# Maximum Rainfall from Tropical Cyclone Systems which Cross the Appalachians

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ABSTRACT

The results of a statistical study of maximum measured rainfall amounts of tropical cyclone systems whose paths cross the Appalachian Mountains are presented. The study includes storms from 1900 through 1969 and considers primarily the maximum recorded rainfall in mountainous terrain. The criteria are that the tropical cyclone had to pass the 1000-ft contour and that the precipitation was measured inside the outermost 1000-ft contour. In some cases the maxima were recorded at altitudes below the 1000-ft contour; these locations were in valleys surrounded by higher elevations. Supplemental information is presented for maximum rainfall anywhere after storm landfall, although passage of the system over the Appalachian region remained a criterion.

The data are modelled by the gamma distribution. Probabilities of exceeding a specified rainfall amount and rainfall amounts for specified probability levels are presented in tabular and graphical form.

## 1. Introduction

The threats of high winds, waves and storm surges generated by tropical cyclones in coastal areas are widely recognized. The threat from these systems of sudden and severe floods in the mountains is less fully recognized. Heavy amounts of rainfall, particularly in short time periods, can be severely damaging. In this paper rainfall amounts from tropical cyclone systems whose centers crossed the Appalachians or encountered the 1000-ft contour of this range are studied. The 1000-ft contour was chosen arbitrarily in order to permit a decision in each case as to whether a system would be included in the study.

Tropical storm rainfall has been studied by previous investigators. Background is provided by authors such as Schoner and Molansky (1956) and Dunn and Miller (1960). Cry (1965) provides information on the tracks and frequencies of hurricanes and tropical storms, 1871–1963, and in 1967 provides detailed information on the effects of tropical cyclone rainfall. Goodyear (1968) presented information on 46 well-developed tropical storms that crossed the Gulf Coast between Apalachicola, Fla., and Brownsville, Tex., during the years 1940–65. He found that the rainfall pattern along the coast and near the point of landfall was, in general, well-organized. This pattern exhibits significant variations in the placement and timing of average and maximum point rainfalls during the 24 hr preceding and following landfall. He defined landfall as both the time and place of entry of the low pressure center. Alaka (1968) presented a climatology of Atlantic tropical storms and hurricanes. DeAngelis (1969) discussed hurricane Camille. A bibliography on hurricanes and severe storms of the Coastal Plains Region was given by the Coastal Plains Center for Marine Development Services (1970). A detailed study of Camille was made by Schwarz (1970). Another study report on Camille is by Dikkers *et al.* (1971).

The statistics presented in this study differ from those presented by other investigators. A subset of data is treated, the subset being only the maximum point rainfall measured from tropical cyclones which passed over or encountered the Appalachians after landfall. Maximum rainfall amounts which fell within a 24-hr period and during the total storm period are studied. The maximum of all storms could fall in less than a 24-hr period. In the case of Camille this actually occurred. Clearly, all of the probabilities given here are conditional. In addition, these probabilities are not restricted to any one specified geographic point. Probabilities of specified amounts of rainfall will be presented in both tabular and graphical form. This study is a report on only one aspect of the tropical cyclone phenomenon.

Alaka (1968) indicates that point rainfall measurements underestimate the true amounts. The loss from raingages may amount to 50% when the wind reaches or exceeds 22.5 m sec$^{-1}$. He refers to Dunn's (1951) article. To the extent that this is true, the statistics of point recorded rainfall presented herein will underestimate the probability of a stated rainfall amount.

## 2. Source of data

The general sources of data are the publications of the U. S. Government. Some of these are as follows:

1. Technical Paper series of the U. S. National

TABLE 1. Maximum recorded 24-hr precipitation in the Appalachian region of the United States from tropical cyclone systems crossing the 1000-ft contour. Period of record 1900–69, inclusive.

| No. | Precipitation (inches) | Latitude (N) | Longitude (W) | Elevation (ft) | Month | Dates | Year | Location |
|---|---|---|---|---|---|---|---|---|
| 1 | 31.00** | 37.39 | 78.57 | 600 | Aug | 19–20 | 1969 | Tye River, Va. |
| 2 | 2.82 | 43.19 | 75.07 | 1190 | June | 26 | 1968 | Hickley, N. Y. |
| 3 | 3.98 | 35.18 | 82.55 | 5400 | Sept | 12 | 1965 | Haywood Gap, N. C. |
| 4 | 4.02 | 42.19 | 74.01 | 340 | July | 30 | 1960 | Cairo, N. Y. |
| 5 | 9.50 | 38.31 | 78.26 | 3535 | Sept | 30 | 1959 | Big Meadows, Va. |
| 6 | 4.50 | 40.29 | 83.53 | 1000 | June | 28 | 1957 | Russels Point, Ohio |
| 7 | 11.40 | 42.01 | 74.25 | 2650 | Aug | 12–13 | 1955 | Slide Mt., N. Y. |
| 8 | 10.71 | 38.31 | 78.26 | 3535 | Oct | 15 | 1954 | Big Meadiws, Va. |
| 9 | 6.31 | 41.24 | 76.35 | 2020 | Aug | 30–31 | 1954 | Eagles Mere, Pa. |
| 10* | 4.95 | 40.16 | 77.22 | 650 | Sept | 1 | 1952 | Bloserville 1-N, Pa, |
| 11* | 5.64 | 35.41 | 82.20 | 2765 | Aug | 28 | 1949 | North Ford #1, N. C. |
| 12 | 5.51 | 36.01 | 81.56 | 3430 | Sept | 17 | 1945 | Crossnore, N. C. |
| 13 | 13.40 | 38.31 | 78.26 | 3535 | Oct | 14–15 | 1942 | Big Meadows, Va. |
| 14* | 9.72 | 35.46 | 81.26 | 1050 | Aug | 13 | 1940 | Rhodhiss Dam, N. C. |
| 15* | 6.47 | 35.07 | 82.36 | 3118 | Aug | 18 | 1939 | Caesars Head, S. C. |
| 16 | 10.16 | 42.29 | 72.00 | 1030 | Sept | 20 | 1938 | Hubbardston, Mass. |
| 17* | 4.21 | 37.38 | 79.27 | 725 | June | 18 | 1934 | Balcony Falls, Va. |
| 18 | 11.60 | 41.56 | 74.23 | 1415 | Aug | 23–24 | 1933 | Peekamoose, N. Y. |
| 19 | 4.75 | 35.07 | 82.36 | 3118 | Sept | 21 | 1932 | Caesars Head, S. C. |
| 20 | 6.85 | 35.00 | 83.06 | 3100 | Oct | 16 | 1932 | Rockhouse, N. C. (Horse Cove) |
| 21* | 6.25 | 35.00 | 83.06 | 3100 | Sept | 25 | 1929 | Rockhouse, N. C. (Horse Cove) |
| 22* | 3.42 | 37.16 | 79.56 | 907 | Sept | 19 | 1928 | Roanoke, Va. |
| 23 | 11.80 | 35.07 | 82.36 | 3118 | Aug | 15 | 1928 | Caesars Head, S. C. |
| 24 | 0.80 | 41.46 | 74.09 | 1245 | Oct | 19 | 1923 | Mohonk Lake, N. Y. |
| 25 | 3.69 | 41.37 | 73.53 | 150 | Oct | 24 | 1923 | Wappinger Falls, N. Y. |
| 26 | 3.10 | 35.11 | 82.12 | 1063 | Sept | 23 | 1920 | Landrum, S. C. |
| 27 | 22.22 | 35.54 | 82.02 | 2740 | July | 16 | 1916 | Altapass, N. C. |
| 28* | 7.43 | 35.02 | 83.12 | 3850 | July | 9 | 1916 | Highlands, N. C. |
| 29* | 5.00 | 34.59 | 85.21 | 2100 | Oct | 1 | 1915 | Lookout Mt., Tenn. |
| 30* | 4.58 | 35.02 | 83.12 | 3850 | Sept | 5 | 1915 | Highlands, N. C. |
| 31 | 4.46 | 34.00 | 84.12 | 1025 | June | 14 | 1912 | Norcross, Ga. |
| 32 | 8.00 | 35.00 | 83.06 | 3100 | Sept | 18 | 1906 | Horse Cove, N. C. (Rockhouse) |
| 33 | 3.73 | 35.12 | 85.55 | 1950 | Oct | 10–11 | 1902 | Sewanee, Tenn. |
| 34 | 3.50 | 36.05 | 81.52 | 3800 | Sept | 28 | 1901 | Linville, N. C. |
| 35* | 6.20 | 36.49 | 85.30 | 631 | Sept | 13 | 1900 | Marrobone, Ky. |
| 36* | 0.67 | 44.25 | 72.00 | 711 | Sept | 11 | 1900 | St. Johnsbury, Vt. |

* Station *not* same as "Total Max Precip" as shown in Table 2.
** This value is in doubt. An accepted verified value is 27.00 inches which occurred at Massies Mill, Va. (Schwarz, 1970).

TABLE 2. Maximum recorded total precipitation in the Appalachian region of the United States from tropical cyclone systems crossing the 1000-ft contour. Period of record 1900–69, inclusive.

| No. | Precipitation (inches) | Latitude (N) | Longitude (W) | Elevation (ft) | Month | Dates | Year | Location |
|---|---|---|---|---|---|---|---|---|
| 1 | 31.00* | 37.39 | 78.57 | 600 | Aug | 19–20 | 1969 | Tye River, Va. |
| 2 | 3.74 | 43.19 | 75.07 | 1190 | June | 26–27 | 1968 | Hickley, N. Y. |
| 3 | 5.04 | 35.18 | 82.55 | 5400 | Sept | 11–12 | 1965 | Haywood Gap, N. C. |
| 4 | 4.02 | 42.19 | 74.01 | 340 | July | 30 | 1960 | Cairo, N. Y. |
| 5 | 10.84 | 38.31 | 78.26 | 3535 | Sept | 29–30 | 1959 | Big Meadows, Va. |
| 6 | 4.50 | 40.29 | 83.53 | 1000 | June | 28 | 1957 | Russels Point, Ohio |
| 7 | 15.15 | 42.01 | 74.25 | 2650 | Aug | 11–14 | 1955 | Slide Mt., N. Y. |
| 8 | 11.22 | 38.31 | 78.26 | 3535 | Oct | 15–16 | 1954 | Big Meadows, Va. |
| 9 | 6.31 | 41.24 | 76.35 | 2020 | Aug | 30–31 | 1954 | Eagles Mere, Pa. |
| 10 | 6.18 | 39.56 | 77.38 | 640 | Aug-Sept | 31–2 | 1952 | Chambersburg 1-ESE, Pa. |
| 11 | 6.28 | 42.42 | 74.55 | 1240 | Aug | 29–30 | 1949 | Cooperstown, N. Y. |
| 12 | 11.00 | 36.01 | 81.56 | 3430 | Sept | 13–18 | 1945 | Crossnore, N. C. |
| 13 | 18.93 | 38.31 | 78.26 | 3535 | Oct | 13–16 | 1942 | Big Meadows, Va. |
| 14 | 16.64 | 37.34 | 79.16 | 1000 | Aug | 12–17 | 1940 | Arnolds Valley, Va. |
| 15 | 11.07 | 34.35 | 83.20 | 1050 | Aug | 12–18 | 1939 | Toccoa, Ga. |
| 16 | 15.60 | 42.29 | 72.00 | 1030 | Sept | 17–21 | 1938 | Hubbardston, Mass. |
| 17 | 5.08 | 35.46 | 82.16 | 6684 | June | 17–18 | 1934 | Mt. Mitchell, N. C. |
| 18 | 16.00 | 41.56 | 74.23 | 1415 | Aug | 21–24 | 1933 | Peekamoose, N. Y. |
| 19 | 5.27 | 35.07 | 82.36 | 3118 | Sept | 20–21 | 1932 | Caesars Head, S. C. |
| 20 | 9.30 | 35.00 | 83.06 | 3100 | Oct | 15–17 | 1932 | Rockhouse, N. C. (Horse Cove) |

TABLE 2. (*continued*)

| No. | Precipitation (inches) | Latitude (N) | Longitude (W) | Elevation (ft) | Month | Dates | Year | Location |
|---|---|---|---|---|---|---|---|---|
| 21 | 16.36 | 34.19 | 83.38 | 950 | Sept-Oct | 25–2 | 1929 | Gillsville, Ga. |
| 22 | 4.58 | 35.57 | 80.00 | 912 | Sept | 18–20 | 1928 | High Point, N. C. |
| 23 | 13.47 | 35.07 | 82.36 | 3118 | Aug | 13–16 | 1928 | Caesars Head, S. C. |
| 24 | .80 | 41.46 | 74.09 | 1245 | Oct | 19 | 1923 | Mohonk Lake, N. Y. |
| 25 | 4.49 | 41.37 | 73.53 | 150 | Oct | 23–24 | 1923 | Wappinger Falls, N. Y. |
| 26 | 3.10 | 35.11 | 82.12 | 1063 | Sept | 23 | 1920 | Landrum, S. C. |
| 27 | 23.73 | 35.54 | 82.02 | 2740 | July | 14–17 | 1916 | Altapass, N. C. |
| 28 | 18.69 | 35.00 | 83.06 | 3100 | July | 6–11 | 1916 | Rockhouse, N. C. (Horse Cove) |
| 29 | 6.14 | 35.02 | 83.12 | 3850 | Sept-Oct | 30–1 | 1915 | Highlands, N. C. |
| 30 | 5.94 | 35.46 | 82.16 | 6684 | Sept | 4–5 | 1915 | Mt. Mitchell, N. C. |
| 31 | 4.46 | 34.00 | 84.12 | 1025 | June | 14 | 1912 | Norcross, Ga. |
| 32 | 8.00 | 35.00 | 83.06 | 3100 | Sept | 18 | 1906 | Horse Cove, N. C. (Rockhouse) |
| 33 | 3.79 | 35.12 | 85.55 | 1950 | Oct | 10–11 | 1902 | Sewanee, Tenn. |
| 34 | 3.50 | 36.05 | 81.52 | 3800 | Sept | 28 | 1901 | Linville, N. C. |
| 35 | 6.44 | 35.00 | 83.06 | 3100 | Sept | 14–16 | 1900 | Horse Cove, N. C. (Rockhouse) |
| 36 | .81 | 44.26 | 74.11 | 1740 | Sept | 11–12 | 1900 | Gabriels, N. Y. |

* This value is in doubt. An accepted verified value is 27.00 inches which occurred at Massies Mill, Va. (Schwarz, 1970).

TABLE 3. Maximum 24-hr and total precipitation (all values in inches) in the Appalachian region from tropical cyclone systems passing the 1000-ft contour, 1900–69. The first column in each set is in chronological order beginning in 1969 and proceeding back to 1900. The second column presents the same data arranged in descending order of magnitude.

| No. | Sets: 1 All storms (24-hr) | | 2 No more than one storm per year (24-hr) | | 3** All storms (total) | | 4 No more than one storm per year (total) | |
|---|---|---|---|---|---|---|---|---|
| 1 | 31.00* | 31.00* | 31.00* | 31.00* | 31.00* | 31.00* | 31.00* | 31.00* |
| 2 | 2.82 | 22.22 | 2.82 | 22.22 | 3.74 | 23.73 | 3.74 | 23.73 |
| 3 | 3.98 | 13.40 | 3.98 | 13.40 | 5.04 | 18.93 | 5.04 | 18.93 |
| 4 | 4.02 | 11.80 | 4.02 | 11.80 | 4.02 | 18.69 | 4.02 | 16.64 |
| 5 | 9.50 | 11.60 | 9.50 | 11.60 | 10.84 | 16.64 | 10.84 | 16.36 |
| 6 | 4.50 | 11.40 | 4.50 | 11.40 | 4.50 | 16.36 | 4.50 | 16.00 |
| 7 | 11.40 | 10.71 | 11.40 | 10.71 | 15.15 | 16.00 | 15.15 | 15.60 |
| 8 | 10.71 | 10.16 | 10.71 | 10.16 | 11.22 | 15.60 | 11.22 | 15.15 |
| 9 | 6.31 | 9.72 | 4.95 | 9.72 | 6.31 | 15.15 | 6.18 | 13.47 |
| 10 | 4.95 | 9.50 | 5.64 | 9.50 | 6.18 | 13.47 | 6.28 | 11.22 |
| 11 | 5.64 | 8.00 | 5.51 | 8.00 | 6.28 | 11.22 | 11.00 | 11.07 |
| 12 | 5.51 | 7.43 | 13.40 | 6.85 | 11.00 | 11.07 | 18.93 | 11.00 |
| 13 | 13.40 | 6.85 | 9.72 | 6.47 | 18.93 | 11.00 | 16.64 | 10.84 |
| 14 | 9.72 | 6.47 | 6.47 | 6.25 | 16.64 | 10.84 | 11.07 | 9.30 |
| 15 | 6.47 | 6.31 | 10.16 | 6.20 | 11.07 | 9.30 | 15.60 | 8.00 |
| 16 | 10.16 | 6.25 | 4.21 | 5.64 | 15.60 | 8.00 | 5.08 | 6.44 |
| 17 | 4.21 | 6.20 | 11.60 | 5.51 | 5.08 | 6.44 | 16.00 | 6.28 |
| 18 | 11.60 | 5.64 | 6.85 | 5.00 | 16.00 | 6.31 | 9.30 | 6.18 |
| 19 | 4.75 | 5.51 | 6.25 | 4.95 | 5.27 | 6.28 | 16.36 | 6.14 |
| 20 | 6.85 | 5.00 | 11.80 | 4.50 | 9.30 | 6.18 | 13.47 | 5.08 |
| 21 | 6.25 | 4.95 | 3.69 | 4.46 | 16.36 | 6.14 | 4.49 | 5.04 |
| 22 | 3.42 | 4.75 | 3.10 | 4.21 | 4.58 | 5.94 | 3.10 | 4.50 |
| 23 | 11.80 | 4.58 | 22.22 | 4.02 | 13.47 | 5.27 | 23.73 | 4.49 |
| 24 | 0.80 | 4.50 | 5.00 | 3.98 | 0.80 | 5.08 | 6.14 | 4.46 |
| 25 | 3.69 | 4.46 | 4.46 | 3.73 | 4.49 | 5.04 | 4.46 | 4.02 |
| 26 | 3.10 | 4.21 | 8.00 | 3.69 | 3.10 | 4.58 | 8.00 | 3.79 |
| 27 | 22.22 | 4.02 | 3.73 | 3.50 | 23.73 | 4.50 | 3.79 | 3.74 |
| 28 | 7.43 | 3.98 | 3.50 | 3.10 | 18.69 | 4.49 | 3.50 | 3.50 |
| 29 | 5.00 | 3.73 | 6.20 | 2.82 | 6.14 | 4.46 | 6.44 | 3.10 |
| 30 | 4.58 | 3.69 | | | 5.94 | 4.02 | | |
| 31 | 4.46 | 3.50 | | | 4.46 | 3.79 | | |
| 32 | 8.00 | 3.42 | | | 8.00 | 3.74 | | |
| 33 | 3.73 | 3.10 | | | 3.79 | 3.50 | | |
| 34 | 3.50 | 2.82 | | | 3.50 | 3.10 | | |
| 35 | 6.20 | 0.80 | | | 6.44 | 0.81 | | |
| 36 | 0.67 | 0.67 | | | 0.81 | 0.80 | | |

* This value is in doubt. An accepted verified value is 27.00 inches which occurred at Massies Mill, Va. (Schwarz, 1970).
** Locations for Set 3 are shown in Fig. 1.

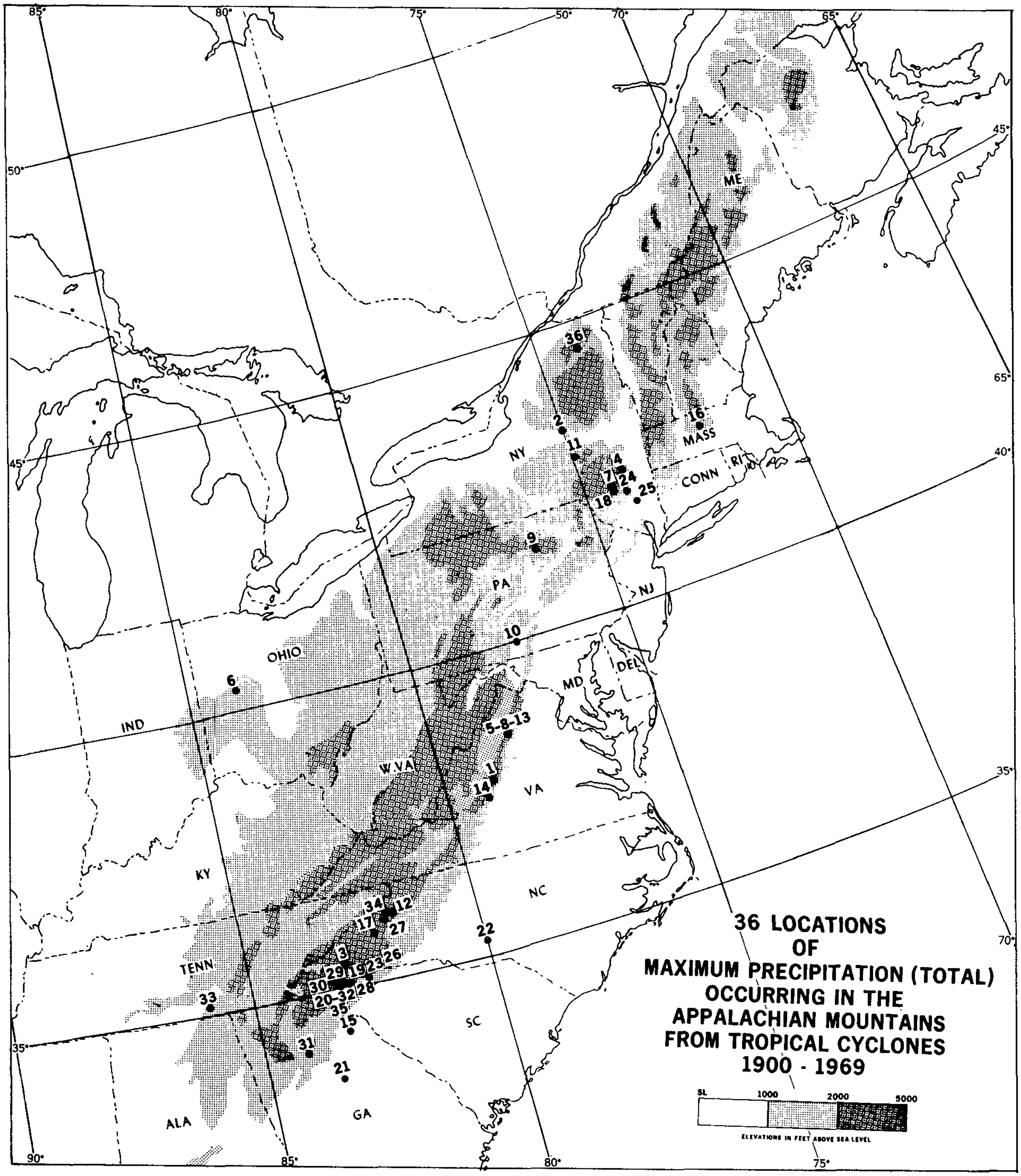


Fig. 1. Locations of Appalachian maximum rainfall from tropical cyclones or cyclone remnants, 1900–69.

Weather Service, formerly the U. S. Weather Bureau

2. Storm Data series of the Environmental Data Service, NOAA (ESSA)
3. Climatological Data National Summaries
4. Special Reports on Hurricanes, NOAA (ESSA)
5. National Hurricane Research Project Reports, National Weather Service (Weather Bureau)
6. Storm Rainfall in the United States, Corps of Engineers, U. S. Army.

Data prior to 1900 are not used because of the difficulty

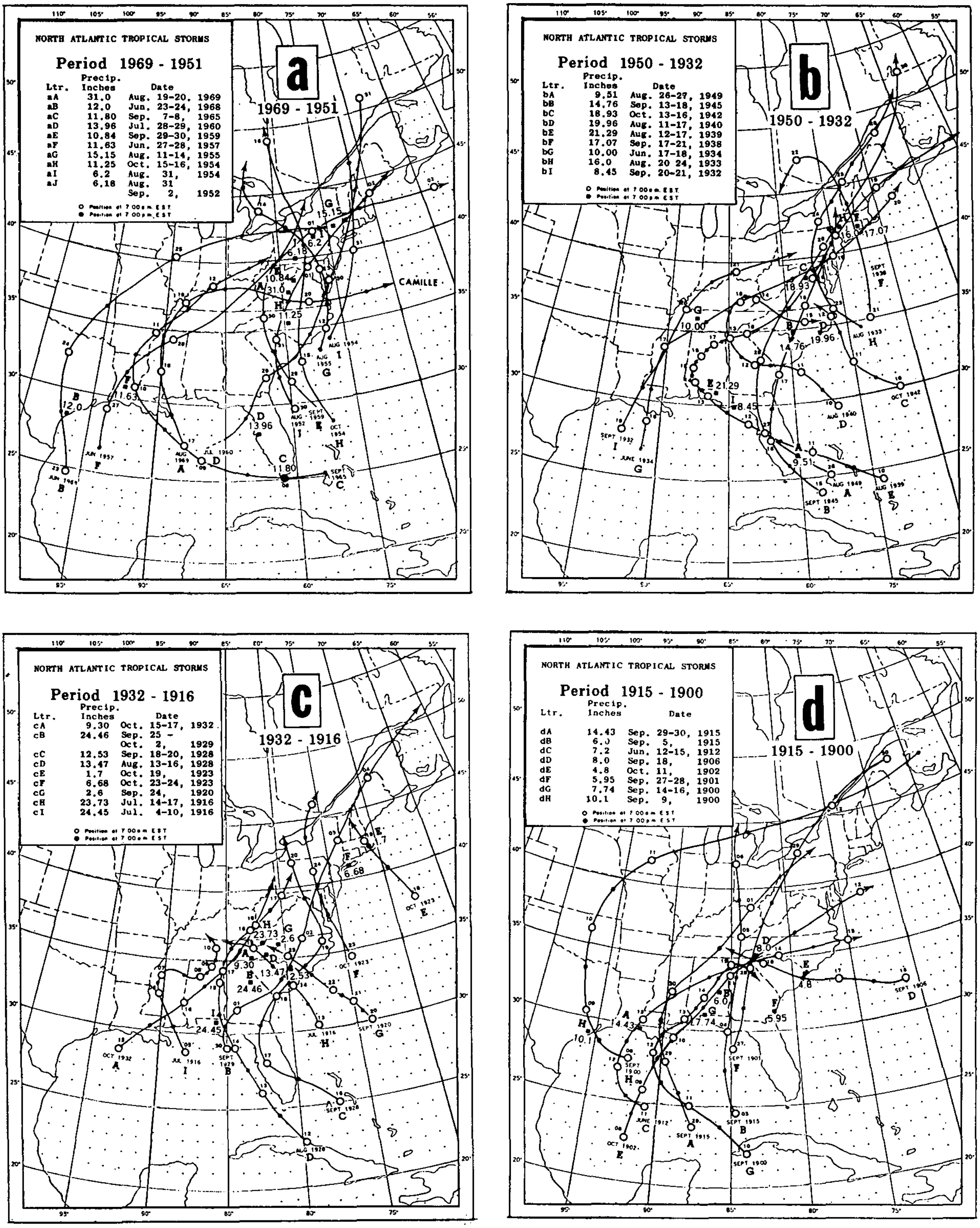


FIG. 2. Tracks of tropical cyclones crossing mountainous regions, eastern United States. Tracks are identified by dates, position, and maximum precipitation amounts recorded.

TABLE 4. Twenty-four-hour recorded maximum precipitation after landfall from tropical cyclones encountering the Appalachians. Only one storm in a year is considered.

| No. | Month | Dates | Year | Precipitation (inches) | Location |
|---|---|---|---|---|---|
| 1 | Aug | 19–20 | 1969 | 31.00* | Tye River, Va. |
| 2 | June | 23 | 1968 | 12.00 | Hoppers Landing, Tex. |
| 3* | Sept | 8 | 1965 | 8.46 | Royal Palm Ranger Station, Fla. |
| 4 | July | 28 | 1960 | 12.11 | Tampa, Fla. |
| 5 | Sept | 30 | 1959 | 9.50 | Big Meadows, Va. |
| 6* | June | 27 | 1957 | 10.40 | Jennings, La. |
| 7 | Aug | 12–13 | 1955 | 11.40 | Slide Mt., N. Y. |
| 8* | Oct | 15 | 1954 | 10.71 | Big Meadows, Va. |
| 9* | Sept | 1 | 1952 | 6.10 | Fayetteville, N. C. |
| 10* | Aug | 27 | 1949 | 9.04 | Avon Park, Fla. |
| 11* | Sept | 16–17 | 1945 | 8.78 | Savannah, Ga. (Airport) |
| 12 | Oct | 14–15 | 1942 | 13.40 | Big Meadows, Va. |
| 13* | Aug | 15–16 | 1940 | 11.50 | Keysville, Va. |
| 14* | Aug | 19 | 1939 | 17.80 | Manahawkin, N. J. |
| 15 | Sept | 20–21 | 1938 | 11.30 | Buck (Portland), Conn. |
| 16* | June | 17 | 1934 | 9.60 | Lafayette, La. |
| 17 | Aug | 23–24 | 1933 | 11.60 | Peekamoose, N. Y. |
| 18 | Sept | 20 | 1932 | 8.25 | Carrabelle, Fla. |
| 19* | Sept | 27 | 1929 | 16.00 | Washington, Ga. |
| 20 | Aug | 15 | 1928 | 11.80 | Caesars Head, S. C. |
| 21 | Oct | 24 | 1923 | 4.38 | Setauket, N. Y. |
| 22 | Sept | 23 | 1920 | 3.10 | Landrum, S. C. |
| 23 | July | 16 | 1916 | 22.22 | Altapass, N. C. |
| 24 | Sept | 30 | 1915 | 14.40 | Franklinton, La. |
| 25 | June | 13 | 1912 | 6.75 | Franklin, La. |
| 26 | Sept | 18 | 1906 | 8.00 | Horse Cove, N. C. |
| 27 | Oct | 11 | 1902 | 4.82 | Conway, S. C. |
| 28 | Sept | 28 | 1901 | 5.95 | Waverly (NR), Ga. |
| 29 | Sept | 9 | 1900 | 10.10 | Brazoria, Tex. |

* Station *not* same as "Total Max Precip" as shown in Table 5.
** This value is in doubt. An accepted verified value is 27.00 inches which occurred at Massies Mill, Va. (Schwarz, 1970).

in obtaining maximum precipitation amounts from the various storms.

Table 1 gives pertinent data for the maximum precipitation amounts within a 24-hr period. The decision criteria are that the storm center had to cross or touch, and that the precipitation had to be measured within the outermost 1000-ft contour somewhere in the foothills of the mountainous regions. The listing begins with the most recent data. For example, hurricane Camille is number 1.

Table 2 presents in the same form as Table 1 pertinent data for the maximum recorded precipitation in the mountains during the total life of the tropical cyclone systems. Some locations shown here replace those shown in Table 1. Fig. 1, prepared from Table 2, provides an idea of the geographical area where precipitation was measured.

Table 3 presents only the precipitation data extracted from Tables 1 and 2. It shows the maximum 24-hr and total precipitation in the Appalachian region from tropical cyclones or remnants thereof passing the 1000-ft contour during the period 1900–69. There are four sets. The first column in each set is in chronological order with the most recent storm first. The second column shows the same data as in the first column but ordered from the greatest to the least. The third and fourth and seventh and eighth columns present the maximum amounts from only one storm per year, whereas the first and second and fifth and sixth present data for all storms.

Fig. 2, in its four subsections, presents a partial map of the southern, eastern, and southwestern United States. The sections show consecutive sub-periods of the total period 1900–69. These show the tracks of the tropical storms and the position and dates of the recorded precipitation maxima.

Table 4 provides 29 cases of 24-hr measured maximum precipitation amounts from tropical cyclones whose paths later crossed the Appalachians. The period of record is as before, 1900–69. If two storms occurred in any one year, only the one maximum amount was used.

Table 5 provides additional information on the storms indicated in Fig. 3. The dates of the storms are arranged chronologically with Camille in 1969 being the first and the 1900 storm at Brazoria, Tex., being the last.

## 3. The Gamma distribution model

It is never possible to show that a particular mathematical or statistical model is the one and only useful model. In many cases, any one of several models may serve to adequately answer a specific problem. The selected model ought to satisfy the physical constraints of the data.

In the case of precipitation the bounds are zero on the low side and unlimited on the high side. Often

TABLE 5. Maximum recorded precipitation after landfall from tropical cyclones encountering the Appalachians.

| No. | Type | Name | Month | Dates | Year | Precipitation total storm (inches) | Location | Latitude (N) | Longitude (W) | Elevation (ft) | Landfall central pressure (mb) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | H | Camille | Aug | 5–22 | 1969 | 31.00* | Tye River, Va. | 37.39 | 78.57 | 600 | 909 |
| 2 | T | Candy | June | 22–26 | 1968 | 12.00 | Hoppers Landing, Tex. | 28.20 | 96.80 | SL | 997 |
| 3 | H | Betsy | Aug-Sept | 27–12 | 1965 | 11.80 | Plantation Key, Fla. (Tavernier) | 25.00 | 80.30 | SL | 941 |
| 4 | T | Brenda | July | 28–31 | 1960 | 13.96 | Tampa, Fla. | 27.58 | 82.32 | 19 | 1005 |
| 5 | H | Gracie | Sept-Oct | 20–2 | 1959 | 10.84 | Big Meadows, Va. | 38.31 | 78.26 | 3535 | 950 |
| 6 | H | Audrey | June | 25–28 | 1957 | 10.63 | Basile 2W, La. | 30.29 | 92.37 | 40 | 947** |
| 7 | H | Connie | Aug | 3–14 | 1955 | 15.15 | Slide Mt. ,N. Y. | 42.01 | 74.25 | 2650 | 962 |
| 8 | H | Hazel | Oct | 5–18 | 1954 | 11.25 | Robbins, N. C. | 35.36 | 79.35 | 450 | 937 |
| 9 | H | Carol | Aug | 25–31 | 1954 | 6.31 | Eagles Mere, Pa. | 41.24 | 76.35 | 2020 | 961 |
| 10 | H | Able | Aug-Sept | 18–2 | 1952 | 6.18 | Chambersburg 1-ESE, Pa. | 39.56 | 77.38 | 640 | 985 |
| 11 | H | | Aug | 23–31 | 1949 | 9.58 | St. Lucie Lock, Fla. | 27.07 | 80.17 | 15 | 954 |
| 12 | H | | Sept | 11–20 | 1945 | 14.76 | Rockingham, N. C. | 34.57 | 79.47 | 210 | 951 |
| 13 | T | | Oct | 11–17 | 1942 | 18.93 | Big Meadows, Va. | 38.31 | 78.26 | 3535 | 1006 |
| 14 | H | | Aug | 5–15 | 1940 | 19.56 | Swansboro, N. C. | 34.41 | 77.15 | 10 | 975 |
| 15 | H | | Aug | 7–20 | 1939 | 21.29 | De Funiak Springs, Fla. | 30.43 | 86.07 | 268 | 991 |
| 16 | H | | Sept | 10–22 | 1938 | 17.07 | Buck (Portland), Conn. | 41.35 | 72.38 | 250 | 943 |
| 17 | H | | June | 4–21 | 1934 | 10.00 | Cedar Hill, Tenn. | 36.33 | 87.45 | 625 | 966 |
| 18 | H | | Aug | 17–26 | 1933 | 16.00 | Peekamoose, N. Y. | 41.56 | 74.23 | 1415 | 970 |
| 19 | T | | Sept | 18–21 | 1932 | 8.45 | Carrabelle, Fla. | 29.53 | 84.40 | 10 | 1004 |
| 20 | T | | Oct | 7–18 | 1932 | 9.30 | Rockhouse, N. C. (Horse Cove) | 35.00 | 83.06 | 3100 | 1000 |
| 21 | H | | Sept-Oct | 22–4 | 1929 | 24.46 | Washington, Ga. | 33.44 | 82.44 | 610 | 975 |
| 22 | H | | Sept | 6–20 | 1928 | 12.53 | Darlington, S. C. | 34.19 | 79.49 | 175 | 929 |
| 23 | H | | Aug | 7–17 | 1928 | 13.47 | Caesars Head, S. C. | 35.07 | 82.36 | 3118 | 994 |
| 24 | T | | Oct | 15–19 | 1923 | 1.70 | Plymouth, Mass. | 41.55 | 70.42 | 55 | 988 |
| 25 | T | | Oct | 14–29 | 1923 | 6.68 | Setauket, N. Y. | 40.57 | 73.06 | 40 | 1000 |
| 26 | H | | Sept | 20–24 | 1920 | 3.10 | Landrum, S. C. | 35.11 | 82.12 | 1063 | 1010 |
| 27 | H | | July | 11–17 | 1916 | 23.73 | Altapass, N. C. | 35.54 | 82.02 | 2740 | 983 |
| 28 | H | | June-July | 29–10 | 1916 | 24.45 | Bonifay, Fla. | 30.47 | 85.41 | 120 | 961 |
| 29 | H | | Sept-Oct | 22–1 | 1915 | 14.43 | Franklinton, La. | 30.51 | 90.10 | 155 | 938 |
| 30 | H | | Aug-Sept | 31–6 | 1915 | 6.00 | Dadeville, Ala. | 32.50 | 85.45 | 630 | 993 |
| 31 | T | | June | 7–16 | 1912 | 7.20 | Franklin, La. | 29.48 | 91.30 | 10 | 1007 |
| 32 | H | | Sept | 3–18 | 1906 | 8.00 | Horse Cove, N. C. (Rockhouse) | 35.00 | 83.06 | 3100 | 945 |
| 33 | H | | Oct | 3–13 | 1902 | 4.82 | Conway, S. C. | 33.50 | 79.06 | 25 | 1006 |
| 34 | T | | Sept-Oct | 21–2 | 1901 | 5.95 | Waverly, Ga. | 31.06 | 81.44 | 20 | 1007 |
| 35 | T | | Sept | 10–15 | 1900 | 8.50 | Marion, Ala. | 32.37 | 87.18 | 263 | 1003 |
| 36 | H | | Aug-Sept | 27–15 | 1900 | 10.10 | Brazoria, Tex. | 29.03 | 95.34 | 25 | 936 |

T: Tropical storm
H: Hurricane
SL: Sea level
* This value is in doubt. An accepted verified value is 27.00 inches which occurred at Massies Mill, Virginia (Schwarz, 1970).
** Estimated

precipitation observations appear as mixed distributions, one part being no precipitation and the other part measured precipitation. One might argue that the atmosphere or the precipitation-producing regimes can produce just so much and no more. In this case there may well be some sort of reasonable limit in some studies. Jenkinson (1955) discusses this feature.

If one accepts the physical constraints of zero as a

TABLE 6. Means, estimates of the gamma distribution parameters, and $\chi^2$ tests for goodness of fit of Appalachian precipitation from tropical cyclones passing inland and over the Appalachian region. Units are inches. Estimates are made from data in Tables 1 and 2.

| Set* | | $N$** | $Y$ (mean) | $\beta$ | $\gamma$ | $X^2$ | Probability of exceeding $\chi^2$ |
|---|---|---|---|---|---|---|---|
| 1 | $a$ | 35 | 6.610 | 2.447 | 2.702 | 7.571 | 0.372 |
| | $b$ | 36 | 7.176 | 3.133 | 2.291 | 9.556 | 0.215 |
| | $c$ | 36 | 7.287 | 3.328 | 2.190 | 7.889 | 0.342 |
| 2 | $a$ | 28 | 7.264 | 1.905 | 3.813 | 9.857 | 0.197 |
| | $b$ | 29 | 7.944 | 2.655 | 2.992 | 9.966 | 0.191 |
| | $c$ | 29 | 8.082 | 2.882 | 2.805 | 9.276 | 0.233 |
| 3 | $a$ | 35 | 8.756 | 4.029 | 2.174 | 7.571 | 0.372 |
| | $b$ | 36 | 9.263 | 4.551 | 2.035 | 10.667 | 0.154 |
| | $c$ | 36 | 9.374 | 4.736 | 1.979 | 10.667 | 0.154 |
| 4 | $a$ | 28 | 9.431 | 3.104 | 3.038 | 17.714 | 0.013 |
| | $b$ | 29 | 10.037 | 3.663 | 2.740 | 13.414 | 0.063 |
| | $c$ | 29 | 10.175 | 3.874 | 2.626 | 13.414 | 0.063 |

* Set 1: Maximum 24-hr precipitation totals from all tropical cyclones. Set 2: Maximum 24-hr precipitation totals from no more than one tropical cyclone per year. Set 3: Maximum precipitation totals from all tropical cyclones (locations shown in Fig. 1). Set 4: Maximum precipitation totals from no more than one tropical cyclone per year.

** $a$: storms through 1968; $b$: storms through 1969 [Camille 27 inches (verified)]; $c$: storms through 1969 [Camille 31 inches (not verified)].

Table 7. Expected probability of arbitrary precipitation amounts being exceeded in the Appalachian region when any tropical cyclone* passes inland and over the 1000-ft contour of the Appalachians.
(See Table 6 for definitions of Sets 1–4, and *a–c*.)

| Precipitation level (inches) | Sets 1 Probability *a* | *b* | *c* | 2 Probability *a* | *b* | *c* | 3 Probability *a* | *b* | *c* | 4 Probability *a* | *b* | *c* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.00 | 0.984 | 0.978 | 0.976 | 0.997 | 0.993 | 0.992 | 0.983 | 0.981 | 0.980 | 0.996 | 0.995 | 0.994 |
| 2.00 | 0.922 | 0.913 | 0.909 | 0.971 | 0.959 | 0.954 | 0.934 | 0.932 | 0.930 | 0.974 | 0.971 | 0.968 |
| 3.00 | 0.825 | 0.821 | 0.817 | 0.907 | 0.893 | 0.887 | 0.864 | 0.865 | 0.863 | 0.930 | 0.926 | 0.923 |
| 4.00 | 0.709 | 0.717 | 0.716 | 0.811 | 0.806 | 0.801 | 0.783 | 0.789 | 0.788 | 0.866 | 0.866 | 0.826 |
| 5.00 | 0.591 | 0.613 | 0.615 | 0.695 | 0.706 | 0.705 | 0.698 | 0.710 | 0.709 | 0.788 | 0.794 | 0.792 |
| 6.00 | 0.480 | 0.515 | 0.519 | 0.574 | 0.605 | 0.607 | 0.614 | 0.631 | 0.632 | 0.703 | 0.717 | 0.716 |
| 7.00 | 0.383 | 0.427 | 0.433 | 0.460 | 0.507 | 0.513 | 0.534 | 0.556 | 0.559 | 0.617 | 0.639 | 0.640 |
| 8.00 | 0.300 | 0.349 | 0.357 | 0.359 | 0.418 | 0.427 | 0.461 | 0.486 | 0.490 | 0.534 | 0.562 | 0.565 |
| 9.00 | 0.232 | 0.283 | 0.292 | 0.273 | 0.340 | 0.351 | 0.394 | 0.423 | 0.427 | 0.455 | 0.489 | 0.494 |
| 10.00 | 0.177 | 0.227 | 0.237 | 0.204 | 0.273 | 0.286 | 0.335 | 0.365 | 0.371 | 0.384 | 0.422 | 0.429 |
| 15.00 | 0.040 | 0.070 | 0.077 | 0.038 | 0.079 | 0.090 | 0.138 | 0.165 | 0.172 | 0.144 | 0.182 | 0.191 |
| 20.00 | 0.008 | 0.019 | 0.023 | 0.006 | 0.020 | 0.024 | 0.052 | 0.070 | 0.075 | 0.047 | 0.070 | 0.077 |
| 25.00 | 0.001 | 0.005 | 0.006 | 0.001 | 0.004 | 0.006 | 0.019 | 0.028 | 0.031 | 0.014 | 0.025 | 0.029 |
| 30.00 | 0.000+ | 0.001 | 0.002 | 0.000+ | 0.001 | 0.001 | 0.007 | 0.011 | 0.013 | 0.004 | 0.008 | 0.010 |

* Probabilities derived from gamma distribution function model statistics of Table 6.

lower bound with the upper bound being unlimited, the gamma distribution will serve. An extensive literature on the use of the gamma distribution as a precipitation model has developed over the past quarter of a century. Thom (1947) discusses the estimation of the model parameters, the scale, and the shape by moments and by maximum likelihood. This paper is followed by Jenkinson (1955), Barger *et al.* (1959a,b) for 2–3 week rainfall, Friedman and Janes (1957), and Thom (1958). Mooley and Crutcher (1968) use the model for rainfall distributions in India, while Strommen and Horsfield (1969) use it for monthly data for the 23 eastern states from the Great Lakes to the Gulf Coast. Yao *et al.* (1971) apply the same technique for monthly data to rainfall in eastern Asia.

Wilk *et al.* (1962) and Thom and Vestal (1968) provide the mathematics and tables of the inverse gamma probabilities which suffice for most requirements. Crutcher *et al.* (1971) extend these developments to an electronic computer program in Fortran IV language and provide graph paper for the plotting of the gamma distributed data. The computer program and graphical techniques described in the last reference

Table 8. Expected maximum amounts of precipitation which will be exceeded in the Appalachian region for various probability levels whenever tropical cyclones* move inland and then over the 1000-ft contour. Units are inches. (See Table 6 for definitions of Sets 1–4, and *a–c*.)

| Probability of exceeding | Sets 1 *a* | *b* | *c* | 2 *a* | *b* | *c* | 3 *a* | *b* | *c* | 4 *a* | *b* | *c* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.80 | 3.22 | 3.21 | 3.17 | 4.10 | 4.06 | 4.01 | 3.80 | 3.86 | 3.84 | 4.85 | 4.92 | 4.89 |
| 0.75 | 3.65 | 3.69 | 3.67 | 4.54 | 4.57 | 4.53 | 4.39 | 4.49 | 4.48 | 5.46 | 5.58 | 5.56 |
| 0.70 | 4.08 | 4.17 | 4.16 | 4.96 | 5.06 | 5.05 | 4.98 | 5.12 | 5.12 | 6.04 | 6.22 | 6.21 |
| 0.65 | 4.50 | 4.64 | 4.65 | 5.37 | 5.55 | 5.55 | 5.57 | 5.76 | 5.77 | 6.62 | 6.85 | 6.87 |
| 0.60 | 4.92 | 5.13 | 5.15 | 5.79 | 6.05 | 6.07 | 6.17 | 6.41 | 6.43 | 7.20 | 7.50 | 7.53 |
| 0.55 | 5.36 | 5.64 | 5.67 | 6.21 | 6.55 | 6.60 | 6.80 | 7.09 | 7.12 | 7.80 | 8.16 | 8.21 |
| 0.50 | 5.81 | 6.16 | 6.21 | 6.64 | 7.08 | 7.14 | 7.46 | 7.80 | 7.85 | 8.42 | 8.85 | 8.92 |
| 0.45 | 6.30 | 6.72 | 6.79 | 7.09 | 7.63 | 7.72 | 8.16 | 8.56 | 8.63 | 9.07 | 9.57 | 9.67 |
| 0.40 | 6.81 | 7.33 | 7.42 | 7.57 | 8.22 | 8.34 | 8.91 | 9.38 | 9.47 | 9.77 | 10.35 | 10.47 |
| 0.35 | 7.37 | 7.99 | 8.10 | 8.09 | 8.86 | 9.02 | 9.74 | 10.28 | 10.40 | 10.52 | 11.20 | 11.35 |
| 0.30 | 8.00 | 8.73 | 8.87 | 8.67 | 9.58 | 9.77 | 10.66 | 11.29 | 11.43 | 11.36 | 12.14 | 12.32 |
| 0.25 | 8.71 | 9.57 | 9.75 | 9.31 | 10.38 | 10.62 | 11.72 | 12.46 | 12.63 | 12.31 | 13.21 | 13.43 |
| 0.20 | 9.55 | 10.57 | 10.79 | 10.07 | 11.34 | 11.62 | 12.98 | 13.84 | 14.05 | 13.43 | 14.47 | 14.75 |
| 0.15 | 10.59 | 11.82 | 12.10 | 11.00 | 12.51 | 12.87 | 14.55 | 15.57 | 15.84 | 14.82 | 16.04 | 16.38 |
| 0.10 | 12.00 | 13.52 | 13.88 | 12.25 | 14.10 | 14.55 | 16.70 | 17.94 | 18.28 | 16.69 | 18.16 | 18.59 |
| 0.05 | 14.30 | 16.32 | 16.80 | 14.26 | 16.69 | 17.30 | 20.23 | 21.85 | 22.31 | 19.72 | 21.63 | 22.20 |
| 0.03 | 15.93 | 18.31 | 18.89 | 15.67 | 18.51 | 19.24 | 22.76 | 24.65 | 25.20 | 21.86 | 24.08 | 24.76 |
| 0.02 | 17.20 | 19.86 | 20.52 | 16.76 | 19.92 | 20.75 | 24.73 | 26.83 | 27.46 | 23.52 | 25.98 | 26.75 |
| 0.01 | 19.32 | 22.46 | 23.25 | 18.57 | 22.28 | 23.27 | 28.03 | 30.51 | 31.26 | 26.29 | 29.17 | 30.08 |

* Amounts derived from Gamma model statistics of Table 6.

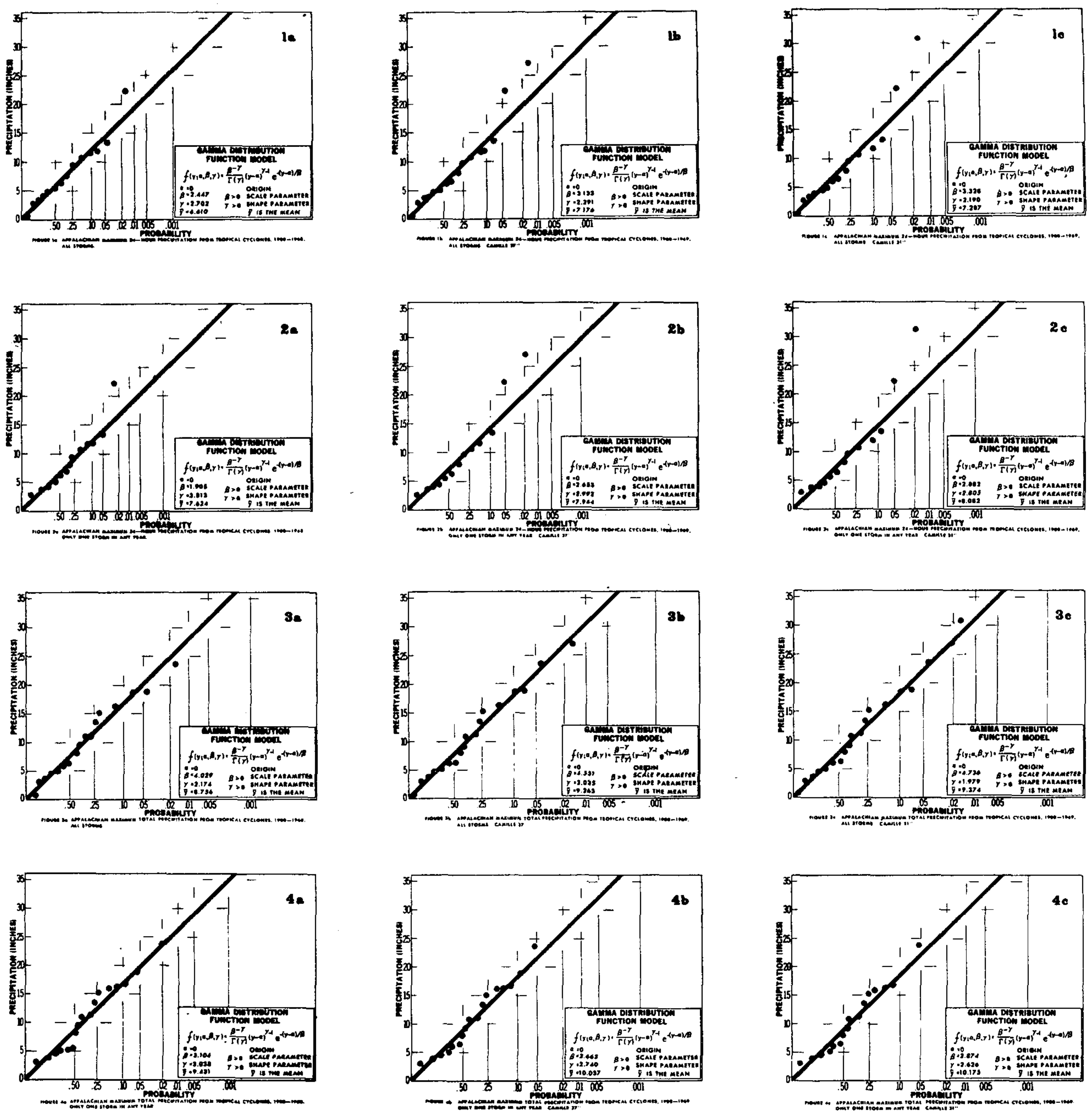


FIG. 3. Probabilities of exceeding specified precipitation amounts in the Appalachian region from tropical cyclones or remnants thereof passing the 1000-ft contour.

above have been used to process the data selected for this study and presented in Table 3.

The general gamma distribution (Wilk *et al.*, 1962) has the probability density function

$$f(y;\alpha,\beta,\gamma) = \beta^{-\gamma}\Gamma(\gamma)^{-1}(y-\alpha)^{\gamma-1}e^{-(y-\alpha)/\beta} \begin{cases} -\infty<\alpha<+\infty \\ 0<\beta,\ \gamma<\infty \\ y>\alpha \end{cases}$$
$$=0 \text{ otherwise}$$

where $\alpha$ is the origin, $\beta$ the scale parameter, and $\gamma$ the shape parameter. For this study $\alpha$ is zero; $\beta$ and $\gamma$ need to be estimated.

## 4. Results

### *a. Precipitation only in the mountains*

Table 6 presents estimates of the gamma distribution function parameters of Appalachian precipitation from tropical cyclones passing inland and over the Appalachian region during the period 1900–69. The estimates were computed following Thom's (1947) procedures.

Table 7 presents the expected probability of arbitrary precipitation amounts being exceeded in the Appalachian region when any tropical cyclone passes inland and then over the 1000-ft contour of the Appalachians.

Table 8 provides the expected maximum precipitation amounts which will be exceeded at selected probabilities in the Appalachian region when produced by a tropical cyclone or its remnants passing inland and then over the 1000-ft contour of the Appalachians.

Pearson's (1900) $\chi^2$ test for the goodness of fit for the gamma model for these data is applied. Essentially, this is a sum of squares of deviations from the expected values as produced by the model divided by the respective expected values. Thus, $\Sigma[(O-E)^2/E]=X^2$, which has a $\chi^2$ distribution. Using ten class intervals, this model is tested with seven degrees of freedom. Table 6 also provides the computed "$X^2$" values and the $\chi^2$ probabilities of exceeding these values.

Fig. 3 graphically shows the information presented in Tables 7 and 8. These are the probabilities of exceeding specified precipitation amounts in the Appalachian region from tropical cyclones or remnants thereof passing the 1000-ft contours. Figs. 3.1a, 3.1b and 3.1c show the distribution of the 24-hr maximum precipitation for all storms, (*a*) 1900–68, (*b*) 1900–69 with 27 inches for Camille, and (*c*) 1900–69 with 31 inches of rain for Camille, respectively. Figs. 3.2a, 3.2b and 3.2c for the same periods and data display the distribution when no more than one storm per year is considered. Figs. 3.3a, 3.3b and 3.3c present similar information for the maximum precipitation from any storm rather than through any 24-hr period. Figs. 3.4a, 3.4b and 3.4c present information for the maximum total precipitation where only one storm in any one year is considered.

### *b. Precipitation after landfall*

In this section information is given about maximum rainfall after storm landfall in the United States from Atlantic or Gulf of Mexico tropical storms or their remnants which passed over the Appalachians during the period 1900–69. The statistics developed here will differ with those presented by other investigators since we are dealing with subsets of data. These subsets are: 1) maxima precipitation recorded anywhere in the eastern United States during 24 hr over the course of no more than one storm in any one year; and 2) maxima precipitation recorded anywhere in the eastern United States during the courses of all storms.

Table 9 provides estimates of the gamma distribution parameters. In addition, the table shows $X^2$ values and the $\chi^2$ probabilities of their being exceeded. The data of Tables 4 and 5 are the basis for the Table 9 information.

Table 10 gives the probabilities of arbitrary precipitation amounts being exceeded from any Atlantic or Gulf of Mexico tropical storm after landfall in the contiguous United States providing the system passes over the Appalachians. Column 1 lists the arbitrarily selected precipitation amounts. Columns 2 and 3 give the probabilities for the 24-hr periods, while Columns 4 and 5 give the probabilities for the maximum total storm, 1900–68 and 1900–69. The Camille datum of 27 inches is excluded from calculations which produce estimates for Columns 2 and 4. The Columns 2 and 4 probabilities would be those derived prior to the Camille storm, while Columns 3 and 5 are those derived after the Camille storm. These permit comparison, though the information contained in Columns 3 and 5 are the ones on which now to rely.

A table for the general data similar to Table 8 for the mountain rainfall is not presented. Those are the amounts that are expected to be exceeded at specified probability levels.

This paper indicates that the gamma distribution function describes well the distributions of maximum rainfall from tropical cyclones entering the contiguous

TABLE 9. Means, estimates of the gamma distribution parameters, and $\chi^2$ test for goodness of fit of precipitation after landfall from tropical cyclones later passing over the 1000-ft contour of the Appalachian region (1900–69). Units are inches. Estimates are made from data in Tables 4 and 5.

| Set* | | $N$** | $Y$ (mean) | $\beta$ | $\gamma$ | $X^2$ | Probability of exceeding $\chi^2$ |
|---|---|---|---|---|---|---|---|
| 1 | *a* | 28 | 10.338 | 1.633 | 6.331 | 8.429 | 0.296 |
| | *b* | 29 | 10.913 | 2.099 | 5.200 | 8.897 | 0.342 |
| 2 | *a* | 35 | 11.945 | 3.209 | 3.723 | 1.286 | 0.989 |
| | *b* | 36 | 12.363 | 3.499 | 3.533 | 2.889 | 0.895 |

* Set 1: Maximum 24-hr precipitation totals from no more than one storm in any one year. Set 2: Maximum storm totals from all tropical cyclones.

** *a*: storms through 1968 [excluding Camille data]; *b*: storms through 1969 [Camille data, 27 inches].

TABLE 10. Expected probabilities of arbitrary precipitation amounts being exceeded in the contiguous United States after landfall from any tropical cyclone passing over the Appalachian region. (See Table 9 for definitions of Sets 1 and 2, and *a* and *b*.)

| Amounts (inches) | Set 1 *a* | Set 1 *b* | Set 2 *a* | Set 2 *b* |
|---|---|---|---|---|
| 1. 0 | 1.000− | 1.000− | 0.999 | 0.999 |
| 2. 0 | 0.999 | 0.998 | 0.993 | 0.993 |
| 3.00 | 0.993 | 0.988 | 0.976 | 0.975 |
| 4.00 | 0.973 | 0.965 | 0.945 | 0.945 |
| 5.00 | 0.932 | 0.922 | 0.900 | 0.902 |
| 6.00 | 0.868 | 0.862 | 0.844 | 0.848 |
| 7.00 | 0.784 | 0.786 | 0.778 | 0.786 |
| 8.00 | 0.686 | 0.699 | 0.708 | 0.719 |
| 9.00 | 0.582 | 0.609 | 0.635 | 0.650 |
| 10.00 | 0.480 | 0.519 | 0.562 | 0.581 |
| 15.00 | 0.130 | 0.182 | 0.265 | 0.291 |
| 20.00 | 0.023 | 0.047 | 0.105 | 0.124 |
| 25.00 | 0.003 | 0.010 | 0.037 | 0.048 |
| 30.00 | 0.000+ | 0.002 | 0.012 | 0.017 |

TABLE 11. Comparative precipitation probabilities of exceeding specified amounts for the Appalachian region, and the general regions affected after landfall including the Appalachians. Based on the gamma distribution model. Camille data are included in calculations.

| Amounts (inches) | Set 1* *a* | Set 1* *b* | Set 2** *a* | Set 2** *b* |
|---|---|---|---|---|
| 10 | 0.273 | 0.519 | 0.365 | 0.581 |
| 15 | 0.079 | 0.182 | 0.165 | 0.291 |
| 20 | 0.020 | 0.047 | 0.070 | 0.124 |
| 25 | 0.004 | 0.010 | 0.028 | 0.048 |
| 30 | 0.001 | 0.002 | 0.011 | 0.017 |

* Set 1 is 24-hr precipitation amounts.
** Set 2 is total storm period amounts.

United States and later passing over the Appalachian region. Table 11 provides some comparative information obtained by use of the model, first, for rainfall specifically in the Appalachian region, and second, for rainfall anywhere along the storm track.

The probabilities of exceeding 10 inches of rain within a 24-hr period somewhere within the Appalachian and general region are 0.273 and 0.519, respectively. Thus, there are about three chances in ten for 10 inches of rainfall to be exceeded somewhere in the mountains in a 24-hr period, while there is a 50% chance of that amount being exceeded somewhere along the track and/or associated with the storm. The odds increase to almost four and six in ten, respectively, for the total life of a storm. Thus, there is a 40% chance of greater than 10 inches of rain some place in the mountains from any tropical storm directly affecting the Appalachians.

The probabilities of exceeding 20 inches of rain within a 24-hr period are 0.020 and 0.047, two in one hundred and almost five in one hundred for the mountainous and general region, respectively. (The general region includes the Appalachian region.) For the total storm amount of 20 inches, the odds again increase, this time to seven and about twelve in one hundred, respectively, for the Appalachians and the general region.

Lesser amounts of rainfall presumably are more likely to produce dangerous flooding in the mountains than in the flatlands. While the heaviest precipitation of a tropical storm is apt to occur near the coast, the high probabilities of large rainfall amounts in relatively short time periods in the mountains create a special flood threat in the mountains, requiring special forecasting vigilance.

## 5. Summary

The study is restricted to those tropical storms or storm remnants whose centers passed over or brushed the 1000-ft contours of the Appalachians. First, the study presents a discussion on the maximum amounts occurring in the mountainous regions. Second, the study treats maximum amounts after landfall, whether in the Appalachians or on the flatlands. The period of record is 1900–1969.

The gamma distribution serves as the model. The standard statistical chi-square test assesses the model's suitability. The resulting information is presented in both tabular and graphical form for the first group and in tabular form for the second group.

Whenever a tropical cyclone system or its remnants passes inland and subsequently over the Appalachians, initial probabilistic forecasts of rainfall amounts can be made which can be monitored and modified continuously.

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REFERENCES

Alaka, M. A., 1968: Climatology of Atlantic tropical storms and hurricanes. ESSA Tech. Rept. WB-6, Silver Spring, Md., 18 pp.

Barger, G. L., R. H. Shaw and R. F. Dale, 1959a: Chances of receiving selected amounts of precipitation in the north central region of the United States. Agricultural and Home Economics Experiment Station, Iowa State University, Ames.

——, —— and ——, 1959b: Gamma distribution parameters from 2- and 3-week precipitation totals in the north central region of the United States. Agricultural and Home Economics Experiment Station, Iowa State University, Ames.

Coastal Plains Center for Marine Development Services, 1970: *Bibliography on Hurricanes and Severe Storms of the Coastal Plains Region.* Publ. 70-2, Washington, D. C., 71 pp.

Crutcher, Harold L., Gerald L. Barger and Grady F. McKay, 1971: A note on a Gamma distribution computer program and graph paper. NOAA Tech. Rept. EDS-11 (in press).

Cry, George W., 1965: Estimation of precipitation probabilities. *Proc. 4th Army Conf. on Tropical Meteorology*, Miami Beach, Fla.

——, 1967: Effects of tropical cyclone rainfall on the distribution of precipitation over the Eastern and Southern United States. ESSA Prof. Paper 1, Washington, D. C., 67 pp.

DeAngelis, Richard M., 1969: Hurricane Camille, August 5–22. Climatological Data, National Summary, **20**, No. 8, Dept. of Commerce, ESSA, 24 pp.

Dikkers, R. D., R. D. Marshall and H. C. S. Thom, 1971: Hurricane Camille—August 1969. NBS Tech. Note 569, Washington, D. C., 67 pp.

Dunn, G. E., 1951: Tropical cyclones. *Compendium of Meteorology*, T. F. Malone, Ed., Boston, Amer. Meteor. Soc., 887–901.

——, and Banner I. Miller, 1960: *Atlantic Hurricanes.* Louisiana State University Press, 326 pp.

Friedman, Don G., and Byron E. Janes, 1957: Estimation of rainfall probabilities. Bull. 332, Storrs Agricultural Experiment Station, College of Agriculture, University of Connecticut.

Goodyear, Hugo V., 1968: Frequency and areal distributions of tropical storm rainfall in the United States coastal region on the Gulf of Mexico. ESSA Tech. Rept. WB-7, Silver Spring, Md., 33 pp.

Jenkinson, A. F., 1955: The frequency distribution of the annual

maximum (or minimum) values of meteorological elements. *Quart. J. Roy. Meteor. Soc.*, **81**, 158–171.
Mooley, D. A., and H. L. Crutcher, 1968: An application of the Gamma distribution function to Indian rainfall. ESSA Tech. Rept. EDS-5, Silver Spring, Md., 47 pp.
Pearson, K., 1900: On the criterion that a given system of deviations from the probable in the case of a correlated system of variables is such that it can reasonably be supposed to have arisen from a random sampling. *Phil. Mag.*, **50**, 157–175.
Schoner, R. W., and S. Molansky, 1956: Rainfall associated with hurricanes and other tropical disturbances. U. S. Weather Bureau, National Hurricane Research Project Rept. No. 3, 305 pp.
Schwarz, Francis K., 1970: The unprecedented rains in Virginia associated with the remnants of hurricane Camille. *Mon. Wea. Rev.*, **98**, 851–859.
Snedecor, G. W., and W. G. Cochran, 1967: *Statistical Methods*, 6th ed. The Iowa State University Press, 593 pp.
Strommen, Norton D., and James E. Horsfield, 1969: Monthly precipitation probabilities by climatic divisions—23 Eastern states from the Great Lakes to the Gulf Coast. Misc. Publ. No. 1160, Economic Research Service, U. S. Dept. of Agriculture, and ESSA, U. S. Dept. of Commerce, 141 pp.
Thom, H. C. S., 1947: A note on the Gamma distribution. Statistical Laboratory, Iowa State College (unpubl. manuscript).
——, 1958: A note on the Gamma distribution. *Mon. Wea. Rev.*, **86**, 117–122.
——, and Ida B. Vestal, 1968: Quantiles of monthly precipitation for selected stations in the contiguous United States. ESSA Tech. Rept. EDS-6, Silver Spring, Md., 46 pp.
Wilk, M. B., R. Gnanadesikan and M. J. Huyett, 1962: Probability plots for the Gamma distribution. *Technometrics*, 4, 1–20.
Yao, Augustine Y. M., Gerald L. Barger and Harold L. Crutcher, 1971: Precipitation probability atlas for eastern Asia. Environmental Data Service, NOAA, Silver Spring, Md.