What is the probability that 6 inches or more of rain from a tropical storm will fall on a particular station during a 6- or 12-hour period?

Or, if the track of the incoming storm is forecast, (a) what place has the highest probability of receiving the maximum rainfall, (b) what is the probability that it will be 8, 10, or more inches, and (c) what is the most likely time of occurrence?

5.2. *Analysis*

Frequency analyses were made for each zone separately, for each of four periods of 12 hours and for the three periods of 6 hours during which rain fell at the greatest rate. The 35 frequency distributions are found in figures 9 to 43.

All the point rainfall accumulations in each 12- or 6-hour time period in a particular zone were plotted with amount of rain as the ordinate and distance to grid center right or left of storm track as the abscissa. The plot for zone A for the 12 hours before landfall is shown in figure 17, which depicts curves for the 2-, 10-, 25-, and 50-percent levels of occurrence. The 2-percent curve separates all the values observed in that zone in that particular time period so that 98 percent of the points are on the curve or below and 2 percent are above. Similarly, the 10-percent line was drawn to show 10 percent of all the points above it and 90 percent below. In doing this it was necessary to keep in mind that the distribution of the point values had a heavy right skew and closely approximated an exponential distribution.

In general, the 25-percent curve (which divides the domain of points so that 25 percent lie above and 75 percent below) showed the least variation in shape from zone to zone and time period to time period. It was used as a guide for shaping the other curves.

The three lower curves fit the pattern of points rather well. The higher values (up to 10.5 in. in fig. 17) exhibit the normal scattering expected in higher values, which makes the 2-percent curve more difficult to fit.

The curves in every zone were adjusted by comparison with those of adjoining zones for the same time and with the same zone for adjacent time periods to preserve representativeness and continuity. This was important because not every storm was represented in every column of points, a factor which contributes to the scatter. Comparisons were made also with the results in sections 3 and 4 before final smoothing of the curves.

5.3. *Comments*

In general, the other cases (figs. 9 to 43) showed the same characteristics as those in figure 17. Some cases, however, exhibit a bimodal shape (with two peaks) as in figure 25. This feature is readily apparent only during the time period from landfall to +12 hours.

There is some question as to whether a bimodal distribution is characteristic of hurricanes in general, as well as of this particular sample of storms. However, it seemed inappropriate to reject, a priori, the possibility of such a distribution in view of the indications of the data. The user is warranted in smoothing out the double peaks if he chooses, maintaining the area under each curve.

The frequency distribution of the 46 highest 6-hour point values (one for each storm) did not show this bimodal trend, and the distribution of the average rain gives only a slight hint of it (top curves, figs. 4 and 6).

An attempt was made to compute the frequency distributions of the point values in the zones by several curve-fitting techniques. The results were generally unsatisfactory.

6. FREQUENCY DISTRIBUTION OF UNREFERENCED MAXIMUM 6- AND 12-HOUR POINT RAINFALLS

In section 4 the distribution of the maximum 6-hour point rainfall was discussed. These rainfall amounts were for 6-hour increments referenced to time of landfall (see subsection 2.5). Although useful, this approach presents only part of the picture. Another way to look at the occurrence of maxima is to list the maximum 6- and 12-hour station rainfall values, without reference to landfall, for every station in the grid during the passage of each of the 46 storms.

6.1. *Maximum 12-Hour Values*

The maximum rainfall amount for any 12 consecutive hours in each storm was listed, with the location of each reporting station. The amounts were then plotted for each zone against distance right or left of the storm track. No note was made of the position of the 12-hour period relative to the time of landfall.

The frequency curves (figs. 44–48) were constructed as described in section 5.2. They are generally similar to those for the frequency distribution of referenced points, even to some tendency for bimodalism. Interpretation of the curves is the same; for example, the 2-percent curve indicates a 2-percent chance that the stations in the given zone will record higher maxima than the values of the curve.

6.2. *Maximum 6-Hour Values*

Figures 49–53 show the frequency distributions for the maximum 6-consecutive-hour rainfalls, i.e., regardless of position relative to time of landfall.

6.3. *Ratio of True to Fixed Maximum Rainfall*

Since the 6- and 12-hour rainfall values discussed in this section were compiled from hourly data and are not storm-referenced, they approximate true maxima. The factors from Weiss (1964) for adjusting to true maxima would be only 1.02 and 1.01 percent for the 6- and 12-hour values, respectively.

7. AREA-POINT RATIOS

Although the point rainfall analyses presented in sections 3 to 6 are useful in themselves, the planning and design of flood protection works require areal rainfall averages. Given the amount of rain expected at a point, with a probability value attached, the areal average rain about that point, at the same probability level, is needed. This was done for the 6- and 12-hour rain amounts for areas up to 1,000 square miles.

7.1. *Frequency Distribution of Area to Point Rainfall Ratios*

The total isohyetal patterns of two storms were used to derive ratios of areal average rainfall to point rainfall. These were the hurricanes of August 6–9, 1940, and August 27–30, 1945, both in southern Louisiana. A fine-mesh grid (less than 3-mile interval) was laid over each isoheytal pattern, and average rain values in each square were read off and tabulated. Contiguous squares were then combined to obtain average rainfall depths over larger areas. Finally, the frequency distributions of the single square values and the related frequency distribution of larger area values were solved on a digital computer for ratios of areal to point rainfall at different levels of frequency, specifically at the 2-, 10-, 25-, and 50-percent levels, for the total storm.

7.2. *Ratios of 6- and 12-Hour Rainfall to 24-Hour*

Most of the rain in the two storms fell in 24 hours. Using the assumption that all the rain fell in 24 hours, the next step was to derive ratios of 6- and 12-hour rainfalls to 24-hour amounts. Using readily available maximum depth-area-duration tables (Corps of Engineers, 1945 and continuing) derived for 14 storms along the Gulf Coast, the average ratios of 24-, 12-, and 6-hour depths for areas up to 1,000 square miles to the 24-, 12-, and 6-hour point values were computed.

Since these ratios were derived using maximum point values and maximum average depths over areas, they may be considered closely equivalent to the 2-percent probability level of occurrence. For this reason they were considered applicable to the area-point ratios of 24-hour total rainfalls at the 2-percent probability level of the two storms of subsection 7.1 for obtaining area-point ratios of 6- and 12-hour rainfalls. Figure 54 shows the results. The 10-, 25-, and 50-percent levels were obtained by using the distribution of the different levels derived from the frequency analyses of area to point rainfall in the two storms.

It is interesting that the 50-percent curves show (fig. 54) all ratios for areas up to 1,000 square miles to be above 1. If the distribution of both the point rainfall values and areal depth averages were normal, the ratio would everywhere have a value of 1. This indicates that the median of the point rainfall values, both 6 and 12 hours, is below the median of the area average depths.

7.3. *Estimating the Areal Rainfall Amount*

Figure 54 is used in conjunction with figures 9 to 43. As an example: What is the rainfall amount that may be expected at the 2-percent level of frequency, over 500 square miles centered 50 miles to the right of the projected hurricane path and 30 miles inland, during the 6 hours after landfall?

1. From figure 2*A* it is found that 30 miles inland is in zone B.

2. Figure 31, which is for zone B and for the 6 hours after landfall, gives a point value of about 3.2 inches on the 2-percent curve and 50 miles to the right of the storm track.

3. Figure 54, at 500 square miles, shows the ratio of areal average depth to point rainfall (for 6 hours) to be approximately 0.8.

4. The expected depth over the area is 0.8×3.2, or 2.6 inches which may be expected to be exceeded

only 2 percent of the time at this particular relative position during the passage of a storm.

8. SUMMARY

In 46 well-developed tropical storms and hurricanes that entered the Gulf Coast between Apalachicola, Fla., and Brownsville, Tex., during the years 1940 through 1965, the rainfall pattern along the coast and near the point of landfall was in general well-organized. It exhibited significant variations in the placement and timing of average and maximum point rainfalls during the 24 hours preceding and following landfall.

8.1. *Average Rainfall*

The averages of the point rainfall values over the grid for the 12-, 24-, and 48-hour periods showed the maximum 25 to 50 miles to the right of the track. For the total 48-hour period the highest average value on a smoothed-out composite isohyetal chart was 5.8 inches and occurred in zone A, i.e., within 25 miles inland. The coast-to-inland rain profile was rather flat but dropped off markedly 75 miles inland (zone D).

It rained a little more heavily on the right side in the second 24-hour period than in the first. A definite maximum appears inland during the second 24 hours, with an average point value of 3.5 inches 25–50 miles inland (zone B).

The four 12-hour periods are characterized by a landward movement of the maximum from offshore during the first 12 hours to successive inland zones.

8.2. *Frequency Distribution of the Maximum 6-hour Referenced Point Rainfall*

The maximum 6-hour point values, one in each of 46 storms, ranged from 11.00 inches to 0.95 inch, with 15 storms showing values between 3 and 4 inches. The frequency distribution is noticeably skewed with a median of 3.79 inches, well below the midpoint of the range. Irrespective of time, there is a 7-percent probability that the 6-hour maximum will occur within 25 to 50 miles to the right of the track and 25 to 50 miles inland (zone B). Irrespective of place, the most probable time of the maximum (a 29-percent probability) is during the 6-hour period from 6 hours before landfall to landfall.

Combining probabilities of time and space, there is about 21-percent probability that the maximum 6-hour value will occur from 6 hours before to 6 hours after landfall and in a 75-mile square immediately to the right of and landward from the point of landfall.

8.3. *Frequency Distribution of All Point Rainfalls*

The frequency distributions of all 6- and 12-hour referenced point rainfalls are presented in figures 9 through 43. Except for some cases where the distributions are bimodal, the patterns agree very well with those of the maxima, and strongly resemble the patterns of the average storm rainfall.

8.4. *Frequency Distribution of 6- and 12-hour Maximum Unreferenced Point Rainfall*

Figures 44 through 53 show the frequency distributions of 6- and 12-hour maximum unreferenced point rainfalls at all reporting stations. The distributions show the same general features found in the referenced frequency distribution of all points.

8.5. *Area-Point Ratios*

The 6- and 12-hour point values of figures 9 to 43 at the various frequency levels may be adjusted for areas up to 1,000 square miles by means of the area-point relation in figure 54.

REFERENCES

Cline, I. M., 1926, *Tropical Cyclones*, MacMillan Company, New York, 301 pp.

Corps of Engineers, U.S. Army, 1945 and continuing, "Storm Rainfall in the United States."

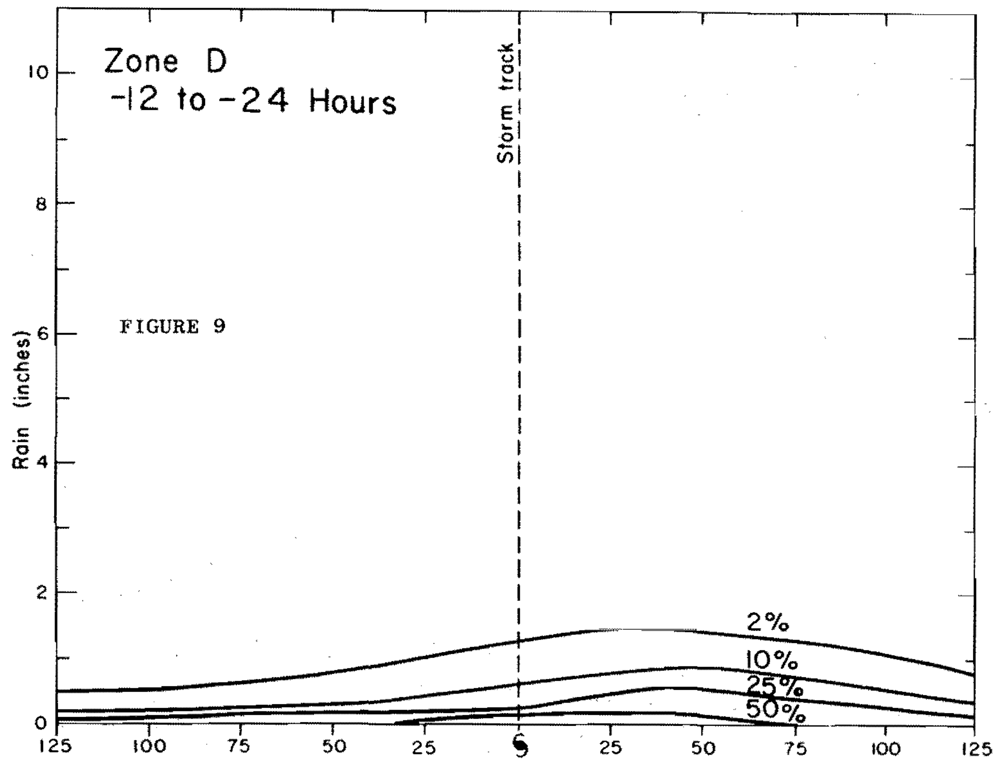
Cry, G. W., 1965, "Tropical Cyclones of the North Atlantic Ocean," Weather Bureau Technical Paper No. 55.

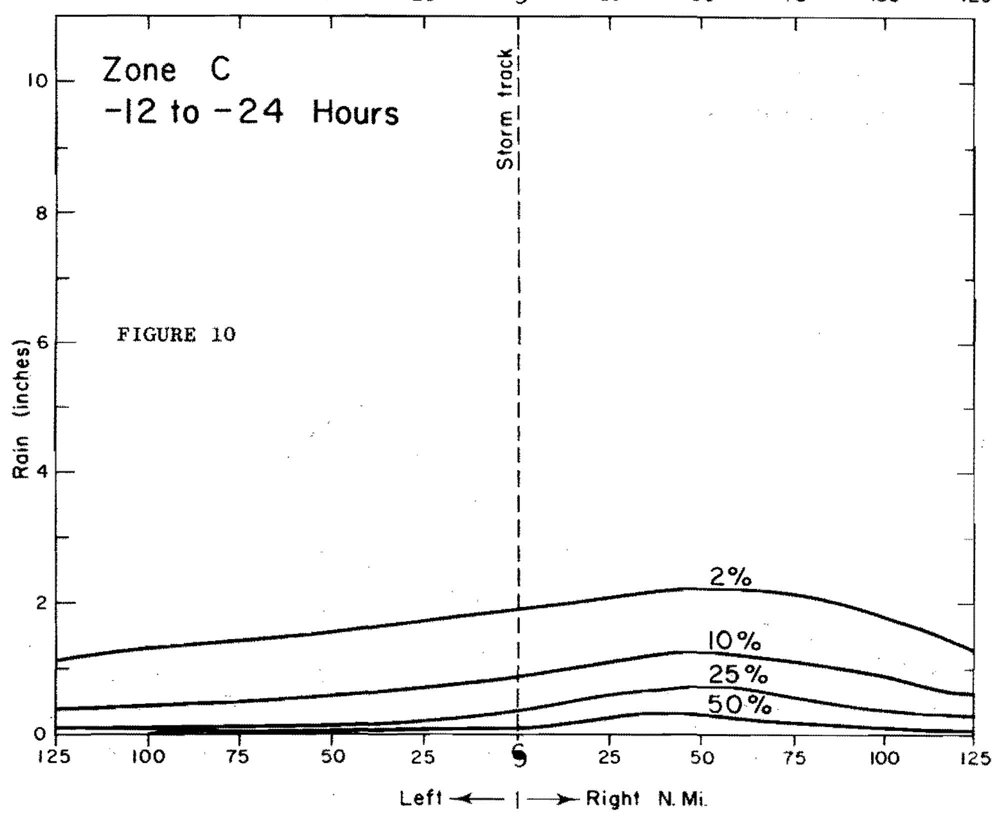
Graham, H. W., and Nunn, D. E., 1959, "Meteorological Considerations Pertinent to Standard Project Hurricane, Atlantic and Gulf Coasts of the United States," Weather Bureau, National Hurricane Research Project Report No. 33.

Miller, B. I., 1958, "Rainfall Rates in Florida Hurricanes," *Monthly Weather Review* 86, No. 7: 258–264.

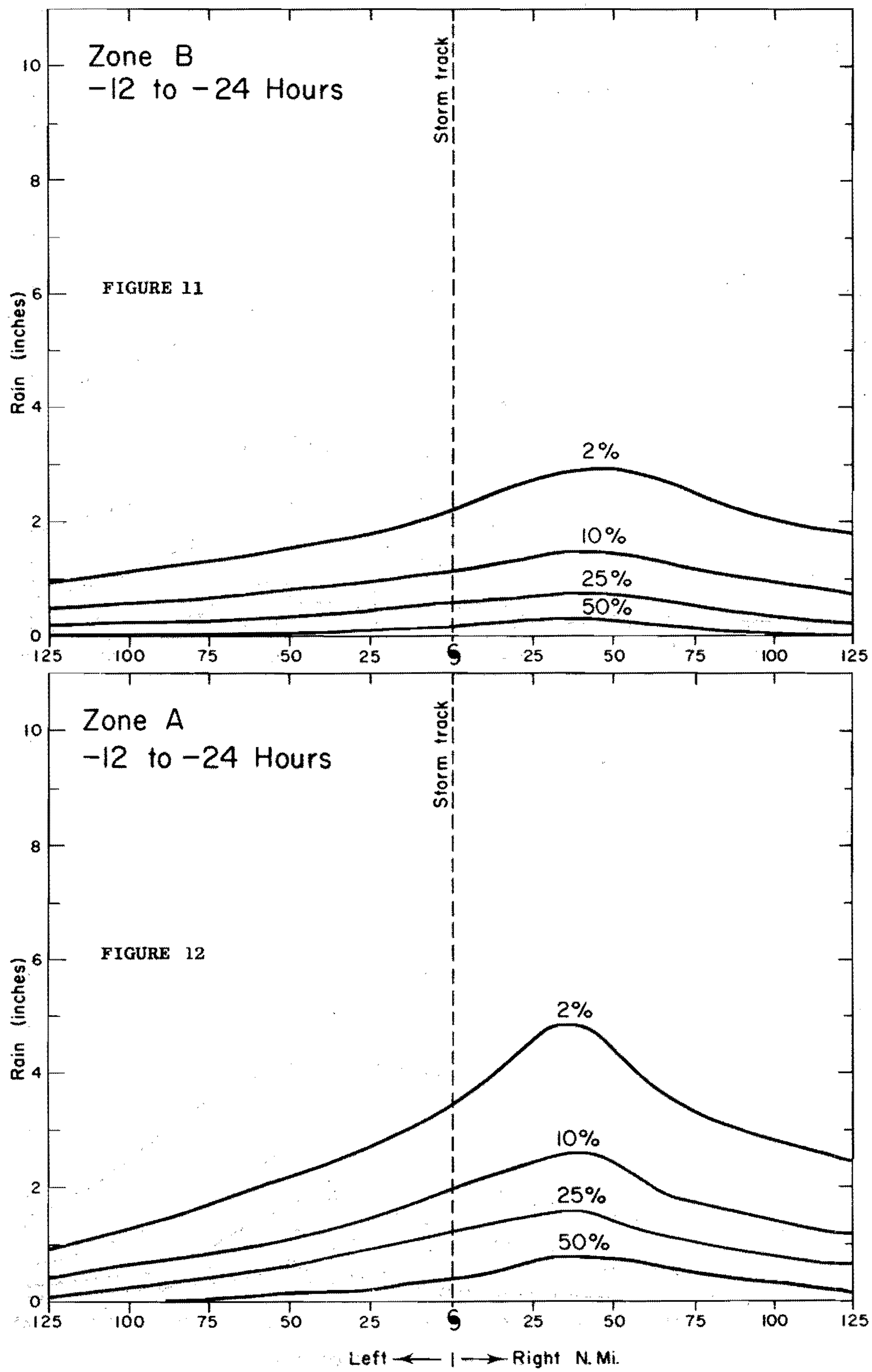
Schoner, R. W., 1968, "Climatological Regime of Rainfall Associated With Hurricanes After Landfall," Weather Bureau Technical Memorandum ER–29.

Weiss, L. L., 1964, "Ratio of True to Fixed Interval Maximum Rainfall," American Society of Civil Engineers, *Journal of the Hydraulics Division* 90, No. HY1: 77–82.

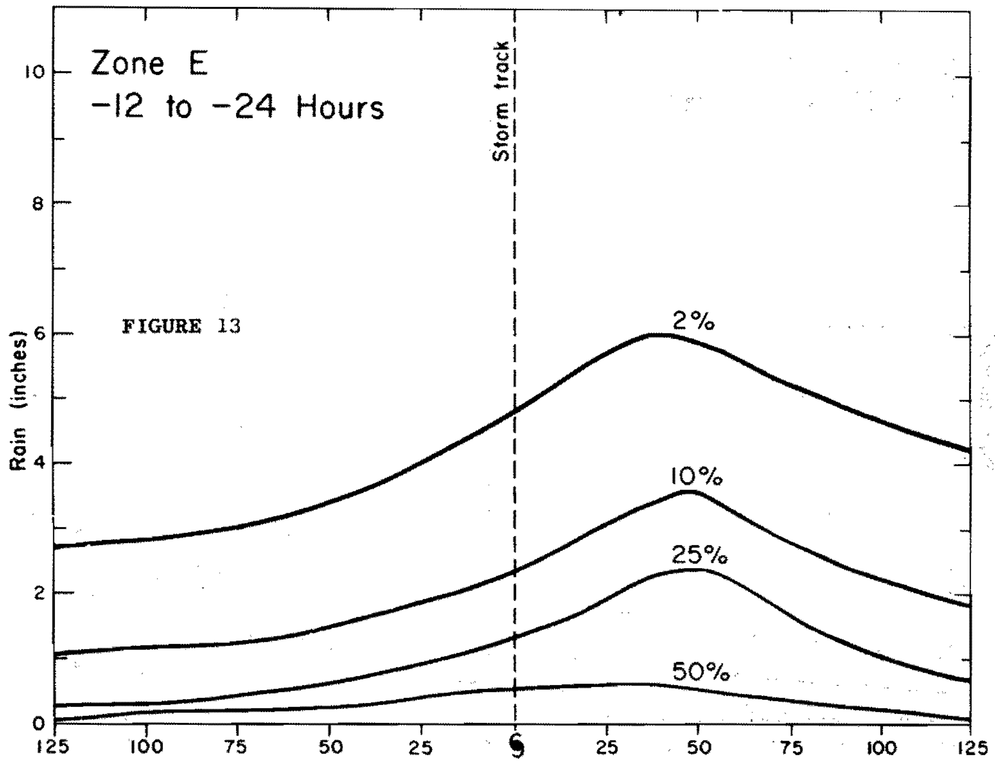


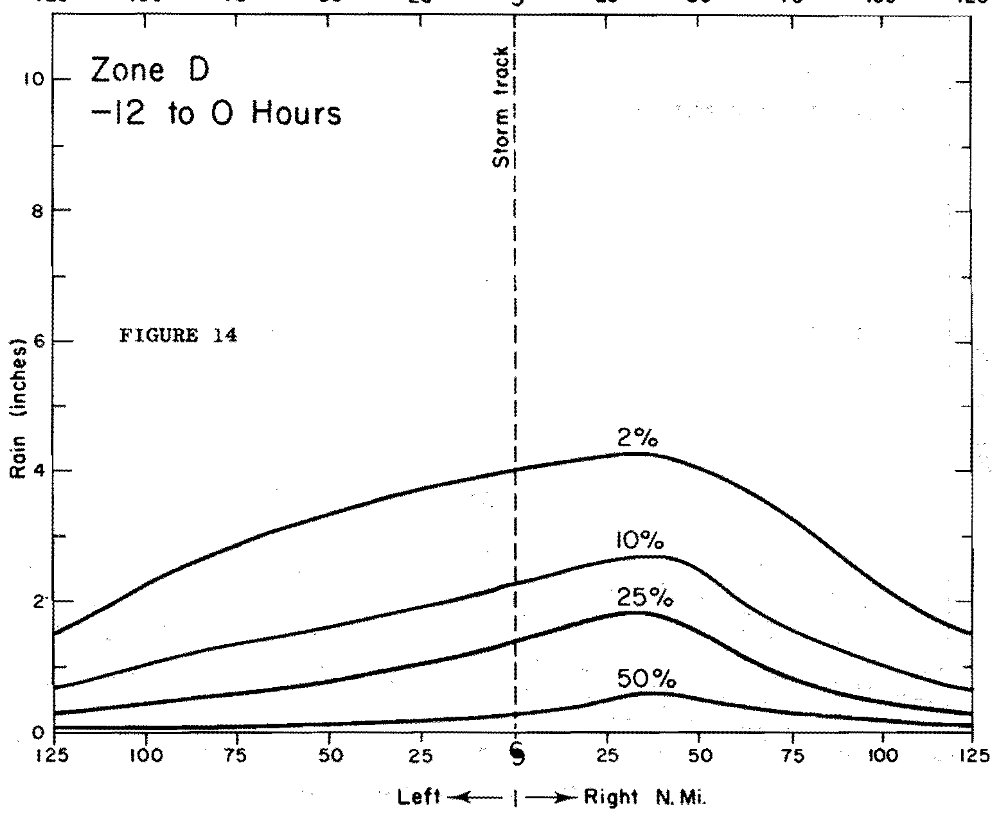


FIGURES 9–10.—Rainfall for selected frequency levels for 12 to 24 hours before landfall, zones D and C

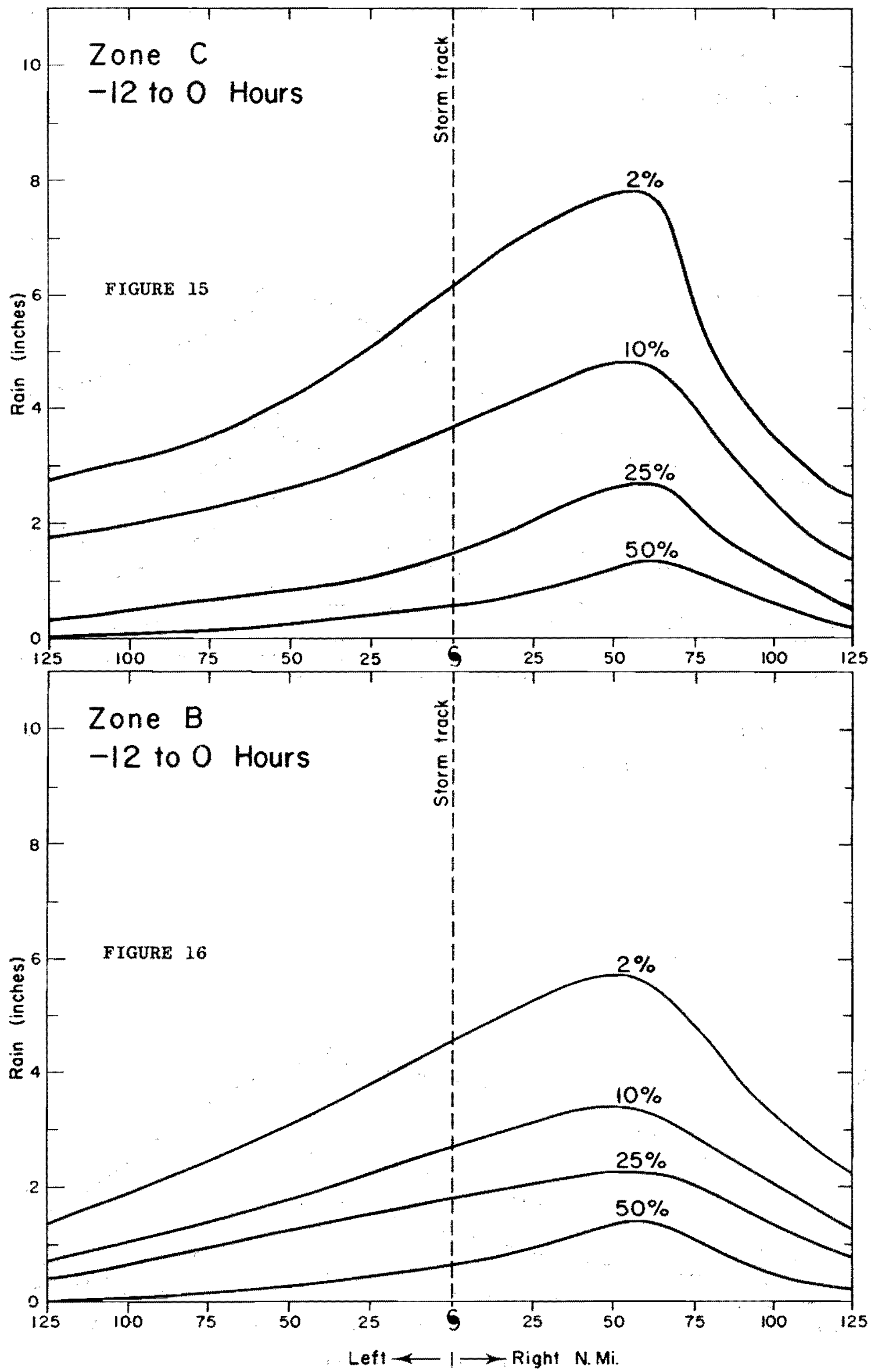


FIGURES 11–12. —Rainfall for selected frequency levels for 12 to 24 hours before landfall, zones B and A

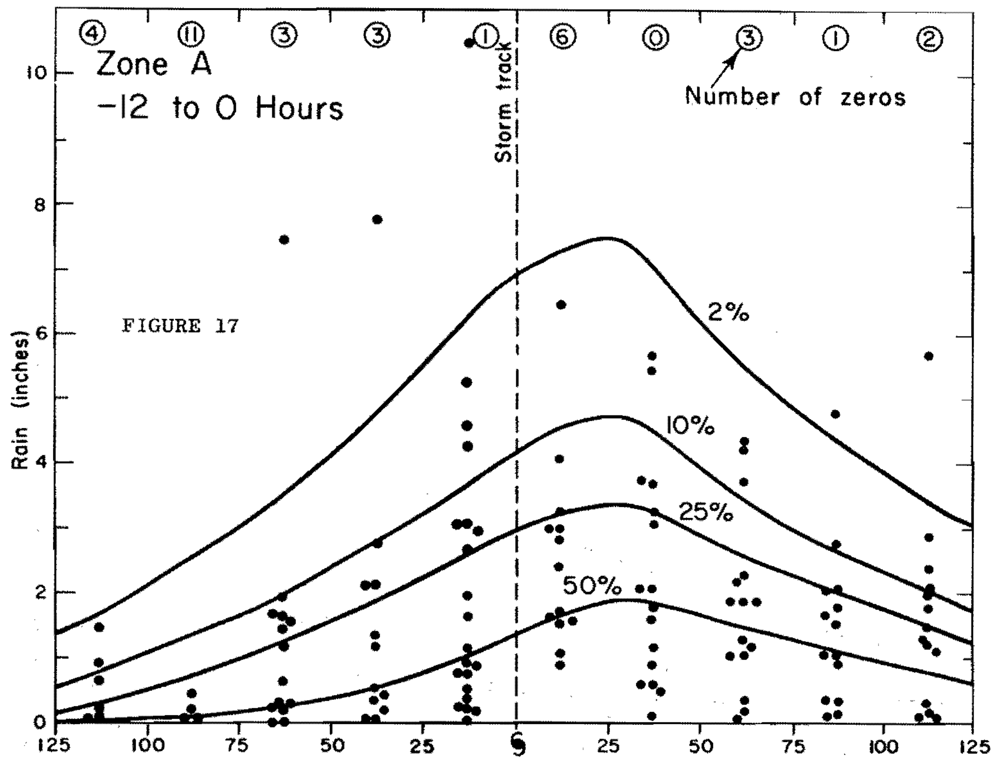


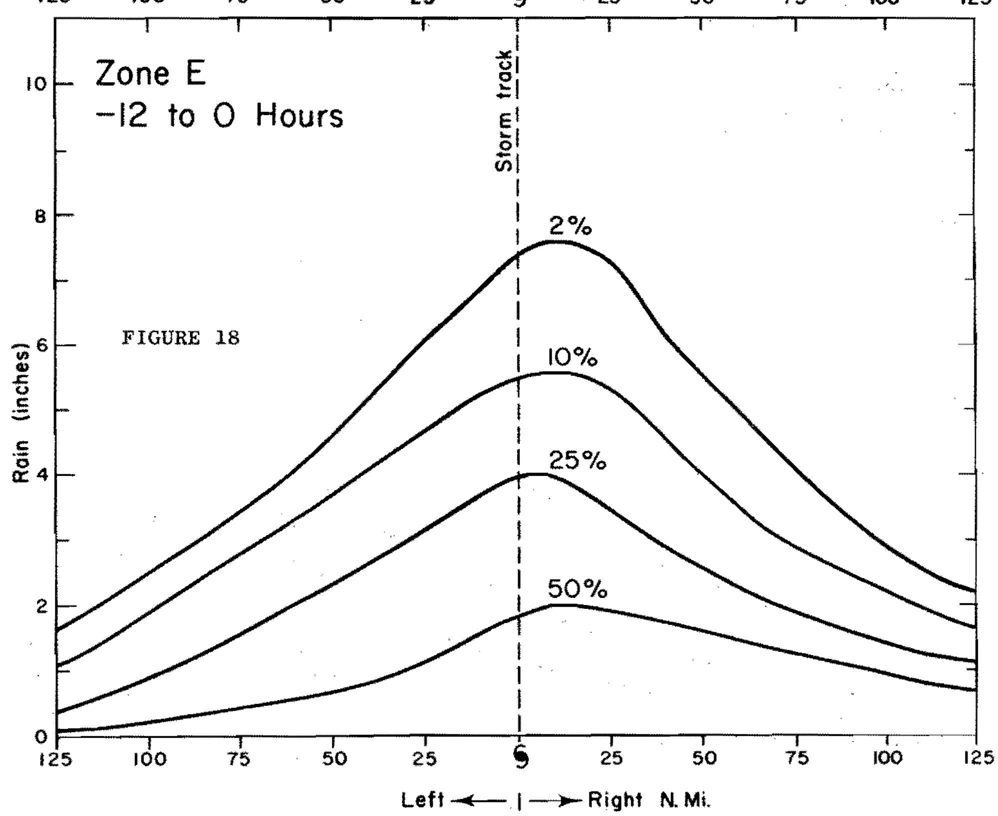


FIGURES 13–14.—Rainfall for selected frequency levels for 12 to 24 hours before landfall, zone E, and 12-hour period before landfall, zone D

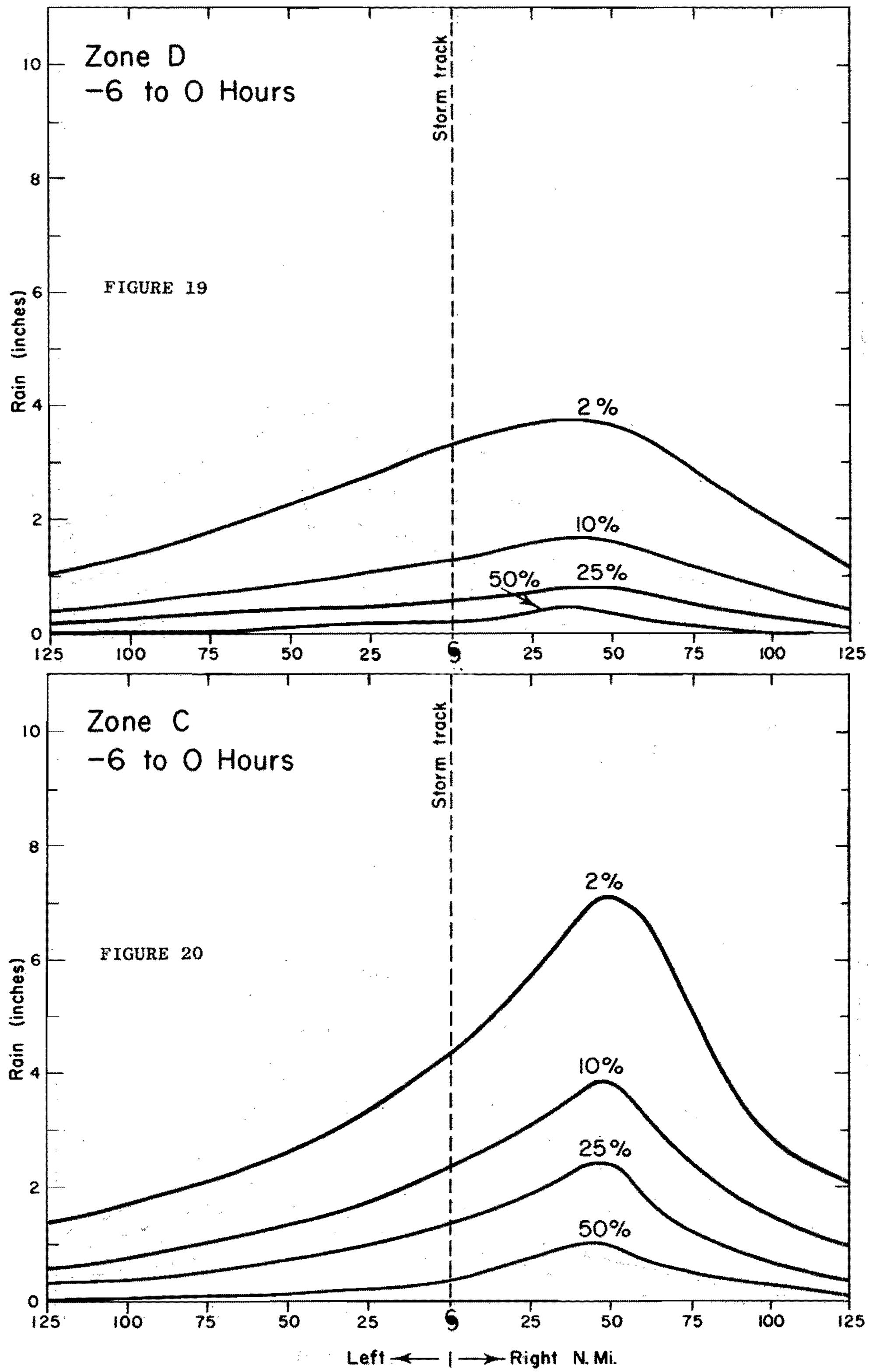


FIGURES 15–16.—Rainfall for 12-hour period preceding landfall for selected frequency levels, zones C and B

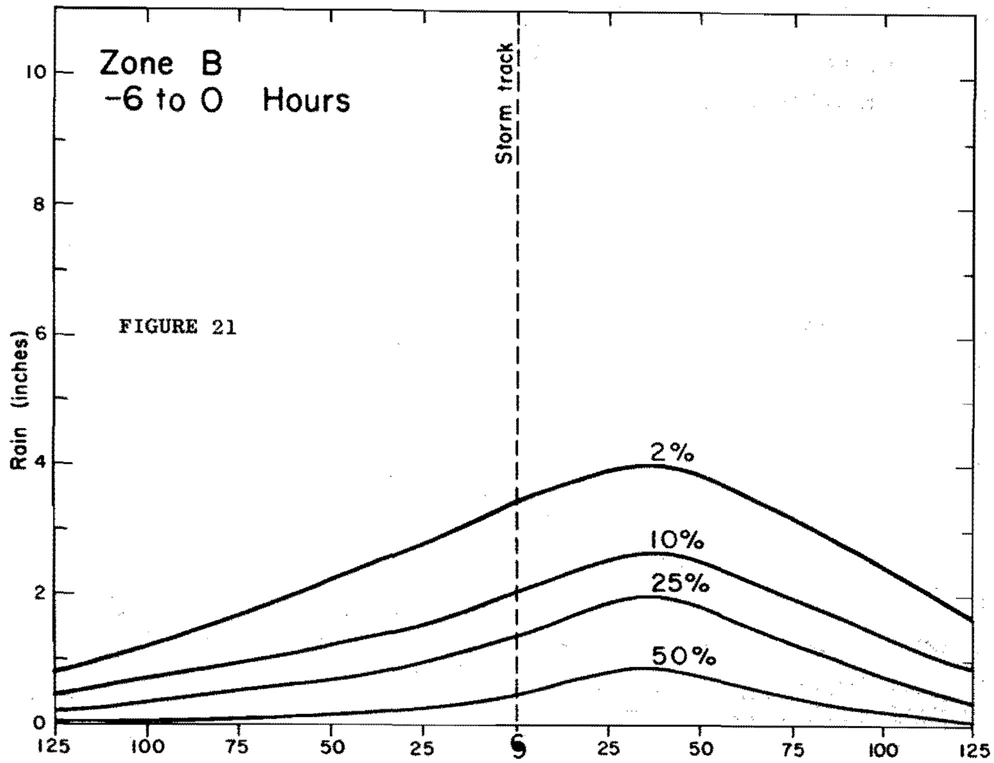


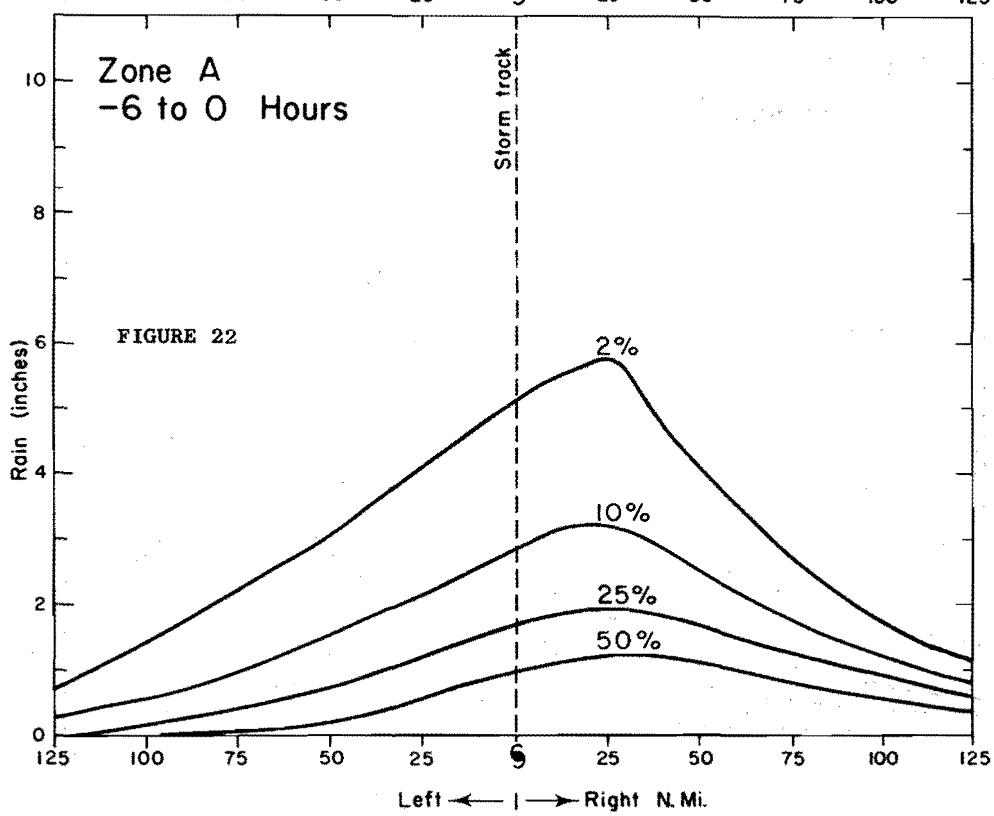


FIGURES 17–18.—Rainfall for 12-hour period preceding landfall for selected frequency levels, zones A and E

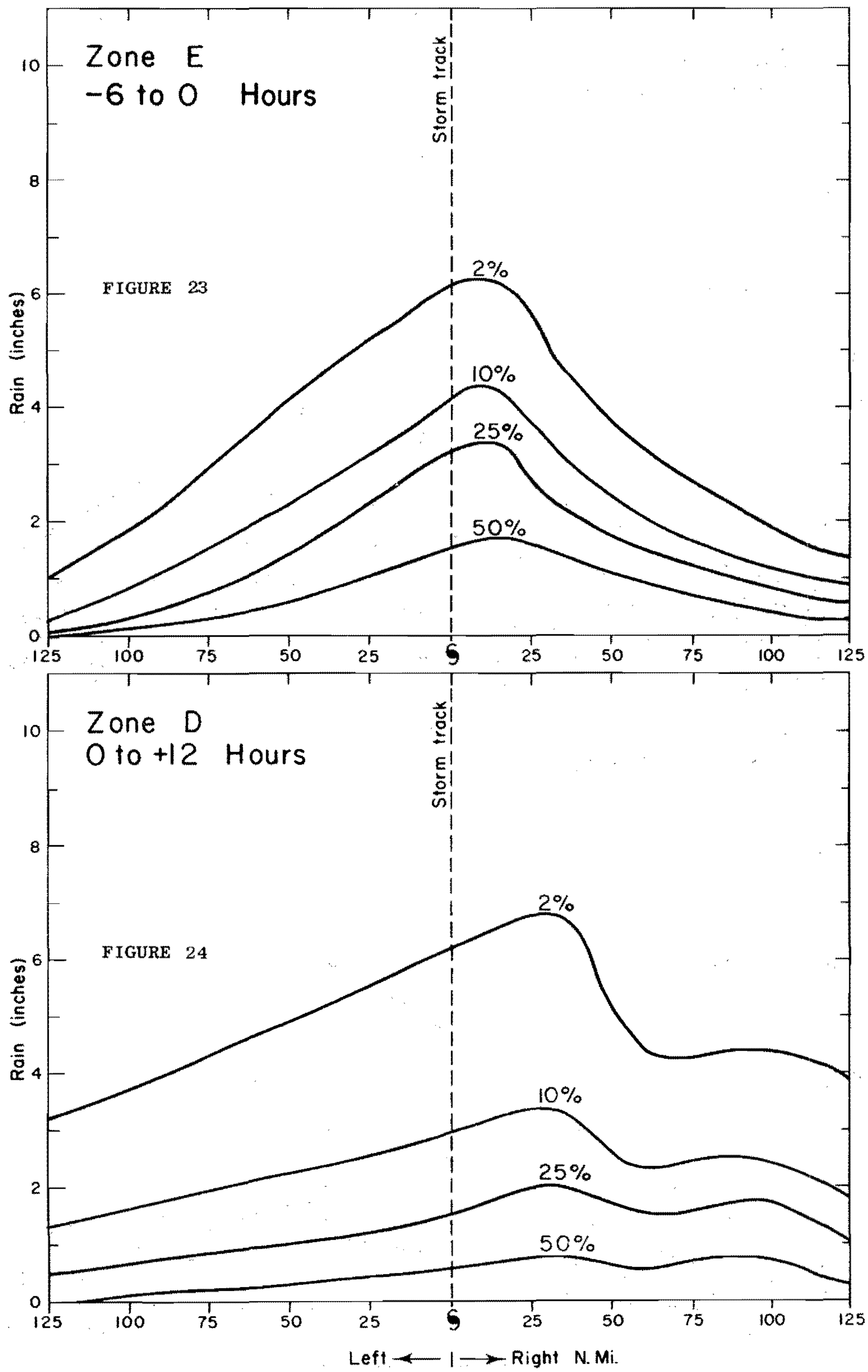


FIGURES 19–20.—Rainfall for 6-hour period preceding landfall for selected frequency levels, zones D and C

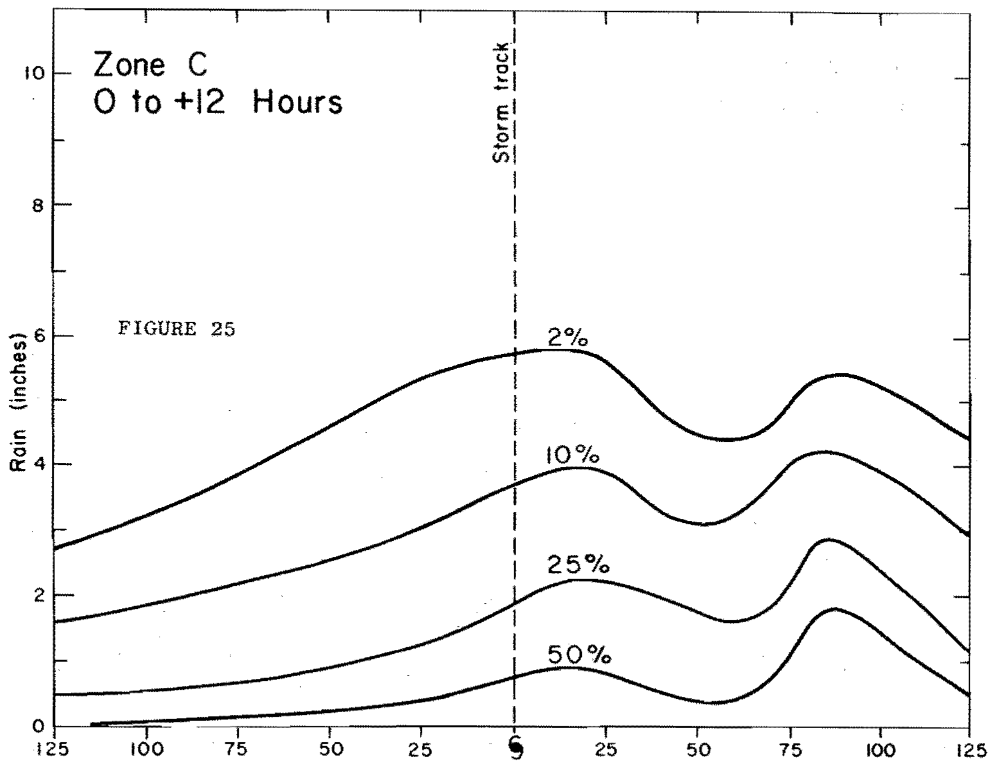


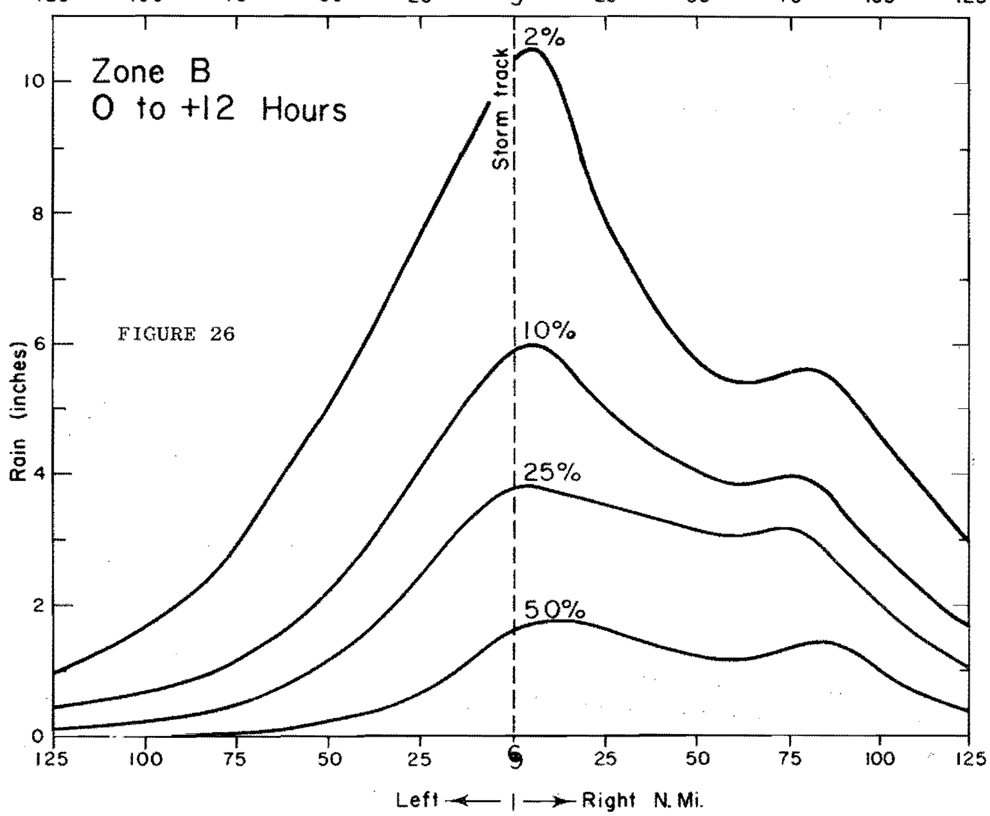


FIGURES 21–22.—Rainfall for 6-hour period preceding landfall for selected frequency levels, zones B and A

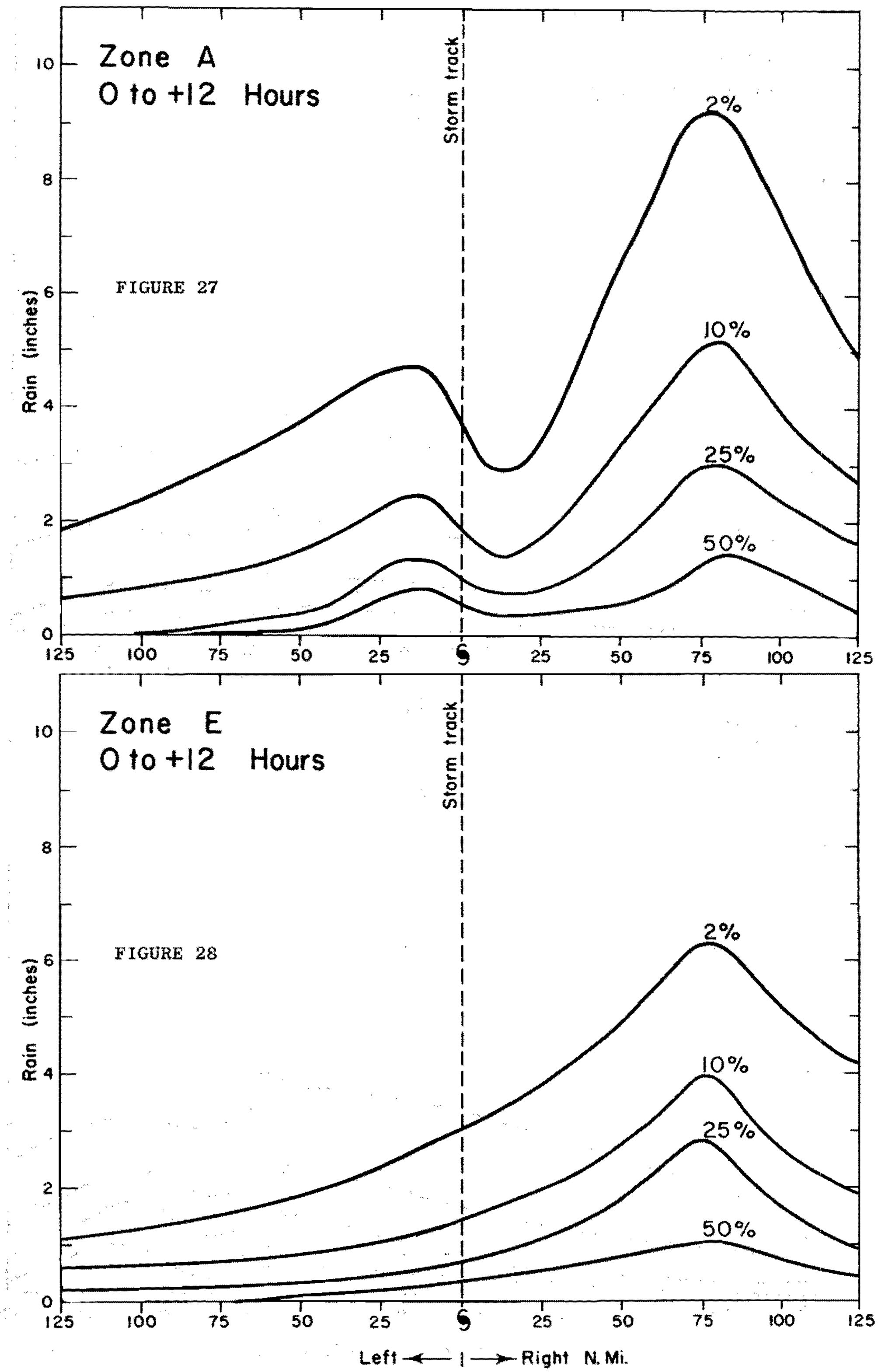


FIGURES 23–24.—Rainfall for 6-hour period preceding landfall, zone E, and 12-hour period after landfall, zone D, for selected frequency levels

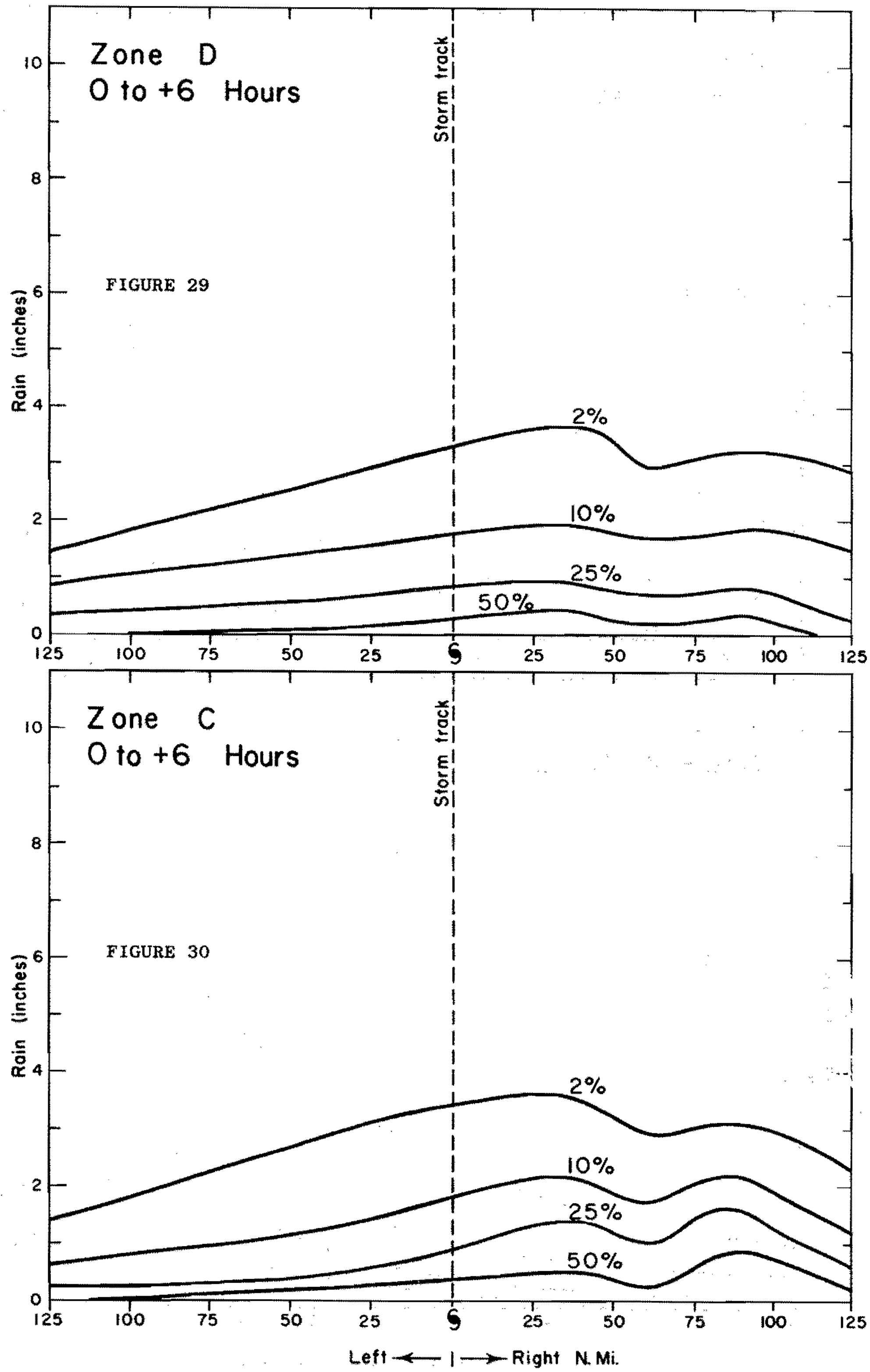




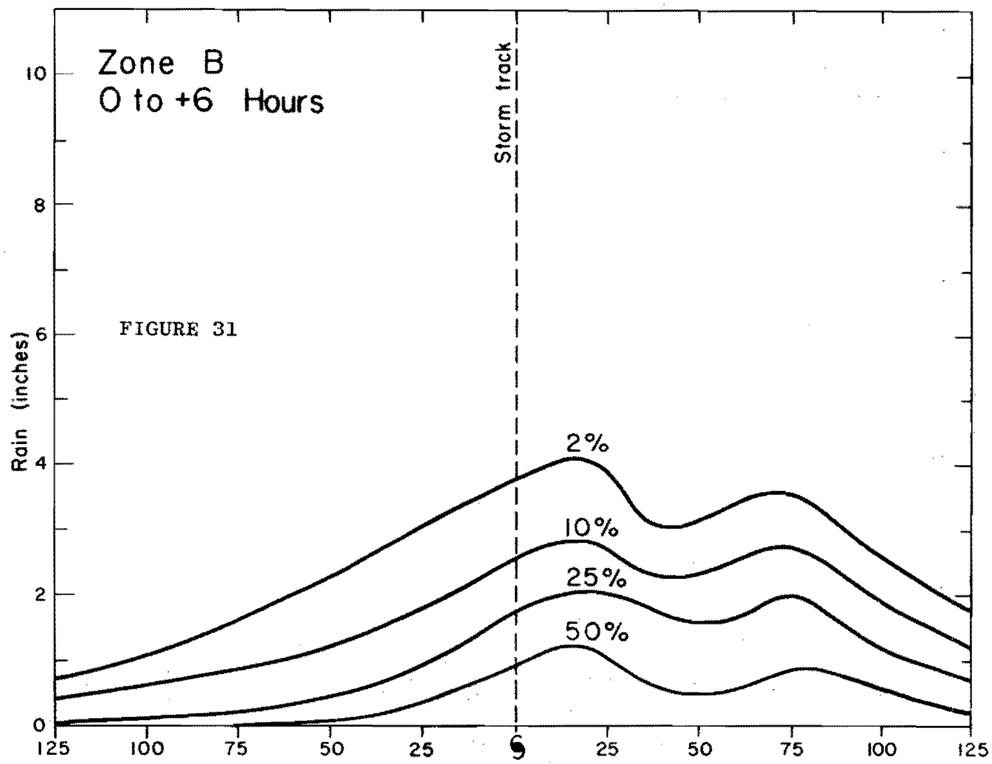
FIGURES 25–26.—Rainfall for 12-hour period after landfall for selected frequency levels, zones C and B

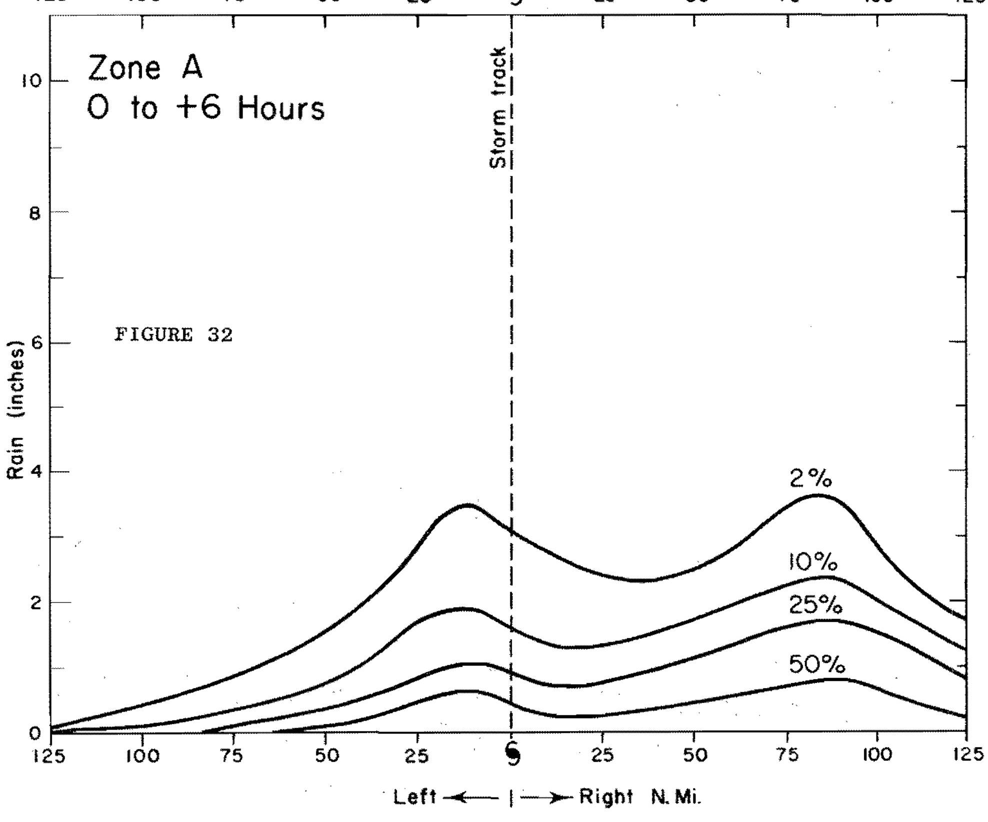


FIGURES 27–28.—Rainfall for 12-hour period after landfall for selected frequency levels, zones A and E

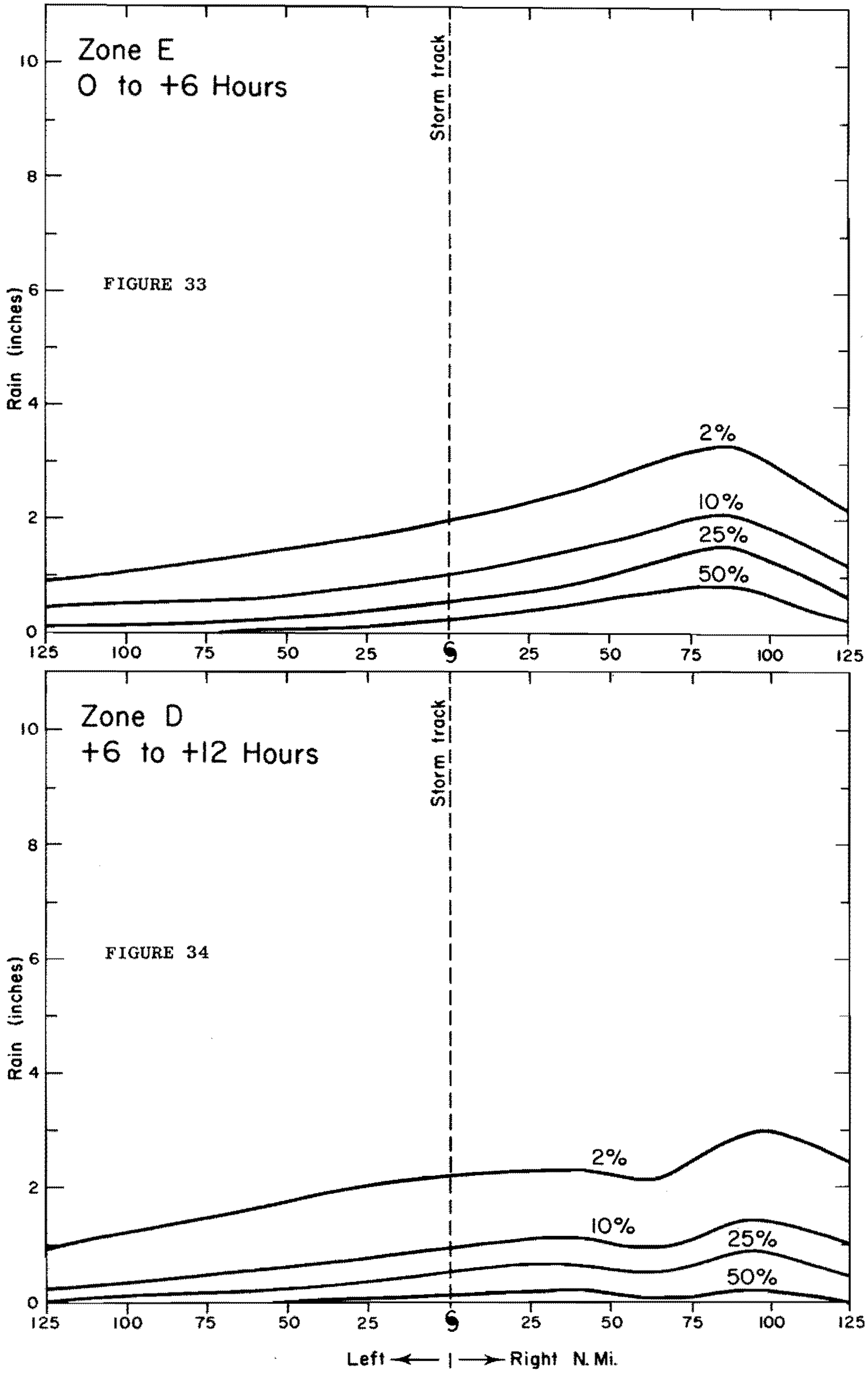


FIGURES 29–30.—Rainfall for 6-hour period after landfall for selected frequency levels, zones D and C

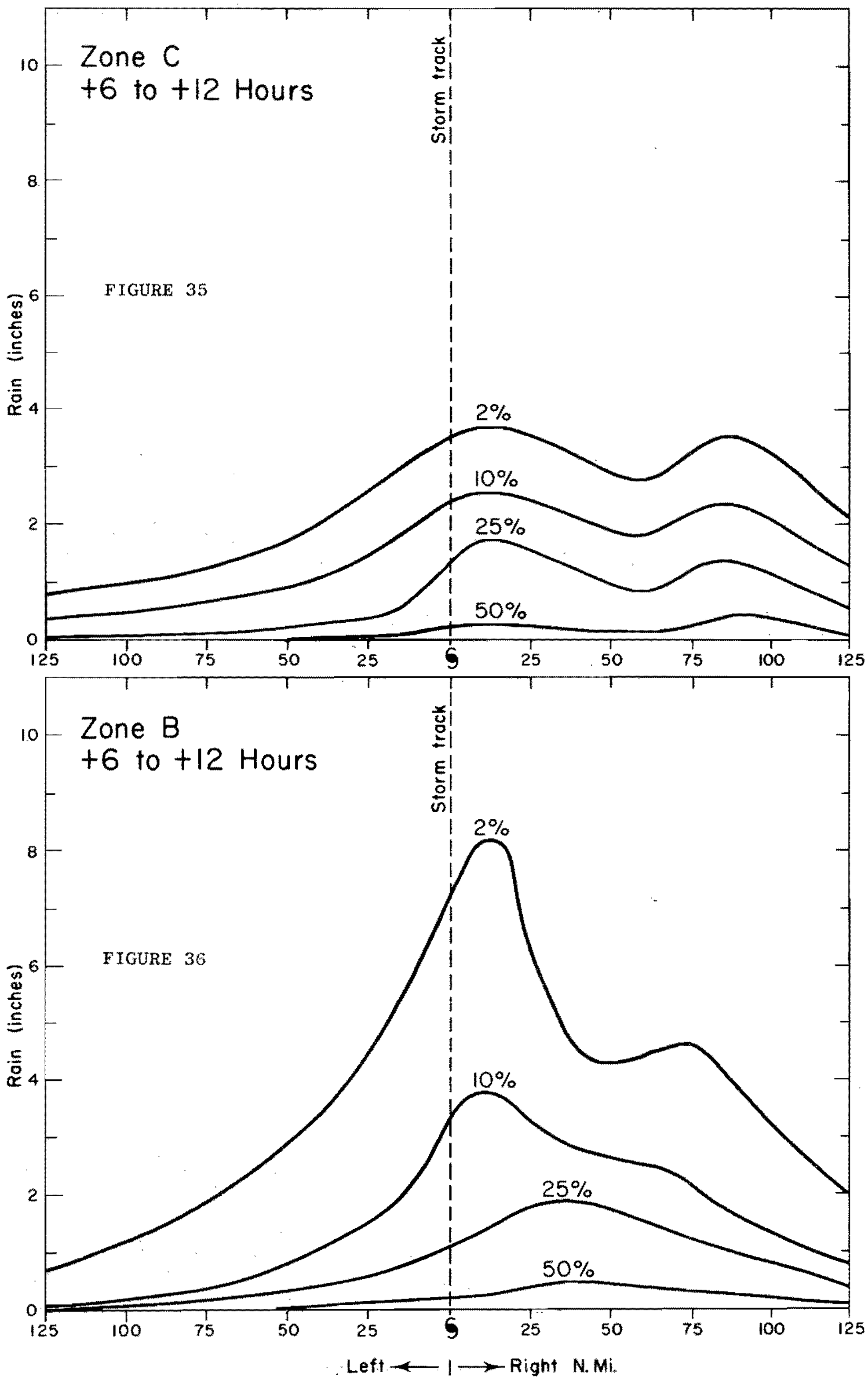




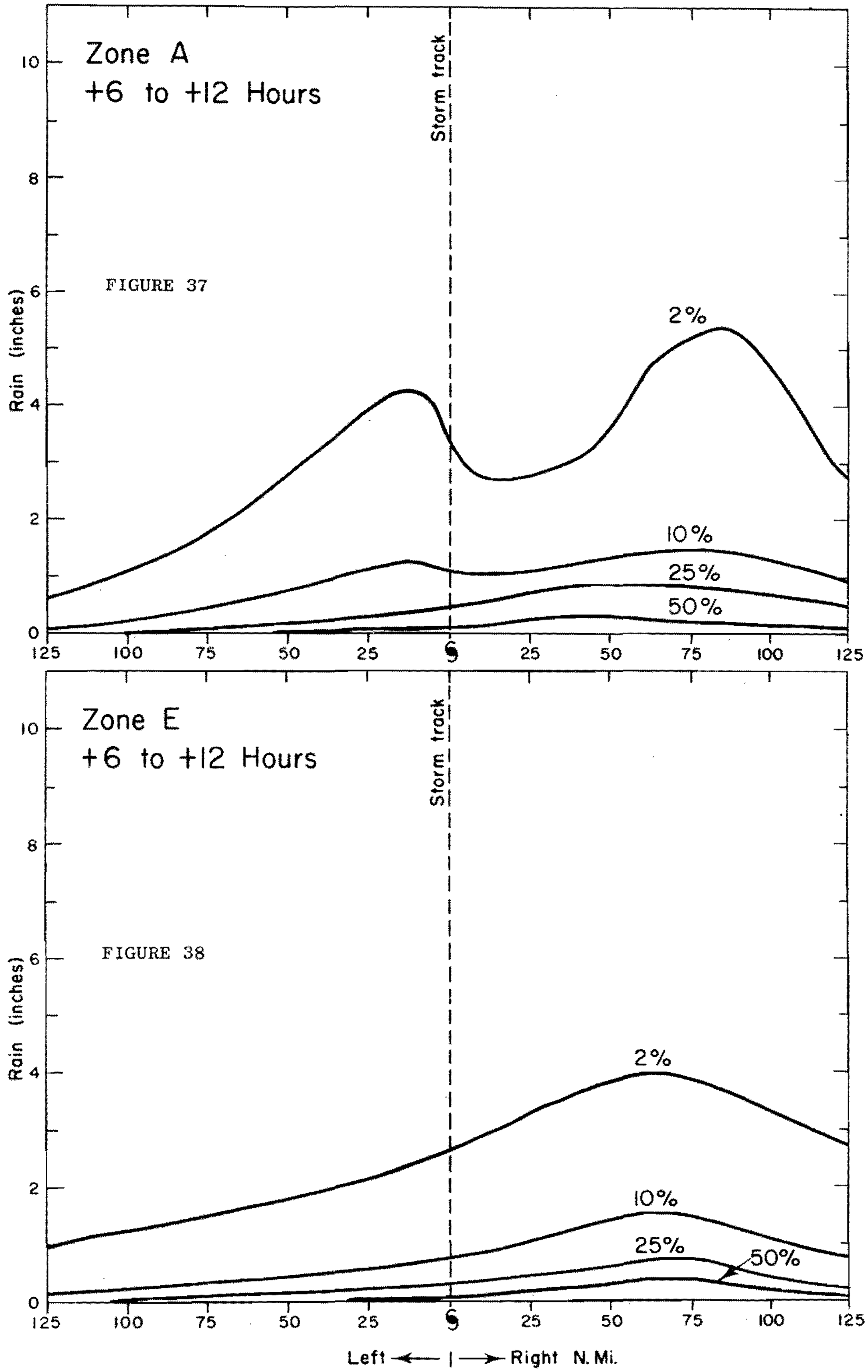
FIGURES 31–32.—Rainfall for 6-hour period after landfall for selected frequency levels, zones B and A



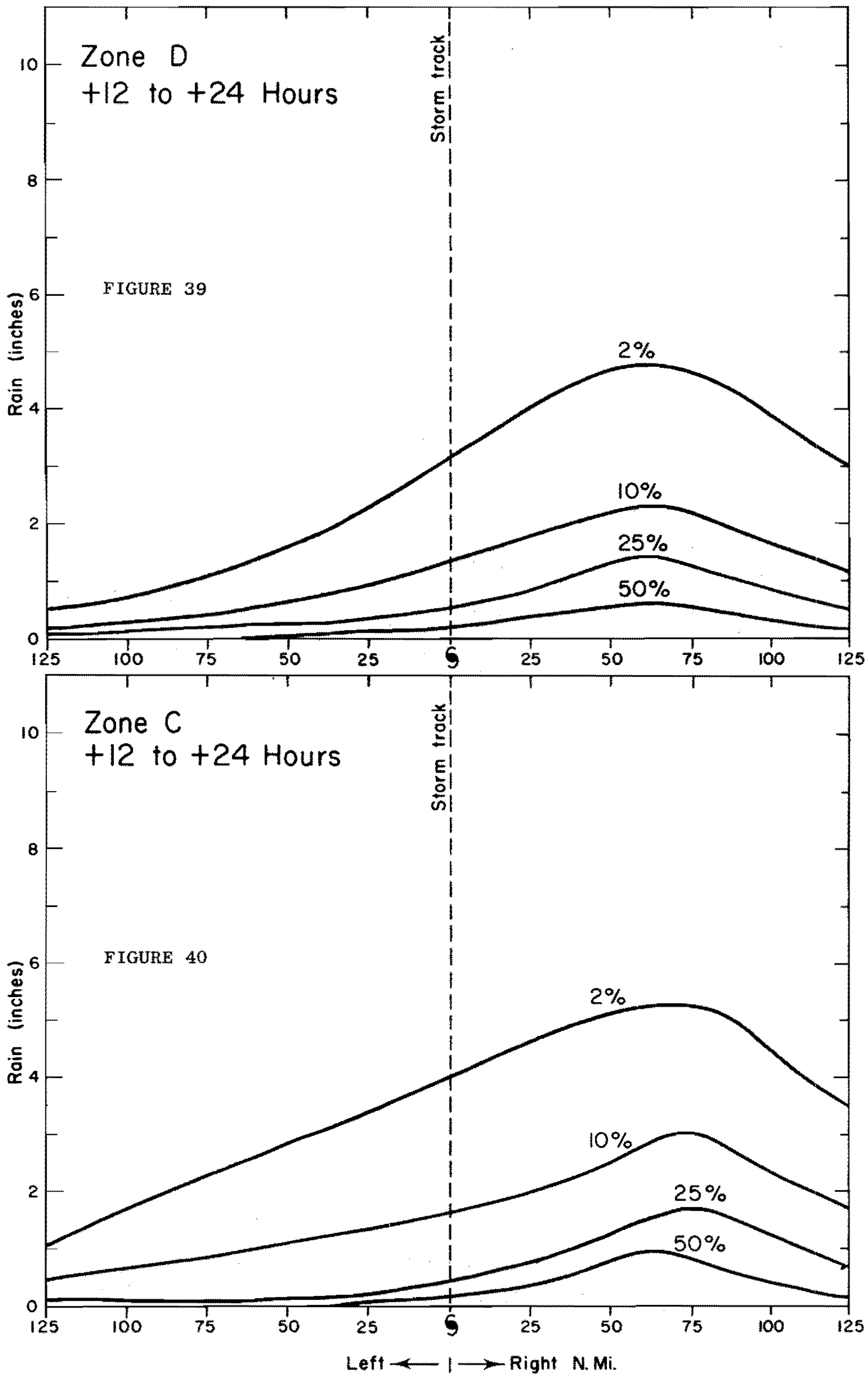
FIGURES 33-34.—Rainfall for first 6-hour period after landfall, zone E, and second 6-hour period after landfall, zone D, for selected frequency levels



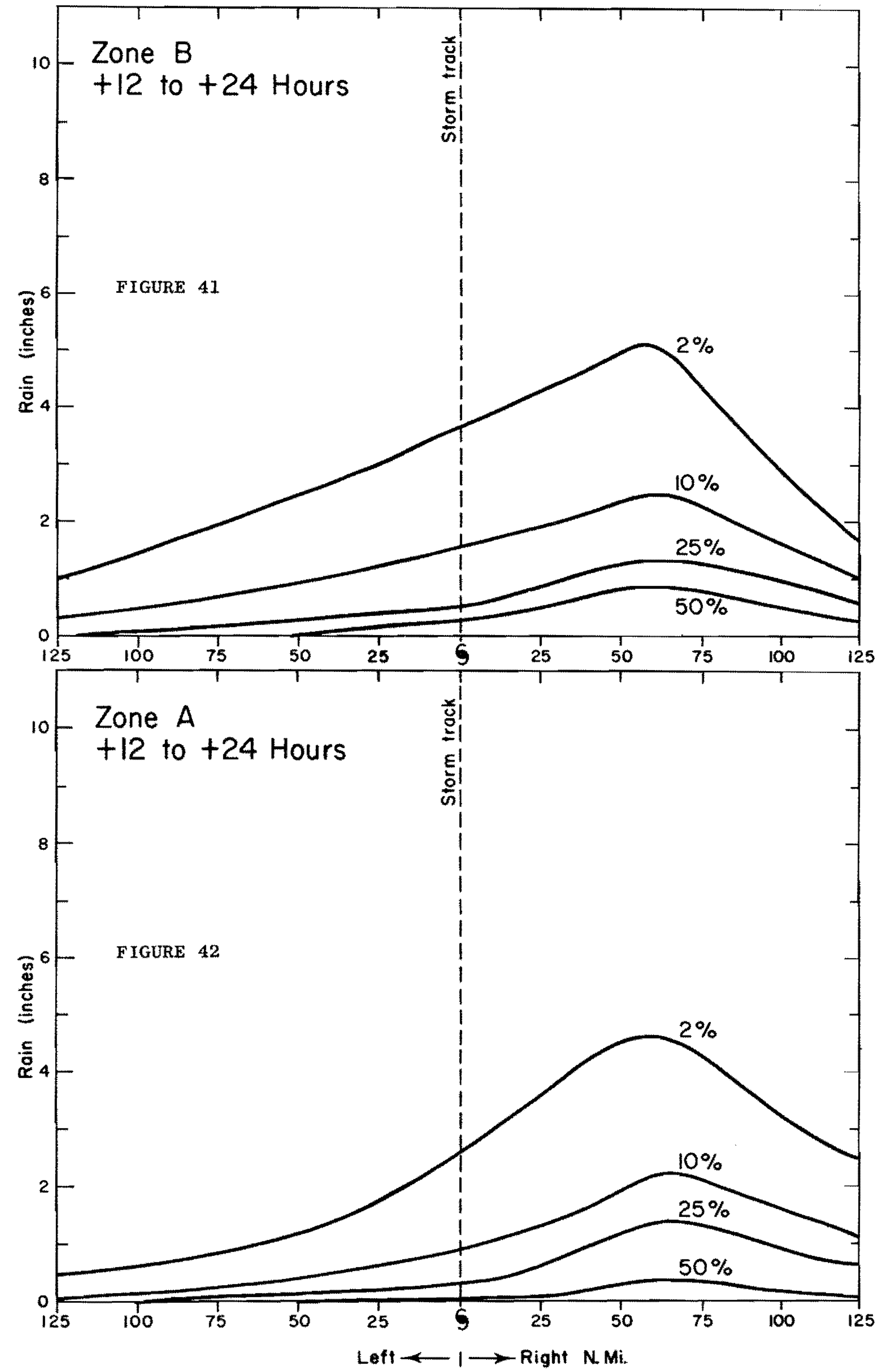
FIGURES 35–36.—Rainfall for the second 6-hour period after landfall for selected frequency levels, zones C and B



FIGURES 37–38.—Rainfall for the second 6-hour period after landfall for selected frequency levels, zones A and E



FIGURES 39–40.—Rainfall for the second 12-hour period after landfall for selected frequency levels, zones D and C



FIGURES 41–42.—Rainfall for the second 12-hour period after landfall for selected frequency levels, zones B and A

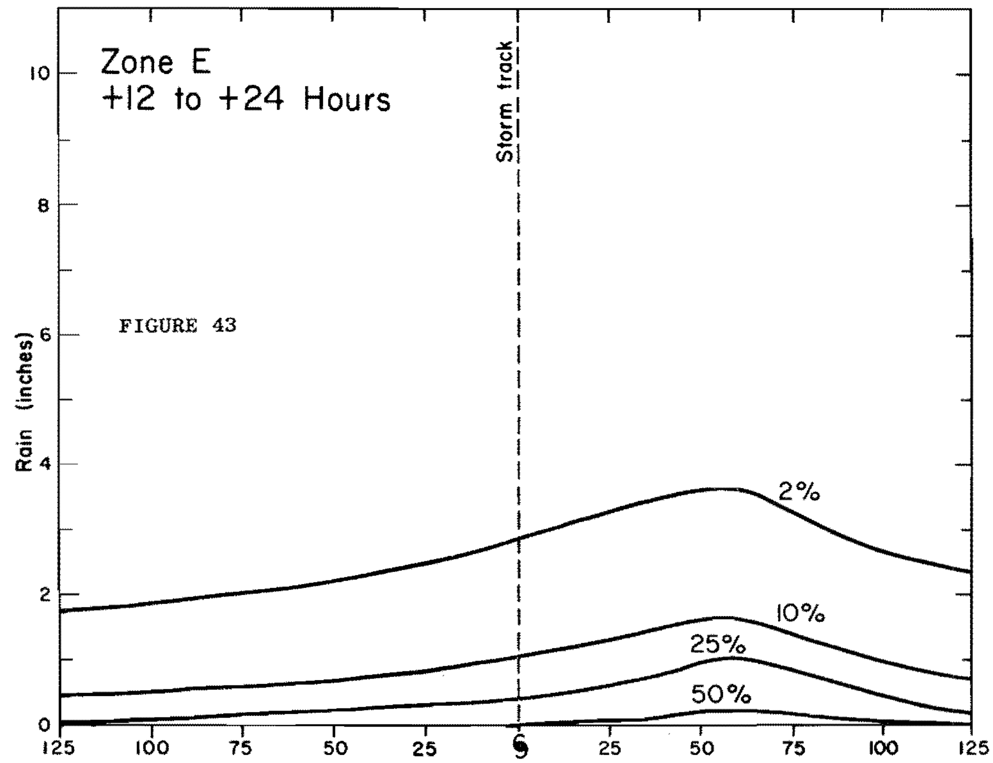


FIGURE 43.—Rainfall for the second 12-hour period after landfall for selected frequency levels, zone E

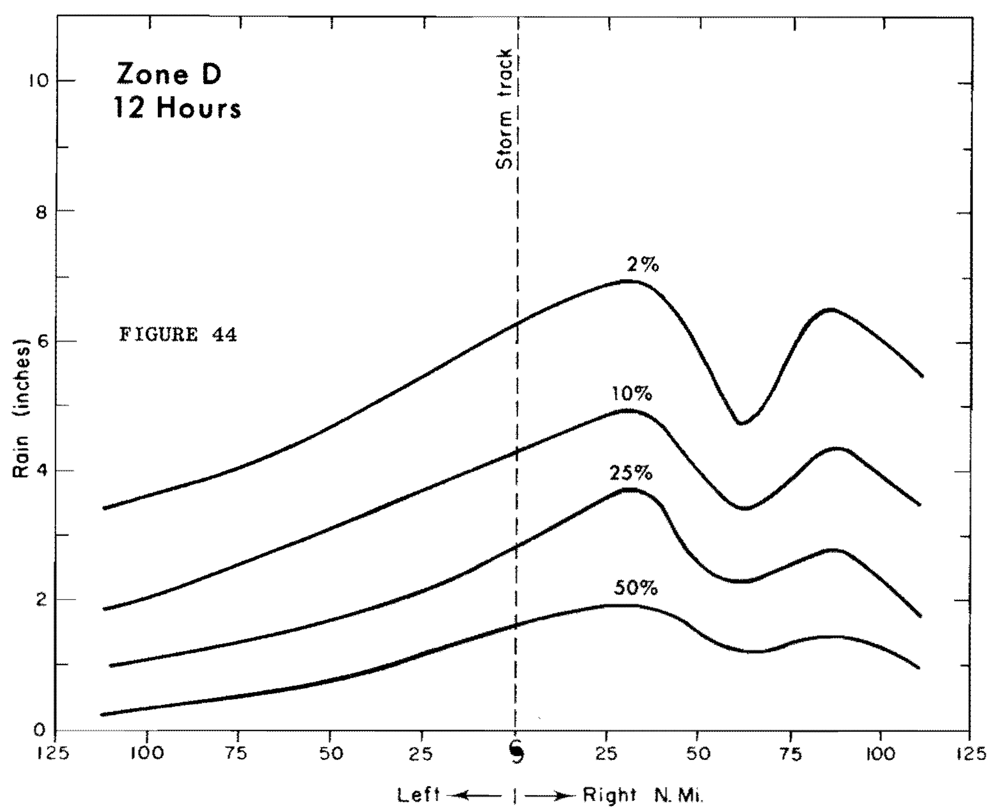
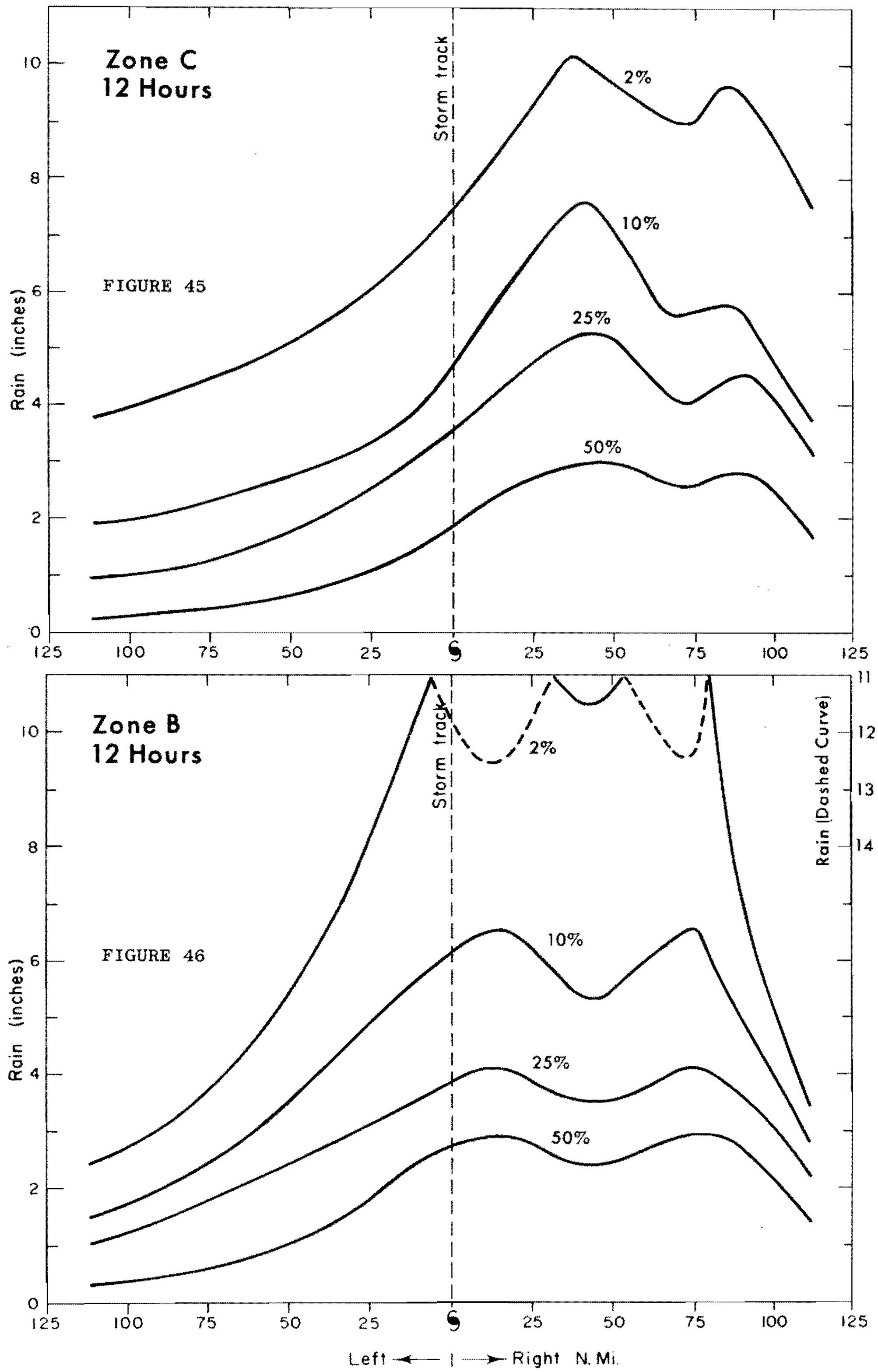
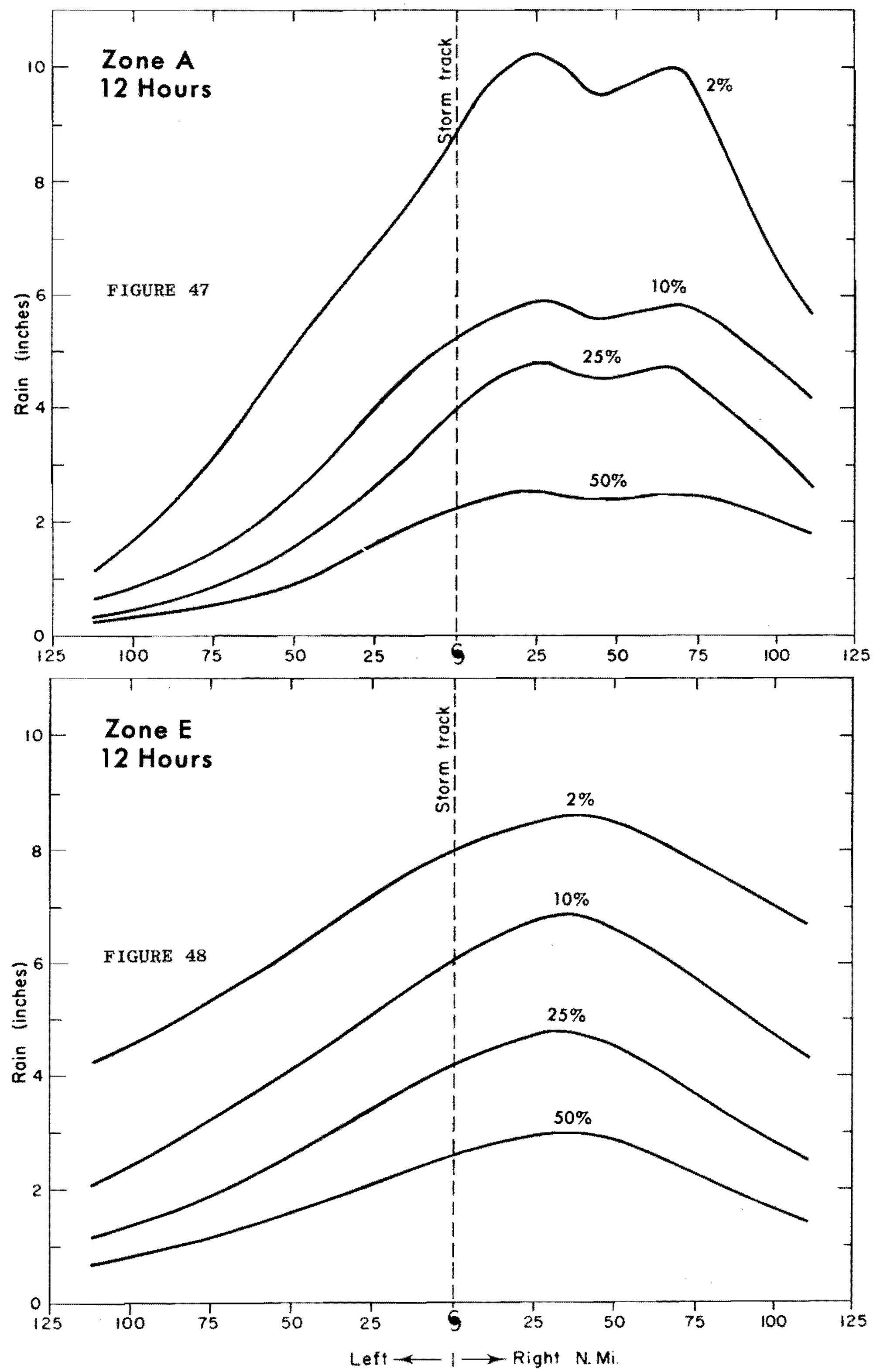


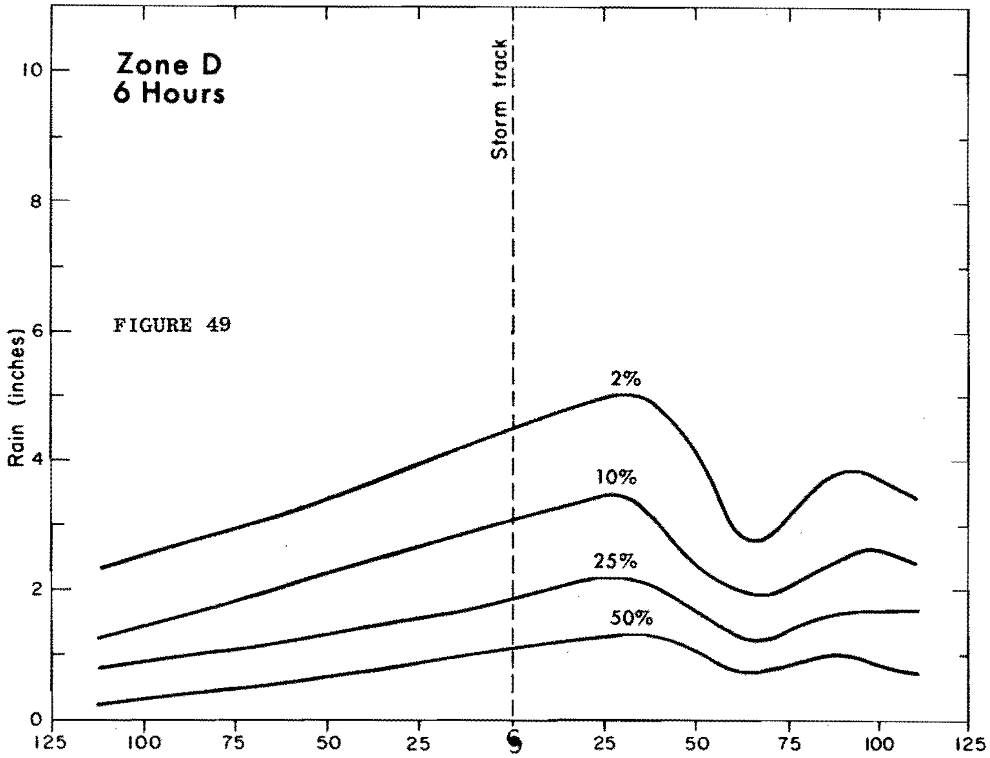
FIGURE 44.—Twelve-hour maximum point rainfall within 48-hour storm period for selected frequency levels, zone D

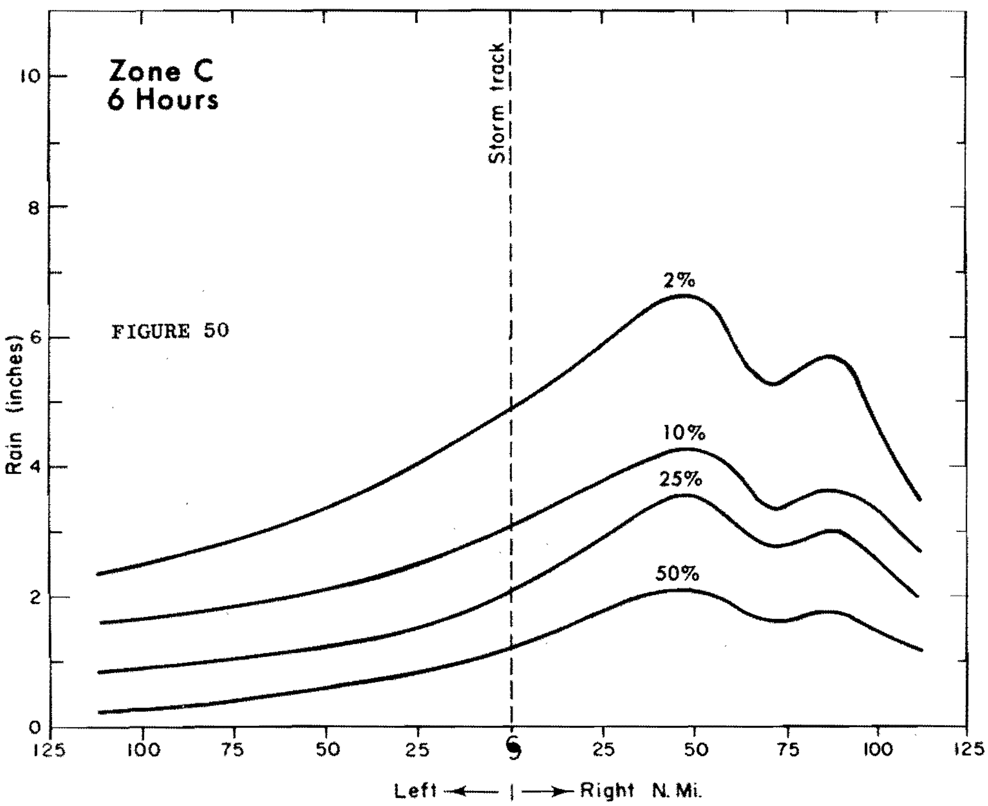


FIGURES 45–46.—Twelve-hour maximum point rainfall within 48-hour storm period for selected frequency levels, zones C and B

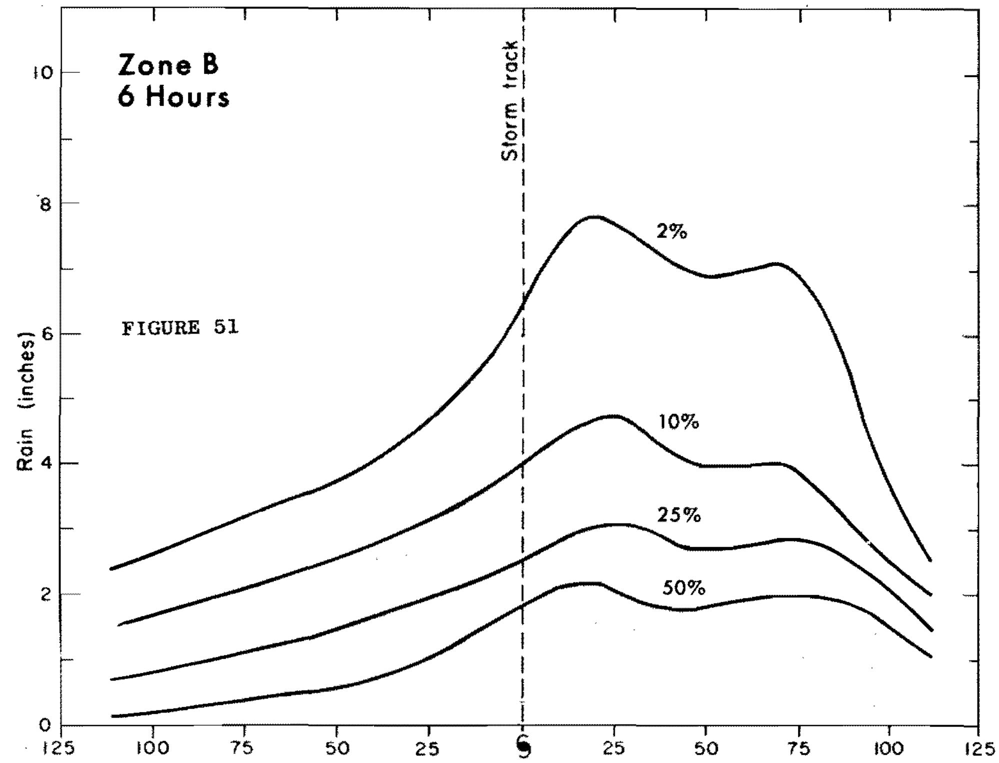


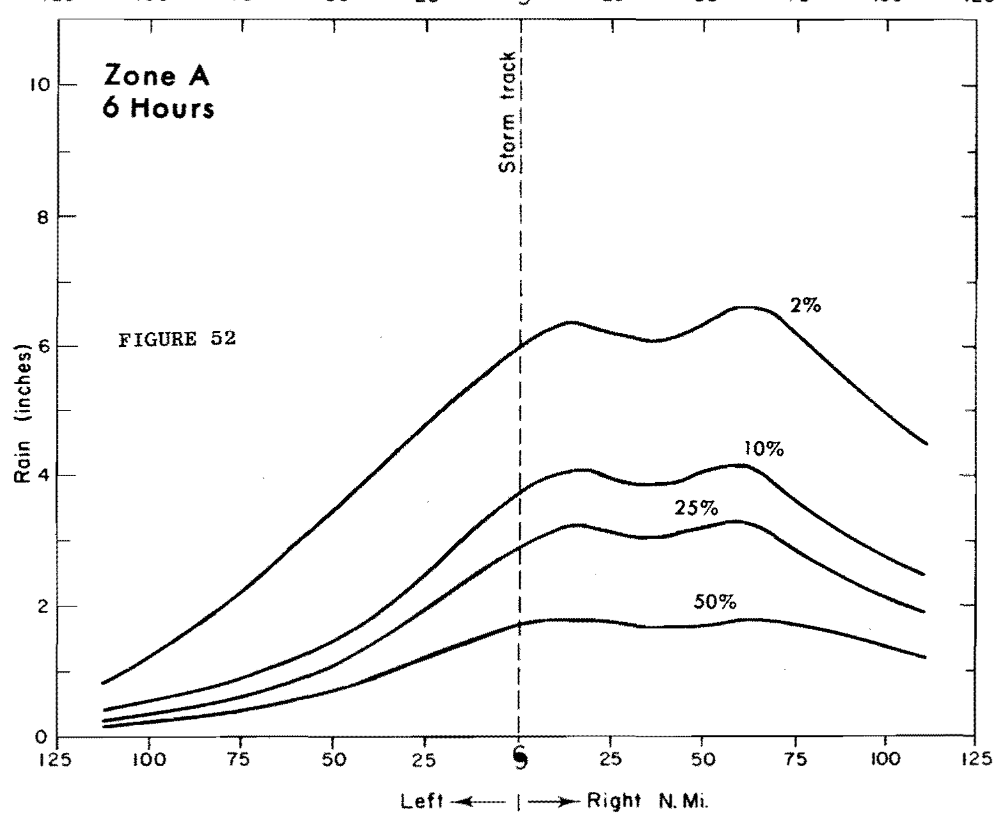
FIGURES 47–48.—Twelve-hour maximum point rainfall within 48-hour storm period for selected frequency levels, zones A and E





FIGURES 49–50.—Six-hour maximum point rainfall within 48-hour storm period for selected frequency levels, zones D and C





FIGURES 51–52.—Six-hour maximum point rainfall within 48-hour storm period for selected frequency levels, zones B and A

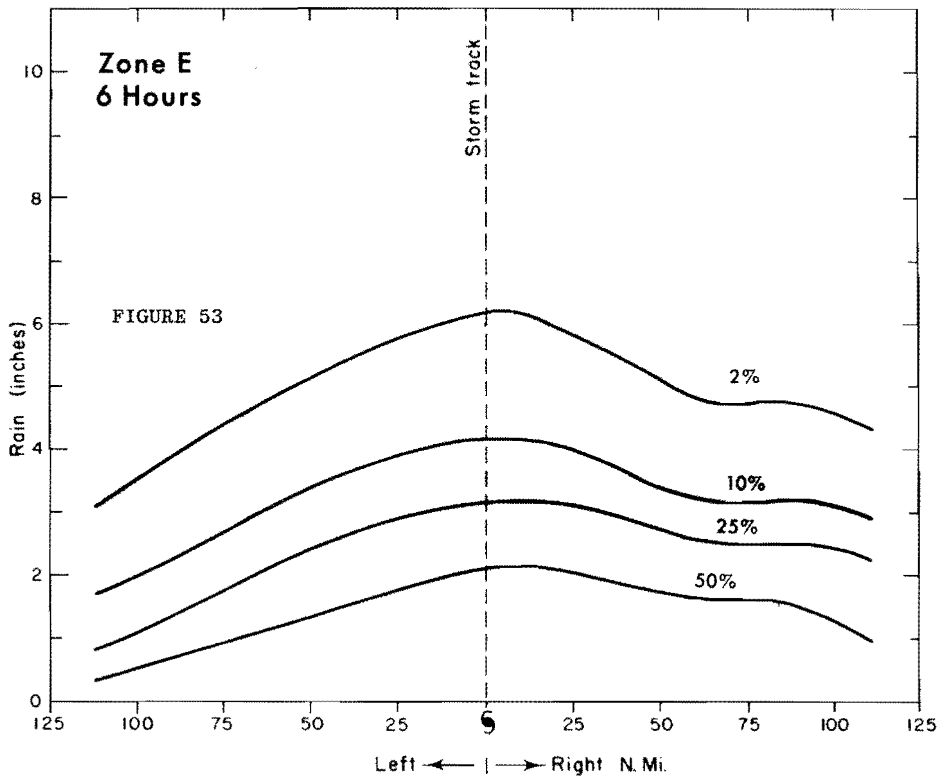


FIGURE 53.—Six-hour maximum point rainfall within 48-hour storm period for selected frequency levels, zone E

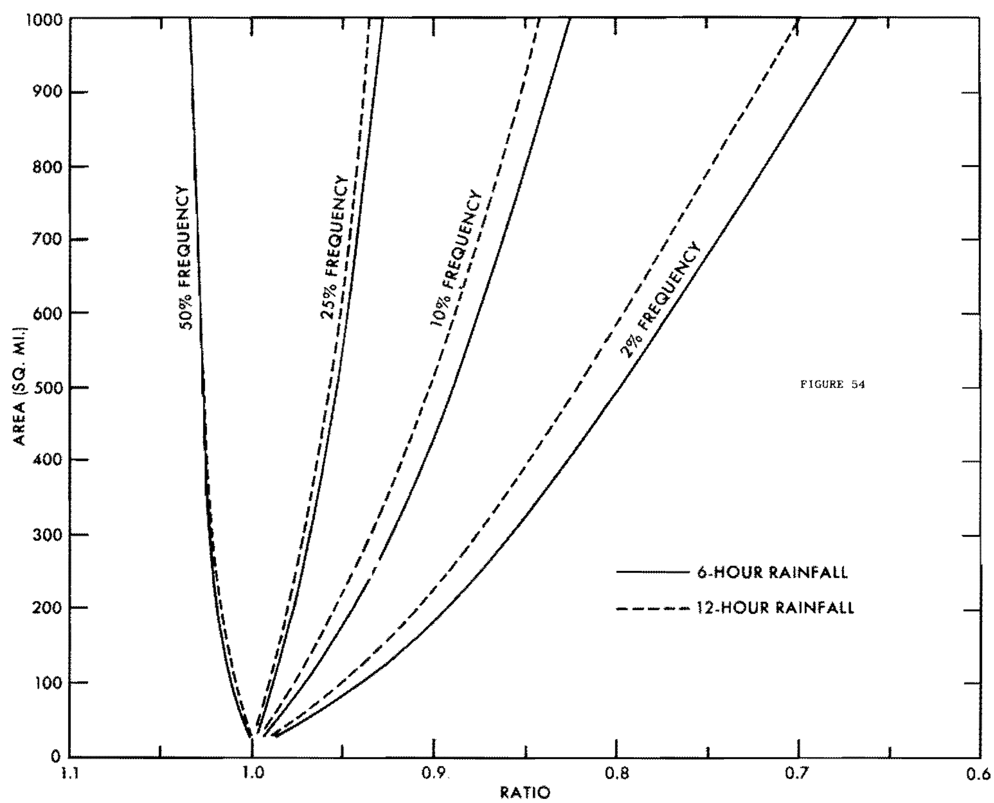


FIGURE 54.—Ratios of areal rainfall to point rainfall for selected frequency levels

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