RAINFALL RATES IN FLORIDA HURRICANES

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ABSTRACT

Hourly rainfall amounts from 16 hurricanes are plotted relative to the center of the storm to obtain the mean areal rainfall rates around the storm. The rates ahead of the center are greater than those to the rear, but the differences in rates between the right and left sides are not large. The frequency distributions of various hourly amounts are tabulated for stations within about 100 miles of the center. Finally, the latent heat of condensation is calculated from the mean areal rainfall data. This is found to be about 6 x 10^{26} ergs per day.

1. INTRODUCTION

Some of the world's heaviest rainfalls have occurred in connection with tropical cyclones; over 20 inches in 24 hours is not uncommon [7]. Several factors influence the total accumulation at a given place. Among the most important are: (1) the rate of ascent of the air within the storm's circulation; (2) the temperature and lapse rates within the area of the storm; (3) the location of the rain gage in relation to the storm's center; (4) the rate of forward motion of the storm; (5) the topography, if the storm is over land, which may greatly increase the upward motion of the air; and (6) the moisture content of the air.

Rainfall rates even in hurricanes, however, vary widely. All the factors listed above except the forward rate of movement also influence rainfall rates. Even near the center of the hurricane, in spite of the large convergence normally present, the hourly rate may be zero if the recording station chances to fall between the spiral rain bands. At the other extreme about 6 inches were recorded in about 1 hour in connection with a Florida hurricane in 1947. Relatively "dry hurricanes" are occasionally observed. In 1941 the center of a hurricane passed about 13 miles south of Miami; winds of 123 m. p. h. were observed at Dinner Key, but only 0.35 inch of rain fell at Miami during the storm. Extremely light rain was also observed as this same storm passed Nassau in the Bahamas. Such occurrences are, however, very rare.

The distribution of the rainfall around the center of the storm is also quite variable and apparently depends upon the stage of development of the hurricane, the direction of movement, the latitude at which the storm is observed, the forward speed of the center, and probably some additional factors. Many years ago Cline [1] investigated hurricane rainfall, using data mostly from storms in the Gulf of Mexico. He concluded that as long as the storm is moving the rainfall is concentrated within the right front quadrant, but that in stationary storms, much of the rainfall shifts to the rear of the center. More recently, Schoner [8] compiled some data on Gulf hurricanes and he also found a greater concentration of rainfall in the right front quadrant than in other parts of the storm. Hughes [4] computed the rainfall distribution from the mean convergence around the center as deduced from low-level aircraft reconnaissance winds and obtained a relatively symmetrical distribution around the center. This may be because there were insufficient wind observations to define an asymmetrical distribution, especially within 60 miles of the center. Dunn [2] suggests that in general the more immature the hurricane and the lower the latitude at which it is observed, the more symmetrical the rainfall from the standpoint of both intensity and area, and that it is only when the storm begins to recurve at more northerly latitudes that the greatest concentration of rainfall shifts to the front quadrants.

The purposes of this investigation were to determine the mean areal distribution of rainfall rates relative to the center of the hurricane and to establish the frequency distribution of various rates around the center. A knowledge of the mean hourly rates (by areas) might be of some use in forecasting total accumulation at any specified location, although obviously such a forecast would necessarily have to take into account the forward speed of the storm, the increased lift due to topography or frontal surfaces, and frictional influences as the storm moves over land.

2. SELECTION OF DATA

Hourly rainfall data from hurricanes whose centers crossed Florida or moved within about 300 miles of some portion of the State were used to obtain the mean areal distribution. Data from 16 hurricanes were used, and portions of their tracks during the periods for which rainfall data were tabulated are shown in figure 1. The storms which recurved off the east coast and those that moved northward in the eastern Gulf of Mexico were in-

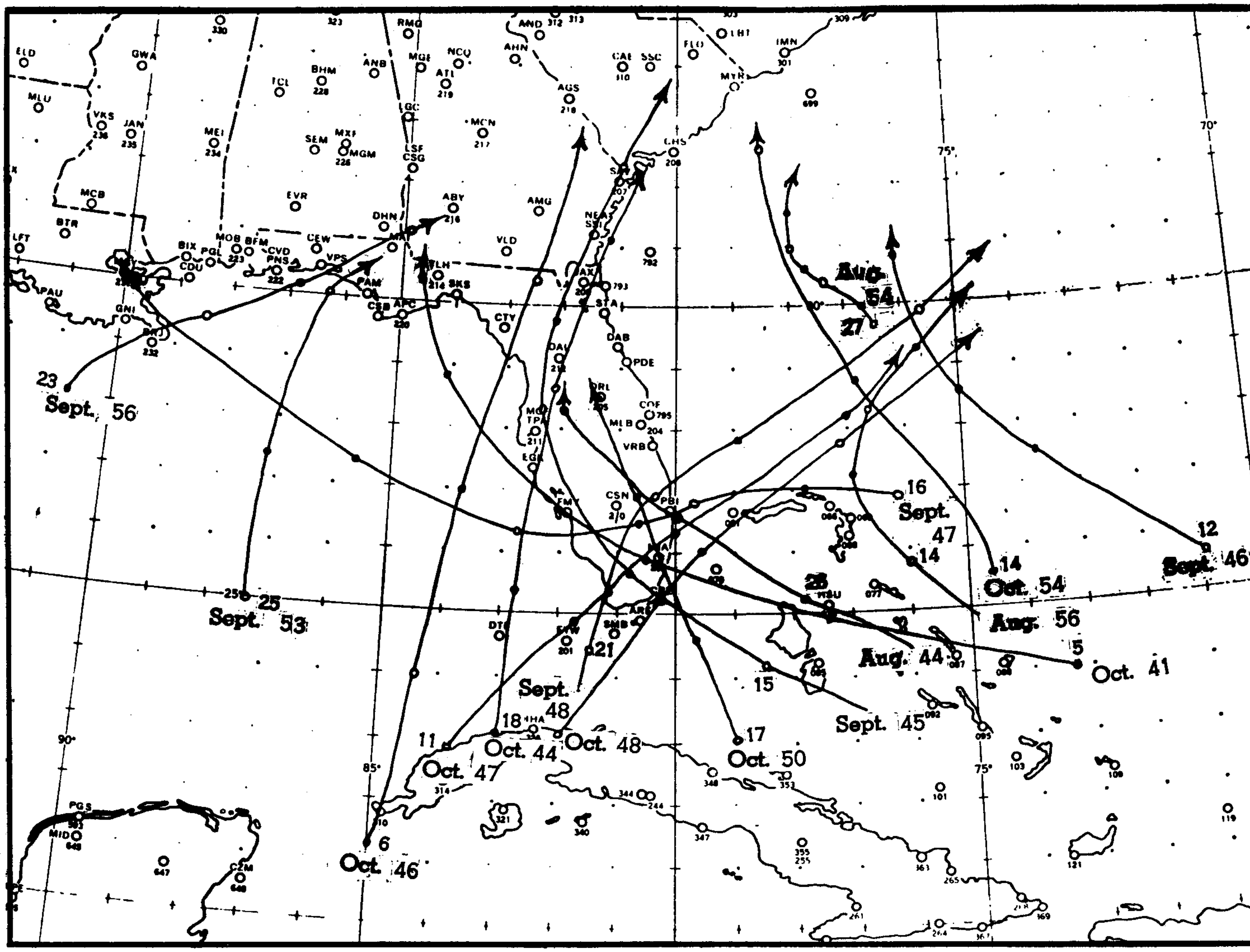

Figure 1.—Tracks of hurricanes used in preparation of the mean areal rainfall distribution around Florida hurricanes. Open circles indicate 7 a. m. EST positions and dark circles 7 p. m. positions. Only those portions of the tracks for the hours during which rainfall data were tabulated are shown.

cluded to obtain data for the outer edges of the hurricane. An examination of hurricane rainfall totals [7] suggests that there is little correlation between the intensity of the wind circulation and the rate of rainfall, but for this study only storms of hurricane intensity were used; i.e., as soon as the winds around the center dropped below hurricane intensity, rainfall data were no longer tabulated for that storm.

The tabulations were made from hourly rainfall amounts measured by recording rain gages in Florida from 1941 through 1956. The locations of stations for which data were available are shown in figure 2. During that period some of the earlier recording stations were closed, new ones were established, and others were moved to new locations within the same city. For these reasons, the network of stations was not constant throughout the period, but the number was reasonably stable. Most of the more important recording gages were maintained permanently throughout the entire period upon which this study is based.

Since the data are all from Florida, they are almost completely free from orographic effects and from extratropical influences. The resulting rainfall patterns are then, it is believed, as accurate a representation as can be obtained of the mean areal rainfall distribution around a hurricane, and one that is relatively free of outside influences. The increased friction as the storm moves over land undoubtedly affects the rainfall, since the angle of inflow and the resultant low-level convergence are also changed, but this factor cannot be taken into account.

3. RAINFALL RATES AND FREQUENCY DISTRIBUTION

The grid shown in figure 3 was used to tabulate the hourly rainfall amounts. The squares represent one degree of latitude on a side. In use the center of the grid (the middle of square 41) is placed over the center of the hurricane and moved with the storm. The grid extends 4.5 degrees of latitude both ahead and behind the center as well as to the right and to the left. In figure 3 are

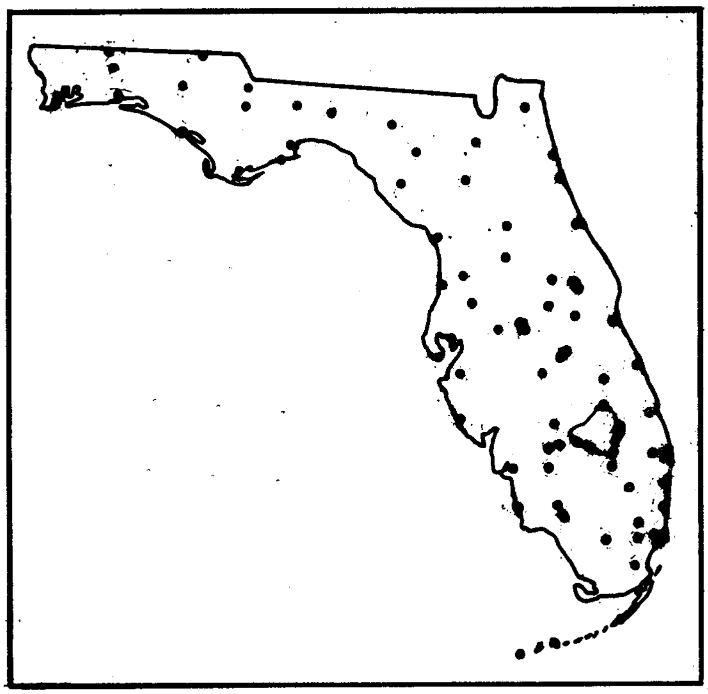

FIGURE 2.—Locations of recording rain gages in Florida from which hourly rainfall data were used.

1 <.005	2 .01	3 .01	4 .04	5 .05	6 .05	7 0	8 0	9 0
10 .01	11 .02	12 .03	13 .06	14 .03	15 .01	16 <.005	17 0	18 <.005
19 .03	20 .04	21 .05	22 .06	23 .08	24 .08	25 .03	26 <.005	27 0
28 .06	29 .07	30 .11	31 .13	32 .18	33 .12	34 .04	35 .03	36 .01
37 .05	38 .07	39 .14	40 .26	41 .26	42 .10	43 .05	44 .02	45 <.005
46 .02	47 .04	48 .07	49 .14	50 .11	51 .06	52 .02	53 .01	54 0
55 .01	56 .01	57 .02	58 .04	59 .06	60 .02	61 .01	62 <.005	63 .01
64 .01	65 .01	66 .01	67 .01	68 <.005	69 .01	70 .01	71 <.005	72 .01
73 <.005	74 .01	75 .01	76 .02	77 .01	78 .01	79 .01	80 <.005	81 .01

FIGURE 4.—Mean hourly areal rainfall relative to the center of the hurricane. Grid as in figure 3.

1 176 *93%*	2 148 *94%*	3 221 *92%*	4 110 *71 %*	5 59 *44 %*	6 12 *75 %*	7 21 *96 %*	8 45 *100%*	9 69 *100%*
10 263 *80 %*	11 257 *80%*	12 270 *68%*	13 191 *44%*	14 141 *52%*	15 102 *68%*	16 140 *89%*	17 213 *98%*	18 153 *97 %*
19 464 *67 %*	20 425 *60%*	21 414 *61 %*	22 319 *49%*	23 307 *47%*	24 325 *50%*	25 415 *68%*	26 294 *90 %*	27 180 *97%*
28 527 *55%*	29 614 *56 %*	30 601 *50 %*	31 632 *32%*	32 579 *27 %*	33 561 *44%*	34 519 *50 %*	35 349 *79%*	36 245 *91%*
37 583 *49%*	38 728 *44 %*	39 777 *38 %*	40 771 *15 %*	41 748 *21 %*	42 654 *46 %*	43 436 *60 %*	44 281 *83 %*	45 173 *94 %*
46 340 *65 %*	47 436 *50 %*	48 405 *48 %*	49 439 *32 %*	50 396 *34 %*	51 310 *51 %*	52 230 *75 %*	53 171 *89 %*	54 189 *98 %*
55 156 *73 %*	56 213 *88 %*	57 205 *73 %*	58 192 *71 %*	59 198 *69 %*	60 139 *78%*	61 154 *86 %*	62 256 *94 %*	63 385 *96%*
64 240 *85 %*	65 354 *90 %*	66 294 *94 %*	67 212 *88 %*	68 255 *92 %*	69 234 *92 %*	70 297 *97 %*	71 345 *96 %*	72 333 *94 %*
73 312 *94 %*	74 261 *93 %*	75 413 *93 %*	76 406 *92 %*	77 424 *92 %*	78 412 *92 %*	79 474 *92 %*	80 363 *94 %*	81 234 *95 %*

FIGURE 3.—Grid used in tabulating rainfall data. The arrow at the left indicates the direction of the storm's motion. The number in the upper left hand corner identifies the square. The number of hours of rainfall data tabulated in each square is shown in the upper center of each square, and the percentage of the total hours during which no measurable rain fell is listed in the bottom center of each square. The sides of the squares represent one degree of latitude. The hurricane is located at the middle of square 41.

shown the identification number of each square (in the upper left hand corner), the number of hours of rainfall data which fell within each (the upper center number), and finally the percentage of the total number of hours during which no measurable rain fell (the lower center number). The arrow at the left of figures 3 and 4 indicates the direction of motion of the storm. More than 26,000 hours of rainfall data were tabulated.

The data were plotted at hourly intervals, which means that the hourly positions of the hurricane centers had to be estimated. This cannot be done with any high degree of precision, and may have resulted in some of the hourly amounts being tabulated in the wrong squares. However, such errors should be random, and with such a large sampling it appears that they can be ignored.

The mean hourly rainfall rates by 1° squares are shown in figure 4. Isohyets could of course have been added, but they would have little meaning since the values plotted at the centers of the squares represent areal means and not point values. The greatest hourly totals (0.26 inch) occur within the center square and just ahead of it. Behind the center the average rates drop off much more rapidly than they do ahead of the storm. To the right the averages are somewhat larger than they are to the left, but the differences are not considered significant. The averages of figure 4 are such that if a storm were moving directly across a rainfall station in the direction indicated by the arrow and at a speed of 10 knots, a 54-hour total of a little more than 5.5 inches would be recorded. This is about one-half the 48-hour total Hughes [4] calculated from theoretical considerations.

The percentage of the total number of hours within each square during which no measurable rainfall was

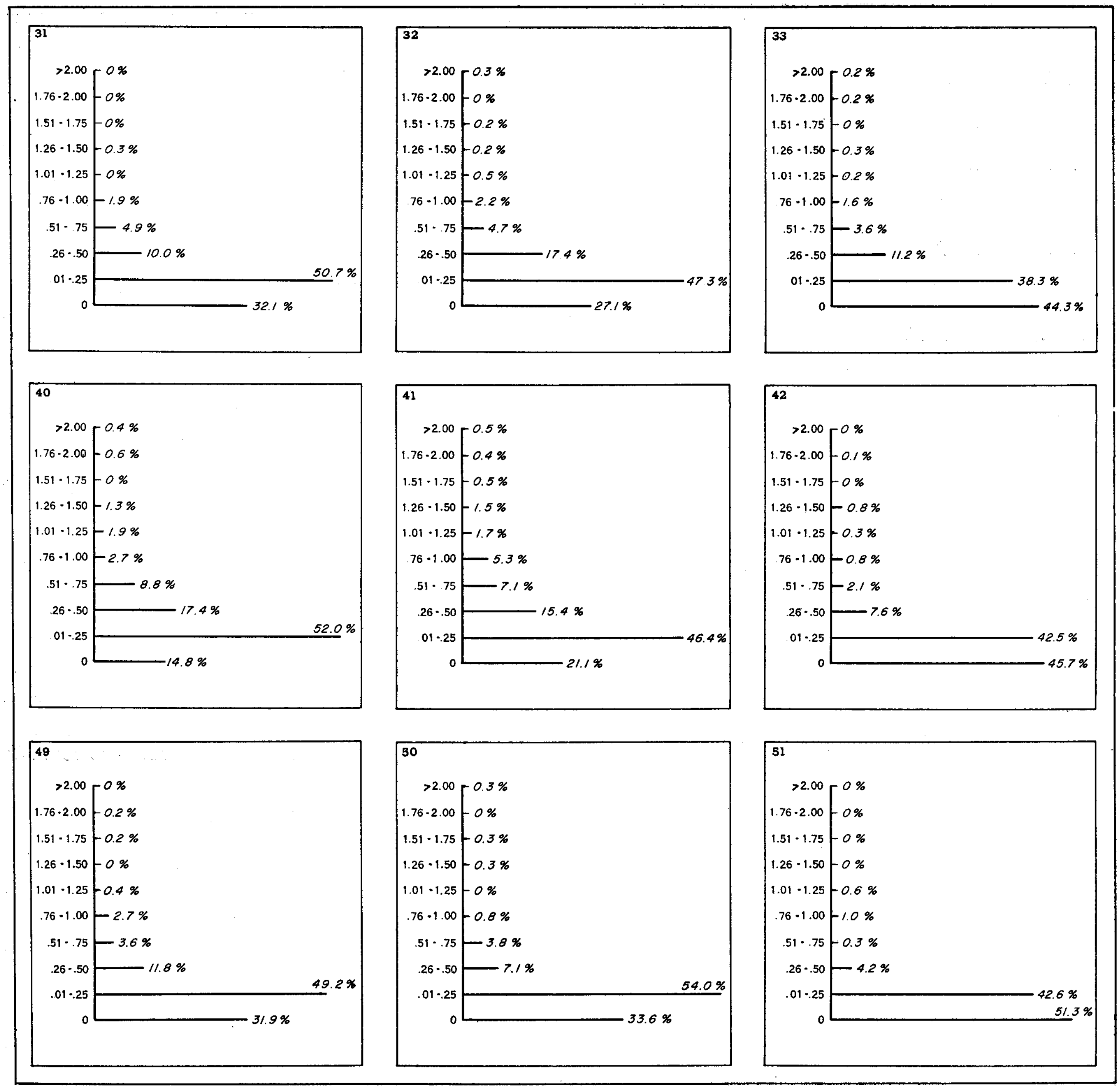

FIGURE 5.—Frequency distribution of hourly rainfall amounts around the center of the hurricane. See figure 3 for the location of the squares by number.

recorded is shown in figure 3. Along three sides of the outer edges of the grid no rain was measured in 90 to 100 percent of the hours, but along the front edge the no-rain cases drop to 49 percent. Square 40, directly ahead of the center of hurricane, has the lowest frequency of no-rain cases, 15 percent. This is even less than the percentage within the square immediately surrounding the center (square 41) in which 21 percent of the hours showed no measurable rainfall. This may reflect the tendency for the rain frequency to decrease through the rear half of the square as the center of the hurricane passes. There may also be a decrease in the rainfall rate through the rear half of this square.

Frequency distributions for other rainfall intervals are shown in figure 5. These data are plotted for the nine inner squares only, all of which lie within about 100 miles of the center of the storm. In all cases the most frequent hourly rainfall is either zero or within the .01–.25-inch

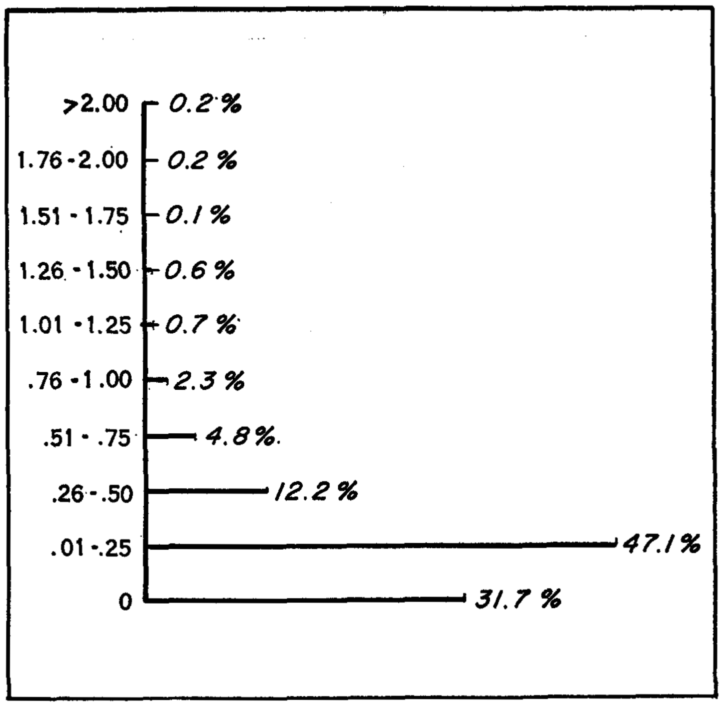

FIGURE 6.—Frequency distribution of hourly rainfall around the center of a hurricane. Data compiled from nine inner squares of figure 5.

range. Figure 6, which represents the overall frequency distribution for the nine inner squares shown in figure 5, reveals that about 12 percent of the cases fell within the .26–.50-inch range. In more than 95 percent of the hours (out of over 5000 hours tabulated within the nine inner squares), the hourly rate was less than 0.75 inch.

It should be emphasized that the foregoing mean values represent hurricane rains resulting primarily from the ascent of moist tropical air only when such ascent is produced by a combination of convection and forced lifting due to convergence coincident with the radial inflow which is present throughout the lower portions of the storm. Orographic and frontal lifting, insofar as possible, have been eliminated. Furthermore, the failure of rain gages to measure the true rainfall when the winds are of hurricane speed makes the values near the center of the storm highly questionable. If some of the higher estimates of the true percentage of rainfall caught by gages in hurricanes are correct [2], then the actual areal means near the center of the storm may be almost twice the values indicated by figure 4. Consequently any use made of the mean hourly rates for quantitative precipitation forecasting should consider at least subjectively the factors listed earlier in this paper, a combination of which may make a substantially greater contribution to the actual rainfall total than the convergence produced by the hurricane winds.

4. COMPARISON WITH EARLIER RESULTS

The rainfall rates shown in figure 4 are relative to the center of a moving hurricane, and the 24-hour accumulation at any one place depends upon the speed with which the center of the hurricane moves and the path the center takes in relation to the rain gage. Figure 7A shows the mean 24-hour isohyetal pattern that would occur if a hurricane moved along the indicated track at a speed of 10 knots with the rainfall rates as shown in figure 4. This period of rainfall encompasses the 24 hours before the center of the hurricane reaches the coast in the vicinity of Miami. It is therefore comparable to Schoner's [9] prehurricane precipitation for Zone 4 (the east coast of Florida). It will be observed that the areal extent of the 24-hour 3-inch isohyet is considerably smaller for the data presented in this study than Schoner found in his analysis. Also, Schoner's data contain a rather large 5-inch isohyet, whereas none is present on figure 7A.

Figure 7B shows the 24-hour rainfall pattern that would result from a storm moving along the track extending from near Miami to the vicinity of Ocala. Again a forward speed of 10 knots and the rainfall rates of figure 4 are assumed. A 4-inch isohyet is present and it is probable that a 5-inch isohyet covers a much smaller area, although the scale used in the preparation of the means does not permit its delineation. This period of rainfall is comparable to Schoner's [9] hurricane precipitation for Zone 4. Again, however, the areal extent of the 3-inch isohyet is much smaller than that found by Schoner.

The explanation for the differences between Schoner's 24-hour precipitation patterns and those presented in figure 7 is not obvious. Since the author does not fully understand the manner in which Schoner determined his isohyetal patterns, no attempt will be made to reconcile this difference at this time.

5. ESTIMATION OF THE "TRUE" HURRICANE RAINFALL RATES

The accuracy of the conventional rain gages in measuring the true rainfall rate decreases as the wind speed increases. Rain gage efficiency is also a function of drop size, so that the correction factor to be applied is not the same for all rates of fall. Therefore, the means shown by figure 4 may be subject to serious error, particularly near the center of the storm.

Hubert [3] has prepared a graph for estimating the correction to be applied to rain-gage catches to correct for the losses due to high winds. For heavy rain, which Hubert defines as a rate greater than 0.11 inch per hour, no distinction is made between shielded and unshielded gages, and the correction varies from zero for no wind to a factor of nearly 1.4 for winds of 100 m. p. h. For rainfall rates less than 0.11 inch per hour, two curves are presented. One is for unshielded and the other for shielded gages. For the shielded gage, the correction factor for light to moderate rain reaches a value of about 2.5 for wind speeds of 100 m. p. h. For unshielded gages the correction factor is even greater.

Hubert does not claim much in the way of accuracy, only that the corrections are in the right direction and bear approximately the proper relation to one another.

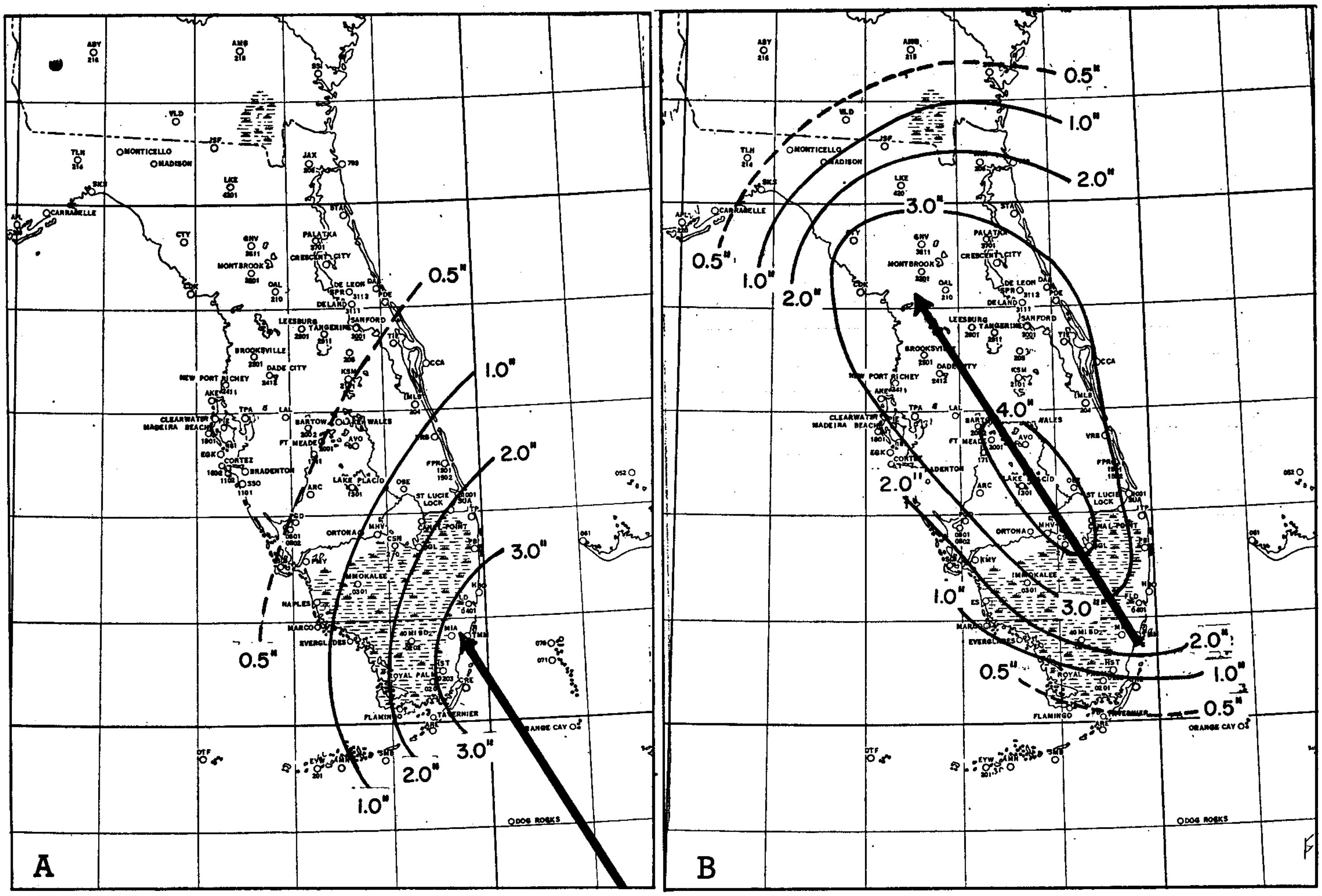

FIGURE 7.—(A) Pre-hurricane precipitation: 24-hour accumulation obtained by using the rates shown in figure 4 as the center of the hurricane moves along the indicated track at a speed of 10 knots. Period ends as the center crosses the coast near Miami. (B) Hurricane precipitation: 24-hour accumulation using the rates shown in figure 4 as the center moves along the indicated track at a speed of 10 knots.

He has labeled the area for winds in excess of about 65 m. p. h. as very doubtful for both light and heavy rainfall.

An attempt has been made to estimate the "true" rainfall rates by using the data from figure 4 and applying the correction factors obtained from Hubert's graph. To obtain the wind speeds at rain-gage levels, the mean wind field by layers, as presented in an earlier report [6], was used. Curves were fitted to the vertical distribution of the wind speeds for various radial distances from the center of the storm. These were then extrapolated from a level of 500 meters (assumed to be represented by the 0–1 km. layer) which is approximately the height of the top of the average rain gage. These reduced values, while probably not too accurate, were used to correct the rates shown in figure 4.

The corrected values, which are offered as an estimate of the "true" mean rainfall rate within Florida hurricanes are shown in figure 8. A comparison with figure 4 shows that the rainfall pattern has become slightly more asymmetrical than before. This is a reflection of the asymmetry in the mean wind field [6]. It will also be noted that the maximum "true" rate has now become 0.34 inch per hour in comparison with the uncorrected maximum value of 0.26 inch per hour. The rates shown in figure 8 are probably slightly more accurate than those of figure 4; however, they should be used with caution since both the factors used to correct for wind speeds and the reduction of the 500-meter winds to rain gage heights are open to question.

6. RELEASE OF LATENT HEAT

Several order-of-magnitude calculations [4, 5] have indicated that the latent heat of condensation released within a hurricane is of the order of 2 to 4×10^{26} ergs per day. The present data afford an opportunity to check these computations by use of the mean data obtained from an unusually large number of cases. Using the entire grid and the means of figure 4, a computation of the latent heat of condensation gives 2.51×10^{25} ergs per hour or 6.02×10^{26} ergs per day. This compares well with the value of 4.36×10^{26} ergs per day obtained by Hughes [4], who based his computation on the rainfall (calculated from low-level

1 T	2 .01	3 .01	4 .06	5 .08	6 .08	7 0	8 0	9 0
10 .01	11 .03	12 .05	13 .10	14 .05	15 .02	16 T	17 0	18 T
19 .04	20 .06	21 .08	22 .11	23 .16	24 .15	25 .05	26 T	27 0
28 .08	29 .11	30 .14	31 .17	32 .25	33 .16	34 .06	35 .05	36 .01
37 .07	38 .10	39 .17	40 .33	41 .34	42 .18	43 .08	44 .03	45 T
46 .03	47 .05	48 .10	49 .17	50 .14	51 .10	52 .03	53 .01	54 T
55 .01	56 .01	57 .03	58 .06	59 .09	60 .03	61 .01	62 T	63 .01
64 .01	65 .01	66 .01	67 .01	68 T	69 .01	70 .01	71 T	72 .01
73 T	74 .01	75 .05	76 .02	77 .01	78 .01	79 .01	80 T	81 .01

FIGURE 8.—An estimate of the "true" rainfall rates in a hurricane. Based on the data of figure 4 corrected for loss of rain from the gage due to high wind speeds.

convergence) within a circle with a radius of 3°, which is about one-third the area used for the present computation. It is somewhat more than the 1.9 x 10^{26} ergs per day calculated by Longley [5], who used actual rainfall reports from a single Florida hurricane (which, incidentally, was used in determining the areal means of figure 4). All values, however, are close enough to establish reasonably the mean value of the heat of condensation released within an average hurricane. Individual storms, however, will obviously vary greatly.

7. SUMMARY

On the average, rainfall rates within Florida hurricanes are greater ahead of than behind the center of the storm. Differences between rates on the right and left sides, however, are not large. The application of these areal means may have some practical value in quantitative rainfall forecasting in connection with hurricanes, but subjective modifications to take into consideration orographic and frontal lifting would have to be made after the storm moves inland. It should also be borne in mind that the accuracy of the means is subject to question because the loss of rainfall by a rain gage is high when the wind speed is great. A computation of the average heat of condensation released within a hurricane gives a value of 6.02 x 10^{26} ergs per day, which compares reasonably well with earlier computations.

ACKNOWLEDGMENTS

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