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NEW YORK UNIVERSITY
COLLEGE OF ENGINEERING
RESEARCH DIVISION

A COMPOSITE ANALYSIS OF
CYCLONIC PRECIPITATION
IN THE EASTERN UNITED STATES

By
Gunther Reiss

Technical Paper No. 3
Project SCUD
Contract No. Nonr - 285 (09)

Sponsored by
The Office of Naval Research

Department of Meteorology and Oceanography
April 1955

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ABSTRACT

Composite six-hourly precipitation maps are presented for twenty extratropical cyclones in the eastern United States.

The cyclones have been separated into two groups, one consisting of cyclones which developed in high latitudes and moved eastward, the other of cyclones which developed in low latitudes and moved northeastward. The life histories of the two precipitation distributions are shown in two series of composite maps. Confidence limits on the composite precipitation maxima are provided.

Introduction

The primary purpose of this study was to determine the quantitative distribution of precipitation in cyclones and to construct a precipitation model from the results obtained.

Qualitative models of the distribution of precipitation in cyclones have existed for a long time, but relatively few attempts have been made to study the quantitative precipitation distribution from the weather forecaster's viewpoint. Quantitative precipitation distributions for a large number of storms have been studied by hydrometeorologists. However, hydrometeorologists are less interested in the distribution with relation to the cyclone center than in the maximum depths that will accumulate over a specified duration on a specified area.

One of the earliest models of a cyclone was constructed by Abercromby (1901) in the latter part of the 19th century. This was some time before the concept of fronts had been introduced. Pertaining to the actual weather in a cyclone, Abercromby stated that the broad features were

"A patch of rain near the center, a ring of clouds surrounding the rain, and blue sky outside the whole system. The center of the rain-area being rarely concentric with the isobars; it usually extends farther in front than in rear, and more to the south than to the north, but is still primarily related to the center."

To the northeast of the center, he found ill-defined showers and a dirty sky. Near the trough of the cyclone, he frequently

encountered a squall or heavy showers, which were more marked south of the cyclone center than to the north.

In 1918, Bjerknes (1918) published a paper describing a model of a cyclone in which the air masses were now separated by a squall-line and a steering-line. In 1921, Bjerknes and Solberg (1921) improved on the previous model, and introduced the cold front and warm front to replace the squall-line and steering-line, respectively. This is the model with which every meteorological student is familiar: the continuous rain along the warm front, extending from the surface position of the front to about one hundred miles in advance; drizzle in the warm sector; and showers along the cold front. This model has remained the guide of forecasters through the years. However, it gives no indication of the quantity of rain to be expected with a storm.

The aim of this study was to construct a chronological sequence of composite rainfall maps which could be used as models of the precipitation distribution associated with a moving cyclone center. The composite technique is, of course, simply a method for obtaining averages by superimposing numerous pictures or data, one upon the other.

Twenty winter cyclones which crossed the eastern United States were selected for study. The cyclones were divided into two groups, depending on their region of origin. It is well known that cyclones originating in low latitudes produce much more precipitation in the eastern United States than do those originating at higher latitudes (Penn, 1948). The relation

between precipitation at New York City and the region of origin of the cyclone has been described by Gosset (1954). The separation of the twenty cyclones into southern and western types was necessary to achieve some measure of homogeneity.

The United States east of the 90th meridian was chosen as the area in which these cyclones were to be studied. The first position of every cyclone within this area was called period 1, the position six hours later, period 2, and so on. A grid nine degrees of latitude by nine degrees of longitude was constructed around these positions with the cyclones located in the center of the grid. The appropriate six-hour precipitation data were plotted on the grid and isopleths were drawn. Composite maps were then made by combining the data of identical periods, separately for southern and western cyclones. The results were ten composite maps, five for the southern cyclones corresponding to periods 1 through 5, and a similar number for the western cyclones.

Standard deviations and confidence limits were computed for the composite precipitation maxima and estimates were made of the sample sizes required for the establishment of reasonably stable means.

Finally, an overall composite map was made of the southern cyclones, combining all periods, and a similar one was constructed for the western cyclones. These two composite charts were also examined by statistical methods.

Data

The precipitation data used in this study consisted of the six-hourly reports from first-order and cooperative stations of the United States Weather Bureau for the periods January-April 1953 and December 1953-April 1954.

Teletype circuit C data gave a rather sparse coverage over the entire United States and Canada. Circuit A gave a fairly dense coverage over the eastern U. S. and extended westward to about 95°W longitude. The combined circuits gave a density of about two stations per one degree square in New England, and one and one half stations per one degree square in eastern New York, Pennsylvania, New Jersey, and Maryland, and about one station per one degree square in the remainder of the country, westward to the 95th meridian.

Data from cooperative weather stations were available for the region east of the Appalachians. The stations had been selected so that there would be one station in every one-quarter degree square, or a density of four stations per one degree square.

The area in which the cyclones were studied was bounded on the west by the 90th meridian, on the north by Canada, and on the east and south by the Atlantic coastline. A third, rather arbitrary, restriction was the requirement that a cyclone would have to remain within this area for more than twelve hours. This restriction eliminated many western cyclones which had recurved to the west of the 90th meridian and passed northward through Lake Superior. It also eliminated some East Gulf

cyclones that were only on land briefly as they passed across Florida. Finally, it eliminated those weak cyclones which formed in or passed into the area and then filled soon afterwards.

Twenty cyclones were found that were suitable for study. Ten of these were southern cyclones and ten were western cyclones. The cyclones were classified according to their region of origin, using the Bowie-Weightman (1914) system. Of the ten southern cyclones, four were South Atlantic lows, three Texas lows, and three East Gulf lows. Of the ten western cyclones, four were Central lows, two North Pacific lows, two North Rocky lows, one Alberta low, and one Colorado low. The tracks of all twenty cyclones are shown in figures 1 and 2. A list of the cyclones and their dates is given in Table 1.

Table 1. List of cyclones studied, including time and date of end of period 1.

Number	Date	Time (GMT)
<u>Southern Cyclones</u>		
1	15 February 1953	0300
2	12 March 1953	1230
3	19 March 1953	0030
4	23 March 1953	1830
5	6 April 1953	1830
6	18 April 1953	1830
7	12 December 1953	0630
8	10 January 1954	1830
9	16 January 1954	0630
10	22 January 1954	0030

Table 1. (Continued)

Number	Date	Time (GMT)
<u>Western Cyclones</u>		
11	11 February 1953	1830
12	13 March 1953	1830
13	10 April 1953	0630
14	16 April 1953	0030
15	16 February 1953	1830
16	9 December 1953	1830
17	27 January 1954	0630
18	26 February 1954	0030
19	13 March 1954	0630
20	19 March 1954	1830

Methods

Since rainfall is measured every six hours, during which period cyclones are usually moving, it is impossible to get an instantaneous picture of the distribution of precipitation in a cyclone. A satisfactory approximation is obtained by noting the geographic position of the cyclone center at the middle of the precipitation period and plotting the six-hour rainfall data around this position.

Three-hourly synoptic charts were drawn and the positions of the cyclone centers were accurately determined. The plotted positions of the cyclones correspond to the following times: 0330 GMT, 0930 GMT, 1530 GMT, and 2130 GMT. The time of the first position within the area which was previously described, was called period 1. The time of the position six hours later was period 2, and so on, until the cyclone was outside the area. The number of periods obtained for the twenty cyclones

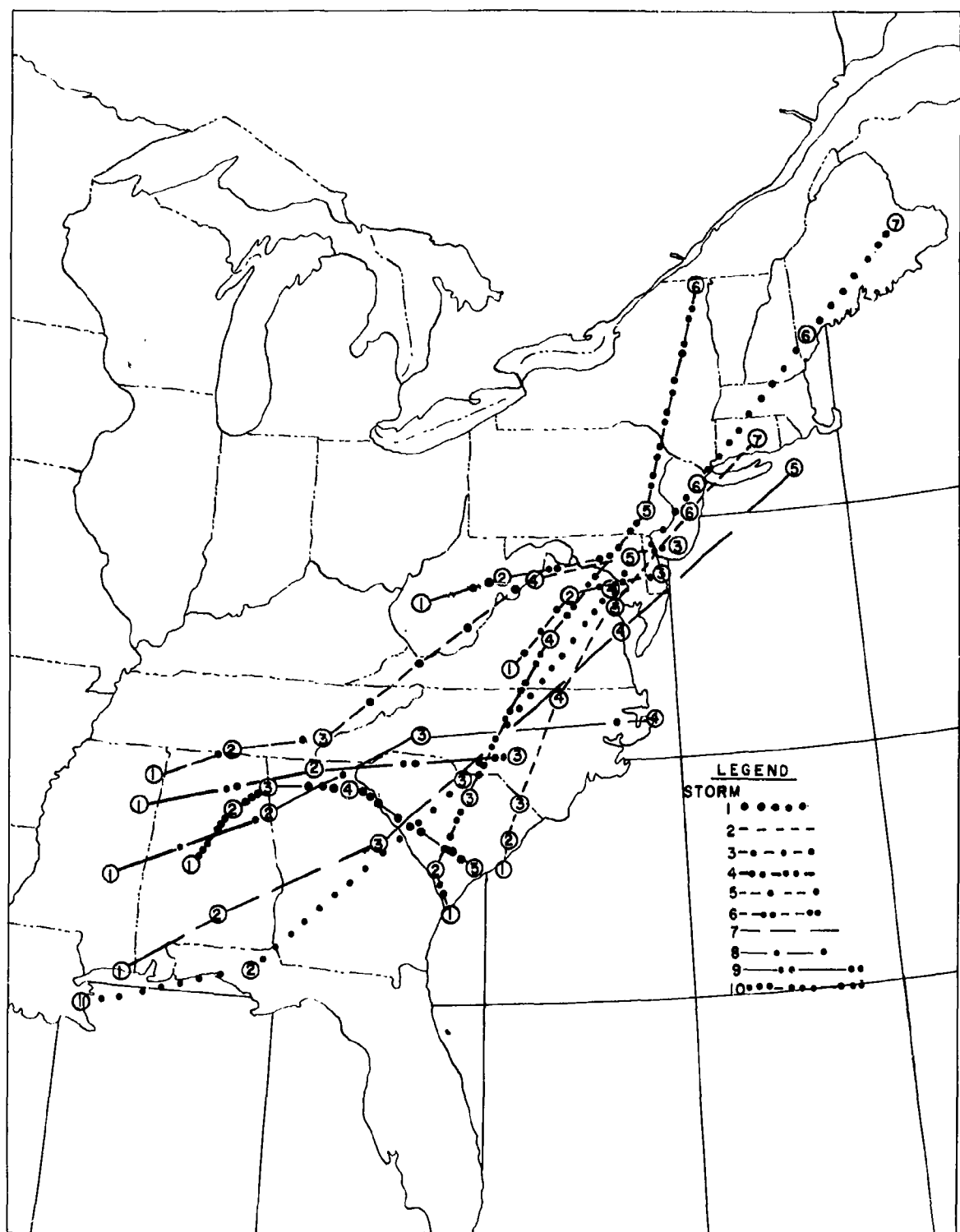


Fig. 1. Tracks of southern cyclones

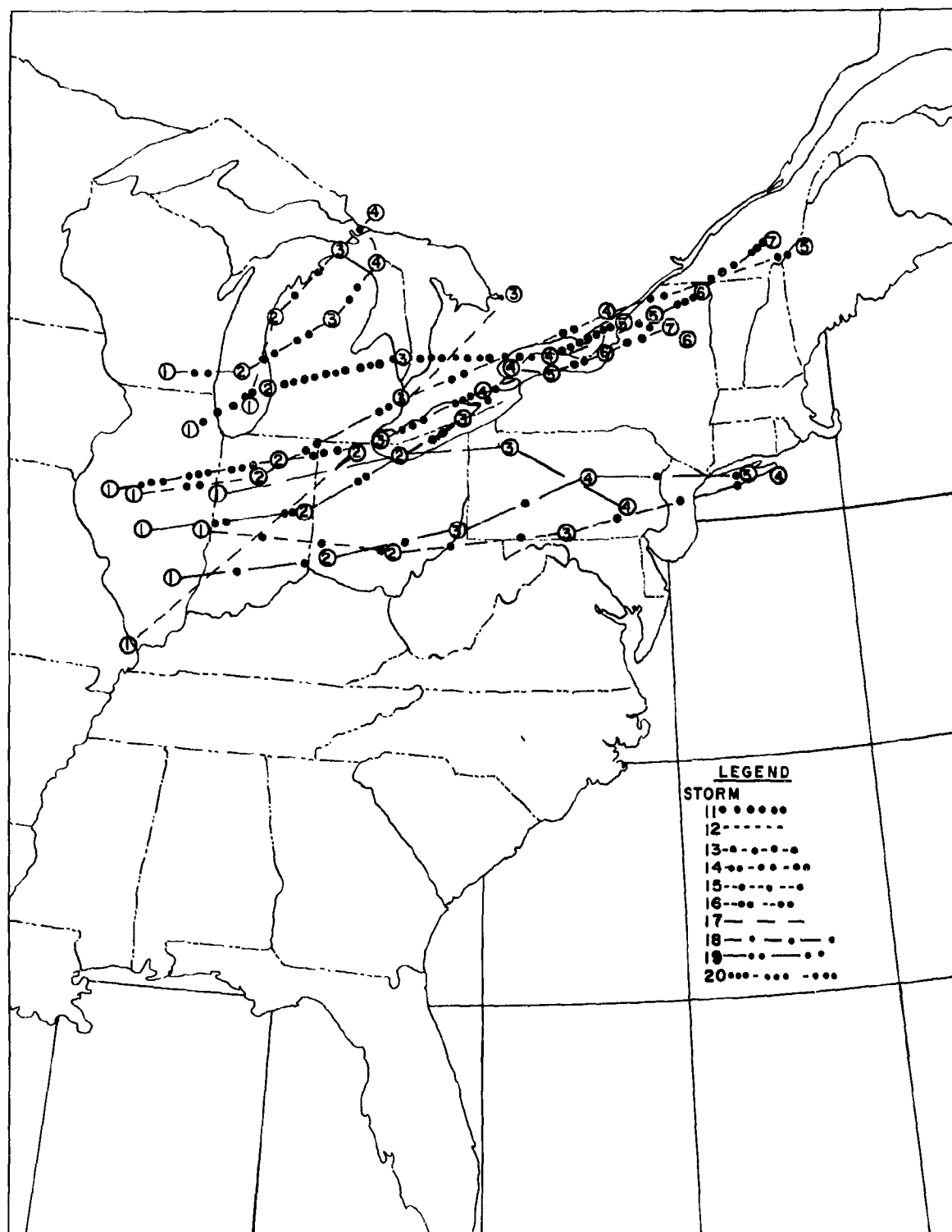


Fig. 2. Tracks of western cyclones

varied between three and seven.

The cyclone positions were then recopied, each on a separate map. A grid nine degrees by nine degrees was constructed so that the cyclone center was in the central square. The choice of the grid of this size was a compromise. A smaller grid would have lost most or part of the precipitation areas. A larger grid would have increased the amount of work without adding materially to the over-all picture. Using a grid composed of degrees of latitude and longitude introduced somewhat of a variation in the area from period to period as the cyclones moved northward. For the same period, however, the variation in area between the ten southern or ten western cyclones was negligible.

The six-hour rainfall for the synoptic period ending three hours after the time of the cyclone position was plotted for all stations within the grid and extending outward about one to two degrees on all sides of it. Isohyets were drawn, smoothing out heavy orographic and convective rainfall. The value of the precipitation at the center of each one degree square, or box as it will be called from here on, was interpolated and recorded. Wherever any part of the grid was to the east of the Appalachian Mountains, the data from the cooperative stations were used in preference to teletype data. The precipitation amounts reported by the four cooperative stations in each box were averaged, and this was assumed to be the value at the center of the box. For this area it was not necessary to do any isoplething.

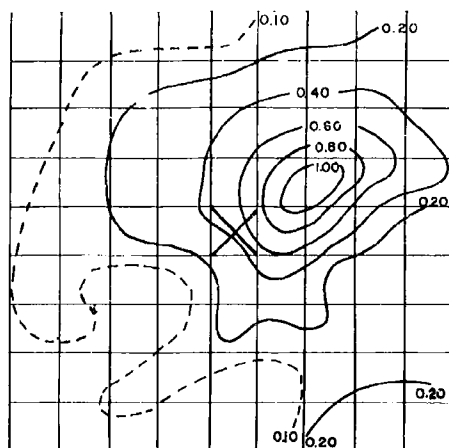
Whenever a cyclone was located near the coast, that portion of the grid that extended into the Atlantic Ocean or Gulf of Mexico was left blank.

The data were then tabulated for each period, separately for western and southern cyclones. The cyclones were listed in a vertical column and the precipitation values for the eighty-one boxes, corresponding to a particular cyclone, were listed horizontally. In this manner, the identical boxes in each cyclone were in vertical columns. The values for each column were added and divided by the number of values, to obtain the mean for each box. These mean values were plotted on printed forms containing the eighty-one box grid with the cyclone center in the central box and isohyets were drawn. The result was a series of composite precipitation maps of ten, or fewer, cyclones for each period for the southern and western cyclone types.

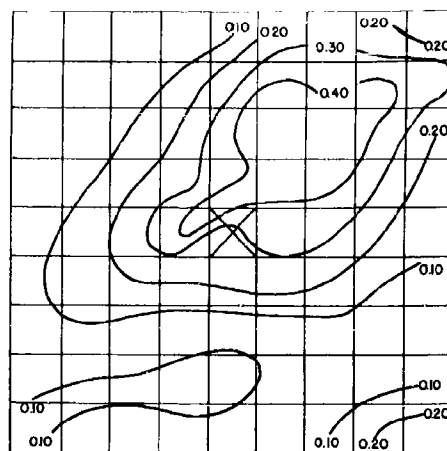
Results

Figure 3 shows the composite maps for the ten southern cyclones for periods 1-5. In period 1 the area of maximum precipitation lies about two degrees east northeast of the cyclone center. A secondary maximum lies in the extreme southeast of the diagram. This secondary maximum was due to a series of instability lines which were present in one cyclone and caused torrential rains. This effect is evident in all the periods.

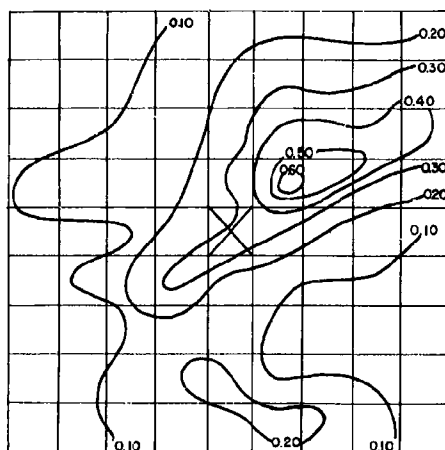
In figure 1, it will be noted that the Texas and East Gulf cyclones were clustered in a comparatively small area, comprising Alabama and Mississippi during the first period. The South



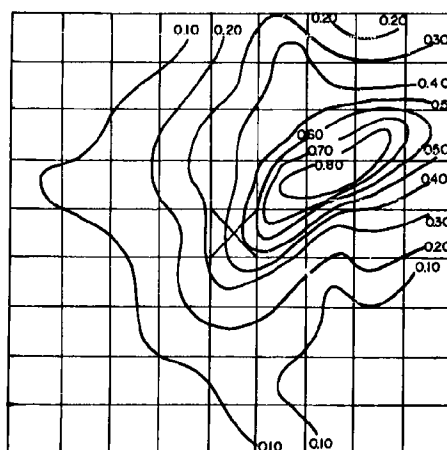
Period 1



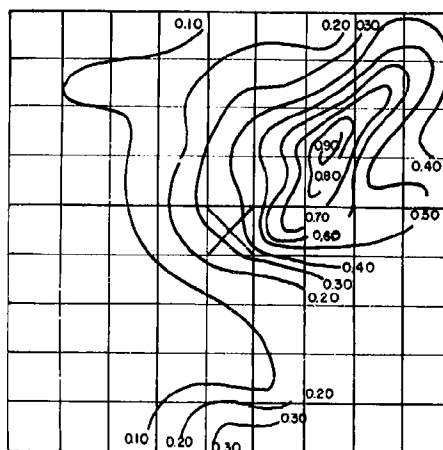
Period 2



Period 3



Period 4



Period 5

Fig. 3. Composite six-hour precipitation maps for ten southern cyclones, periods 1-5. Horizontal lines in the grid are latitude circles drawn for an interval of one degree. Vertical lines are one degree meridians.

Atlantic cyclones, on the other hand, were located quite some distance to the east and consisted of two northern and two southern cases, cyclones 3 and 6, and 2 and 4, respectively. The two southern cyclones were located along the coast of South Carolina. One of the northern cyclones was located in central Virginia and the other in West Virginia. It was therefore decided to construct a composite map eliminating the South Atlantic cyclones and, at the same time, to study these separately. These sub-composite maps are not shown in this paper but will be discussed for every period.

In cyclones 2 and 4 combined, the maximum precipitation in period 1 was off the coast. It was estimated from the isohyets to be only slightly greater than 0.50 inches. A narrow belt of rain, oriented in a north northwest-south southeast direction, was located to the north of the cyclone center, terminating in a secondary maximum far to the north northwest. This secondary maximum was apparently orographic precipitation taking place in the Smoky Mountains.

In cyclones 3 and 6 combined, a precipitation maximum in period 1 was far to the northeast of the cyclone center with a magnitude of only 0.25 inches. Far to the southwest was found another maximum of about 0.35 inches. The two maxima were connected by a narrow belt of rain passing immediately to the north of the cyclone center. With the exception of the area to the northeast, most of this rain was apparently orographic.

The composite map for the remaining six cyclones in period 1, three Texas and three East Gulf lows, looked exactly like

figure 3, period 1, except that the values were higher and the maximum was 1.35 inches.

We can therefore see that since the rainfall in the South Atlantic cyclones was fairly light, their different patterns did not affect the pattern of the total composite map, but did affect the magnitude of the maximum.

In period 2 the pattern did not change too much from that of period 1, but the maximum decreased considerably. The maximum is now only 0.47 inches, and this value was recorded in two boxes. In addition several adjacent boxes have values very close to this.

The composite map of cyclones 2 and 4, for period 2, showed a rather small precipitation area, about three degrees to the north northeast of the cyclone center, with a maximum value of 0.65 inches.

The composite map of cyclones 3 and 6 for period 2, was similar to that for period 1. A maximum with a value of 0.25 inches was about two and one-half degrees northeast of the cyclone center, a secondary maximum of 0.23 inches, apparently due to orographic lifting, was located to the west southwest of the center. A narrow belt of orographic precipitation, connecting these two maxima, passed just to the north and northwest of the cyclone center. Within this connecting belt, just to the northwest of the cyclone center, was a very small maximum of 0.30 inches which corresponded to some of the highest portions of the Allegheny Mountains.

The composite map for the remaining six cyclones in period 2 was very similar to figure 3, period 2, except that the maximum

was larger in this case. The precipitation maximum of 0.66 inches was located about two degrees to the northeast of the cyclone center. A large part of the decrease from period 1 was due to one cyclone, a Texas low, which caused very heavy rain in period 1 when it was near the Gulf of Mexico, but now only had moderate rain associated with it. This phenomenon was probably due to an increase in the stability of the warm air during the intervening six hours. Another reason for the decrease in the maximum of the sub-composite maps, from the previous period, was that the maxima of the individual cyclones did not coincide. This was due to an orographic effect, four of the cyclones lying either in the southern portion of the Appalachian Mountains or immediately to the southwest of the range. The maxima, therefore, could not occur in the usual location, being blocked by the mountains. This effect was most pronounced during the second and third periods.

The sub-composite maps explain the large decrease from period 1, in the precipitation maximum of the total composite map. The most important reason was the decrease of the precipitation maximum in the Texas and East Gulf lows due to the orographic effect. The other reason was that the maxima of the three sub-composite maps did not coincide. The net effect of averaging, therefore, was to spread the area of maximum precipitation and at the same time to decrease its value.

The total composite map for period 3 shows a considerable increase in the precipitation maximum since the previous period. The maximum now has a value of 0.62 inches. Most of this increase in the precipitation maximum can be attributed to the

fact that the maxima of the three sub-composite maps coincided fairly well during this period. In the extreme south there is still this area of rain which was caused by the instability lines in one of the Texas cyclones.

In period 3, cyclones 2 and 4 combined showed two maxima; a primary of 0.93 inches immediately to the northeast of the cyclone center, which corresponded to the actual precipitation maxima for both cyclones, and a secondary maximum far to the north northeast of the cyclone center, which was undoubtedly caused by orographic lifting of the moist tropical air. Cyclone 4 contributed most to this secondary maximum, possibly because it was more intense, and also much farther inland.

Most of the precipitation area for cyclones 3 and 6 combined was now off the coast, somewhere to the east northeast of the cyclone center. The shift in direction of the maximum from northeast to east northeast is similar to the change in direction of the cyclone's tracks. It is evidently a reflection of the change in direction of the upper-air flow. The upper trough seems to have diminished in amplitude and the surface storms themselves weakened during this period.

The composite map of the Texas and East Gulf cyclones for period 3 showed little change from the previous period, with the exception of a small secondary maximum to the southwest of the cyclone center. This secondary maximum was due to heavy cold front showers in several of the cyclones. The primary maximum had a value of 0.65 inches and the secondary of 0.52 inches. The maximum was still low because the maxima of the individual cyclones did not coincide. This occurrence was mentioned for

period 2 and was attributed to an orographic effect. Since a number of cyclones were still located in the mountains, the same explanation would be valid during this period.

The total composite map for period 4 shows the features of both sub-composite maps which are described below. Since the two maxima did not coincide, the precipitation maximum of the total composite map tends to be somewhat low, having a value of 0.87 inches. This composite map was made up of seven cyclones.

In period 4, cyclones 2 and 4 showed a larger precipitation area than in the previous period. It was still to the northeast of the cyclone center. However, the value of the maximum decreased to 0.79 inches. As in the previous period, there was still a secondary maximum in the extreme north northeast of about the same magnitude.

Cyclones 3 and 6 were now off the coast and were therefore abandoned.

The Texas and East Gulf lows had decreased to five in this period. The maximum precipitation area, with a value of 1.10 inches, had moved slightly eastward during this period. However, this and the large increase in magnitude were due largely to a decrease in data. In several of the cyclones, the eastern half of the grid was now off the coast. The few remaining cyclones which made up the precipitation area happened to be the wettest, and the maxima coincided to give a high value to the sub-composite maximum. There was no longer any orographic effect to scatter the cyclone maxima, such as in periods 2 and 3.

The total composite map for period 5 consisting of only six cyclones now, shows a maximum slightly higher and farther north

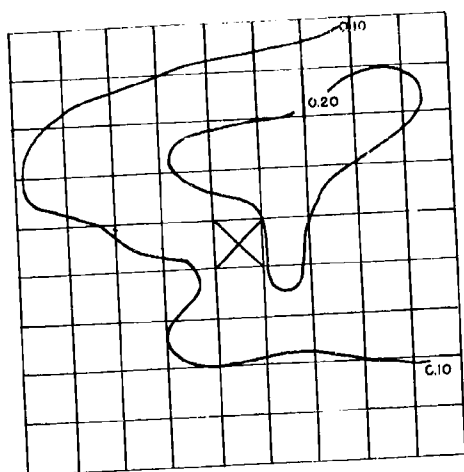
than in the previous period. This increase was again due to the coincidence of the maxima of the two groups which are mentioned below. The rainfall due to the instability lines can still be seen in the extreme south. The southeastern portion of the grid was left blank because most of the cyclones were centered close to the coast during this period.

In period 5 the maximum precipitation for cyclones 2 and 4 was 1.13 inches and was located to the northeast of the cyclone center. The large increase in precipitation since the last period was apparently due to the rapid deepening of these two cyclones.

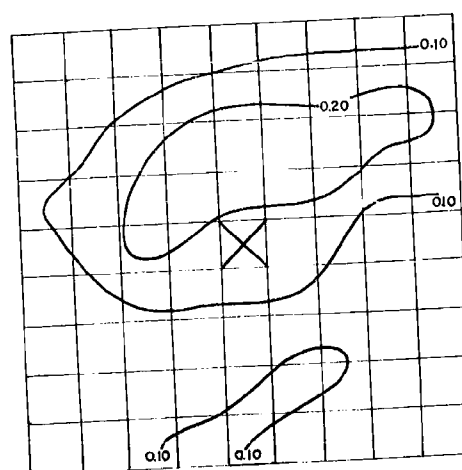
In the composite map for the Texas and East Gulf lows, the maximum moved slightly northward during period 5, and decreased to 0.74 inches. Practically all of the decrease in precipitation can be attributed to one cyclone, number 10, which behaved rather abnormally and moved off the coast in a southeasterly direction (see fig. 1). Apparently this cyclone came under a northwesterly flow aloft causing the precipitation to cease. There were only four cyclones left in this group during this period.

Although several cyclones continued to exist in the area beyond period 5, it was decided not to continue any further. The cyclones were now too few to permit the construction of a satisfactory composite map. Those that existed were close to the coast, so that a large part of the grid would have remained blank.

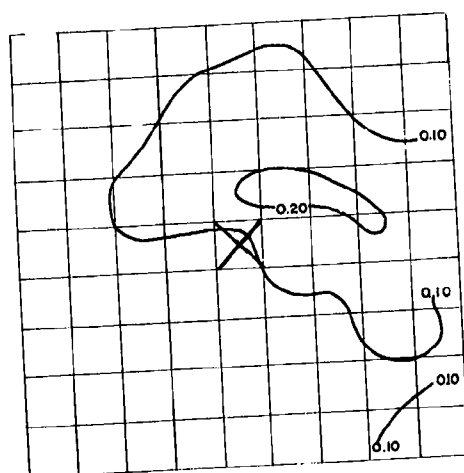
Figure 4 shows the composite precipitation distribution



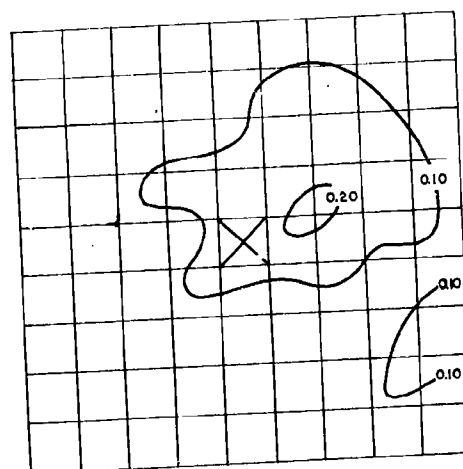
Period 1



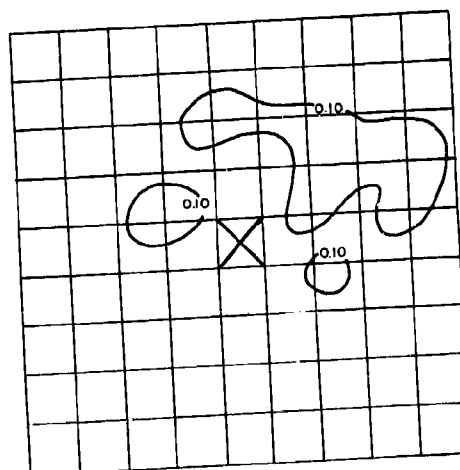
Period 2



Period 3



Period 4



Period 5

Fig. 4. Composite six-hour precipitation maps for ten western cyclones, periods 1-5.

for ten western cyclones for periods 1-5. In period 1 maximum precipitation is to the northeast of the cyclone center with a tongue extending southward to just east of the center. There is considerable precipitation to the southeast, south, and southwest of the center.

Eliminating cyclones 13 and 14 in period 1, since they moved in a more northerly direction, gave a maximum in the same area, but of a slightly larger magnitude. This also eliminated the precipitation areas to the east, southeast, and southwest. The explanation for this is that in cyclones 13 and 14 very little precipitation fell to the northeast of the low. In cyclone 13 the precipitation occurred southwest of the low along the cold front, while in cyclone 14 the precipitation fell mainly to the southeast of the low along the warm front.

Much of the precipitation to the north and northwest of the cyclone center can be attributed to the showers caused by the "lake effect".

The composite map for period 2 shows a westward shift of the maximum but the value remains about the same as for the previous period. This shift of the maximum was due to one cyclone, number 12, in which the precipitation which was northeast of the low, decreased markedly during the period. The shower activity due to the "lake effect" shows up very well to the west and northwest of the cyclone center. The precipitation area in the south was due to cold front showers associated with cyclone 12. Elimination of cyclones 13 and 14 had little effect

on the overall picture.

The composite map for period 3 shows that the area of the maximum precipitation decreased markedly while the magnitude decreased slightly. During this period, many of the cyclones were beginning to fill, with an accompanying decrease in precipitation. Cyclone 17 apparently came under a northwesterly flow aloft and moved in a southeasterly direction with little rain associated with it. In the extreme southeast a precipitation area caused by a secondary cyclone is found, associated with cyclone number 12, which formed along the coast.

The composite map for period 4 shows little change from the previous period. There were only nine cyclones left in this period, and of these several were filling.

The composite map for period 5 was made up of only five cyclones. The 0.20 inch isohyet has disappeared and the rain area no longer shows a distinct pattern.

Statistical analysis

The composite precipitation maps give means for a sample of ten (or fewer) cyclones for a particular period. The problem now is to determine the reliability of the composite maps as models. This requires a determination of the effect of the sample size on the sample mean. Only the boxes with the maximum precipitation in each period were studied. These values were used as the sample means.

The standard deviations were determined for all periods and it was noticed that they were of about the same magnitude as the sample means. The large variance was due to two causes:

first, a variation in the maximum six-hourly precipitation amount from cyclone to cyclone, and secondly, a variation in the distribution of the precipitation from cyclone to cyclone. To find out which of these variations was more important, it was necessary to isolate the variation due to distribution. Therefore, for every period the mean of the ten individual cyclone maxima and the standard deviation were determined (see Table II). The results showed that the means of the maxima were larger than the maximum means. However, the standard deviations are about the same for the maximum mean and the mean of the maxima, indicating that the variance due to variation in precipitation amounts is apparently more important than that due to variation in distribution.

Table II. Comparison of maximum mean precipitation and mean of maxima.

		Max. Mean $\bar{x}$	Standard Deviation s	Mean of Maxima $\bar{x}_m$	Standard Deviation s_m
Southern cyclones					
Period	1	1.05	1.11	1.39	0.96
"	2	0.47	0.40	0.98	0.43
"	3	0.62	0.49	0.83	0.38
"	4	0.87	0.52	1.05	0.46
"	5	0.90	0.49	1.22	0.33
Western cyclones					
Period	1	0.29	0.52	0.67	0.46
"	2	0.28	0.16	0.53	0.33
"	3	0.23	0.19	0.46	0.23
"	4	0.20	0.22	0.35	0.20
"	5	0.19	0.12	0.28	0.09

Student's t distribution (Hoel, 1947) was used to determine the confidence limits on the sample means. The confidence interval is calculated from the following equation:

$$\bar{x} - t_{\alpha} \frac{s}{\sqrt{n-1}} < m < \bar{x} + t_{\alpha} \frac{s}{\sqrt{n-1}} \quad (1)$$

The m is the estimated mean of the population, $\bar{x}$ is the mean of the sample, s is the standard deviation of the sample, n is the number of units in the sample, and t_{α} is a variable (Student's t) which depends upon the number of degrees of freedom ($n - 1$), and the confidence limits that we choose. In this study, calculations were made employing 90% confidence limits ($t_{0.10}$). However, any other degree of confidence could have been used, and the appropriate value of t would be found in statistical tables.

The use of 90% confidence limits signifies that in nine out of ten samples, each sample containing ten cyclones, the sample means as well as the estimated population mean will lie somewhere between the calculated limits. The assumption is made that the distribution of the precipitation variate is normal.

Table III lists the results of these calculations. The results show that the composite maps are not adequate for portraying the mean of the population with any reasonable degree of accuracy. If the maximum box of any period, $\bar{x}$, is used for testing the composite maps it will be seen that, using 90% confidence limits, the population mean may vary as much as 50-100% above or below the value of the sample mean. For example, in southern cyclones, period 1, the maximum precipitation was

1.05 inches. The population mean, with a confidence of 90%, lies between 0.25 and 1.85 inches. The greatest difference between population and sample means would therefore be ± 0.80 inches, or 76% of the actual sample mean. This difference of 50-100% is entirely too large for any practical use and shows that the sample was too small. It was decided that a difference of about 20% would be a tolerable range for constructing an adequate model. It was then necessary to determine how large a sample would be required to achieve this result.

Table III. Confidence limits for sample means.

		Max. Mean $\bar{x}$	Standard Deviation s	90% Confidence Limits
Southern Cyclones				
Period 1		1.05	1.11	0.25 $< m <$ 1.85
" 2		0.47	0.40	0.23 $< m <$ 0.71
" 3		0.62	0.49	0.32 $< m <$ 0.92
" 4		0.87	0.52	0.31 $< m <$ 1.43
" 5		0.90	0.49	0.37 $< m <$ 1.43
Western Cyclones				
Period 1		0.29	0.52	-0.02* $< m <$ 0.61
" 2		0.28	0.16	0.18 $< m <$ 0.38
" 3		0.23	0.19	0.11 $< m <$ 0.35
" 4		0.20	0.22	0.04 $< m <$ 0.36
" 5		0.19	0.12	0.06 $< m <$ 0.32

*The calculations give a negative answer. Since negative precipitation does not exist, it can be assumed to be equal to zero.

For each period, 20% of the sample means were taken and substituted into the following equation to obtain the approxi-

mate number of cyclones that would have to be included in a sample:

$$n = \left[\frac{t_{0.10}s}{\bar{x} - m} \right]^2 + 1 \quad (2)$$

Here n is the number of cyclones required in the sample, s the sample standard deviation, $t_{0.10}$, Student's t distribution equal to 1.700 which is for about 28 degrees of freedom and 90% confidence limits, and $\bar{x} - m$, the difference between the sample mean and the population mean, which is taken to be 20% of $\bar{x}$. The value of 1.700 for $t_{0.10}$ was chosen for reasons of expediency. The value of $t_{0.10}$ decreases only slightly for more than the 28 degrees of freedom, so that the error involved in using the value 1.700 is negligible.

The results of these computations show that for the southern cyclones, periods 1 through 3, the number of cyclones required are 82, 57, and 50, respectively. For periods 4 and 5 the numbers are 28 and 23, respectively.

For the western cyclones, periods 1 through 5, the number of cyclones required are 221, 22, 44, 90, and 26, respectively.

The next problem that came up was whether it would be advantageous to consolidate all the periods of the southern cyclones, and separately, all the periods of the western cyclones into overall composite precipitation maps.

The overall composite map of ten southern cyclones for five periods, is shown in figure 5. This composite map consists of 43 precipitation periods which, in this case, are treated as 43 separate cyclones. The pattern is very similar

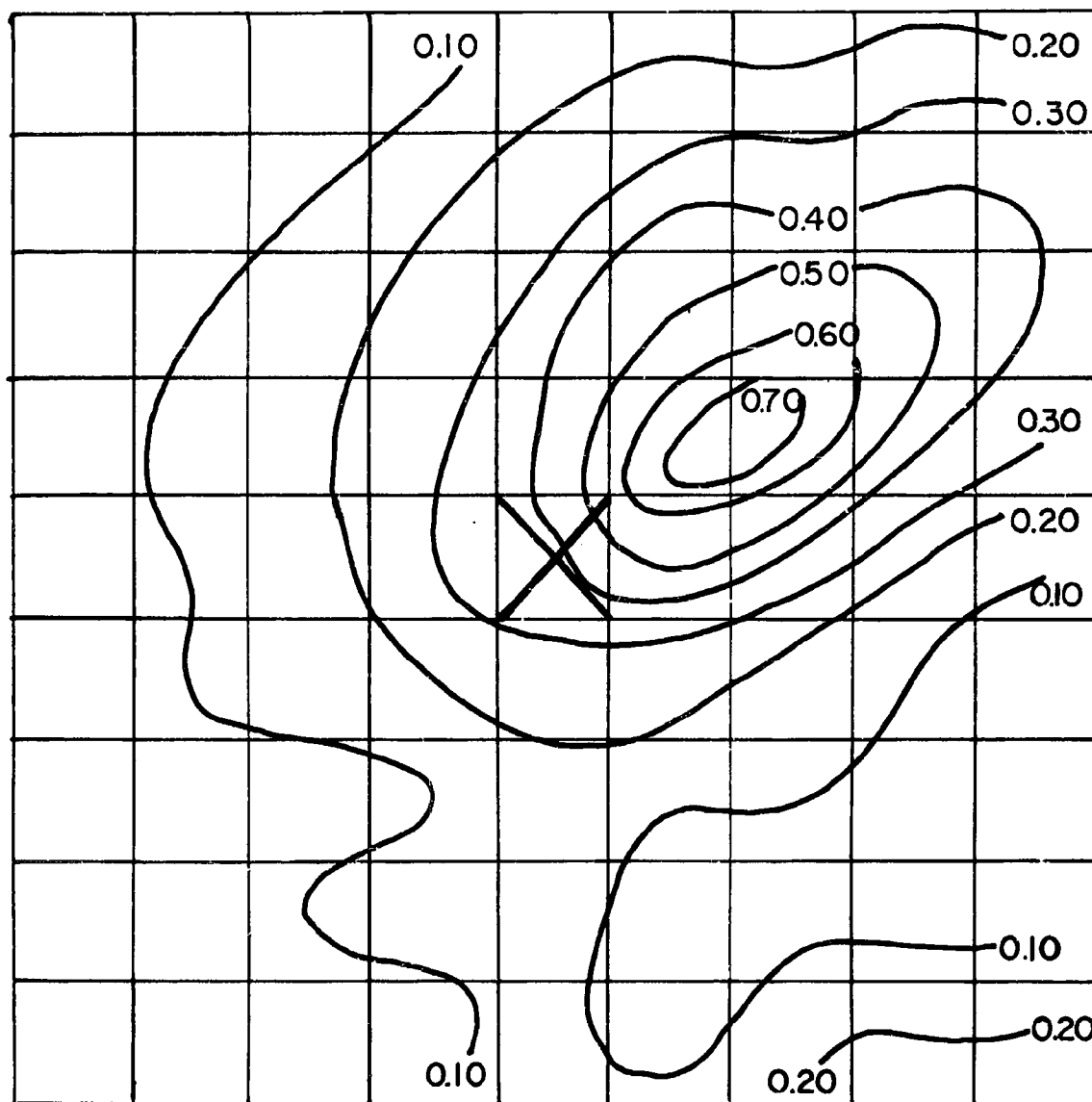


Fig. 5. Composite six-hour precipitation map for ten southern cyclones. Periods 1-5 have been combined into one map One degree grid.

to that of period 1 (figure 3), but the value of the maximum is much lower. The mean of this sample is 0.69 inches and the standard deviation is 0.67. Applying equation (1) and making similar assumptions, the computations show that the mean of the population with 90% confidence, would lie between 0.51 and 0.87 inches. These limits are rather narrow and therefore the composite map is likely to be stable,--that is, if the sample size is increased the composite map will not change much. Computations using equation (2) show that only 63 cyclones, or precipitation periods, are needed to attain a difference of 20% between sample and population means.

A similar overall composite map was made from the western cyclones and this contains 44 precipitation periods (see figure 6). Here the sample mean is 0.20 inches and the standard deviation 0.24. The mean of the population with 90% confidence was found to lie between 0.14 and 0.26 inches. Computations show that 95 cyclones, or precipitation periods, would be needed to attain a difference of no more than 20% between sample and population means, with a confidence of 90%.

There is, of course, some question as to whether five periods of one cyclone can be considered to be five separate cyclones. If a high autocorrelation exists between periods, it is clear that the different periods cannot be considered independent, random samples. The box that coincided with the maximum on the overall composite map, was tested for every cyclone, from period to period, and autocorrelation coefficients were determined.

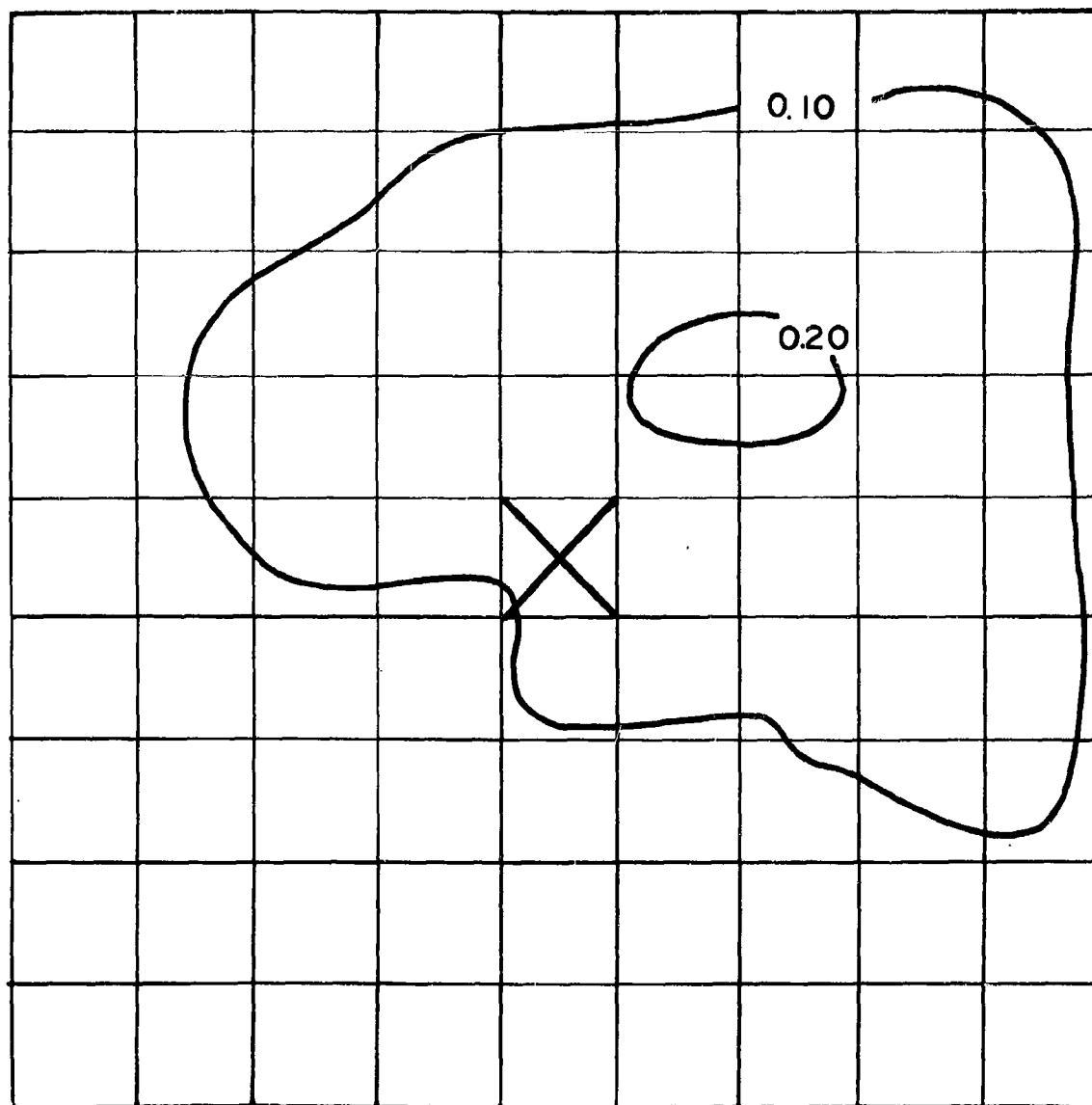


Fig. 6. Composite six-hour precipitation map for western cyclones. Periods 1-5 have been combined into one map. One degree grid.

For the southern cyclones, the autocorrelation coefficient is 0.41; for the western cyclones, 0.11. Since the autocorrelation coefficients are low, they justify the use of the individual periods as independent random cyclones.

The low autocorrelation coefficients can be attributed to two factors: first, the variation in the distribution of precipitation from period to period in the individual cyclones, and secondly to the variation in precipitation amounts from period to period.

Conclusions

The results of this study show that a large sample of storms is needed to develop a precipitation model based on composite maps.

In this study the size of the sample was limited by the short period for which data were available. Since the size of the sample was so small, it was only logical to divide the sample into as few groups as possible. The result was not very satisfactory. Thus South Atlantic, Texas, and East Gulf cyclones were combined into one group even though their positions at any one period were far apart. A similar situation existed for the western cyclones.

Probably the best method of attacking this problem would be to separate all cyclones, over a great many years, into groups according to their region of origin, such as the Bowie-Weightman classification. Mean six-hour positions could be obtained for each group and composite maps constructed for each position. This would be a considerable task as this study has

indicated. A rough estimate is that about twenty years of data would be needed for such a project.

The two overall composite maps (figures 5 and 6) are probably the best quantitative models of precipitation distribution in southern and western cyclones available at this time. These composite maps show that the precipitation is concentrated to the northeast of the cyclone center. The intensity in the southern cyclones is about three and one-half times as great as in the western cyclones. Klein (1948) found similar results as to intensity, and attributed the heavier precipitation in the southern cyclones to deeper troughs, with accompanying greater horizontal convergence and upward vertical motion, abundant moisture, and convective instability of the Gulf air. He also found that when a trough is oriented northeast-southwest, as in the southern cyclones, the precipitation is heavy. When the trough is oriented northwest-southeast, as in the western cyclones, the precipitation is light.

The results of this study show that there is generally a decrease in the maximum precipitation with time. The composite maps for the western cyclones, periods 1 through 5, show that the precipitation decreased slightly from period to period. This fact is even more obvious in the case of the western cyclones if the means of the maxima ($\bar{x}_m$ in Table II) are used. Here there is a much larger decrease in precipitation from period to period.

The composite maps for the southern cyclones show a very large decrease in precipitation from period 1 to period 2, and

then a steady increase right through period 5. The large decrease during period 2 is due to an orographic effect, as was previously explained. This is borne out when reference is made to the means of the maxima ($\bar{x}_m$ in Table II). Here the maximum precipitation during period 2 is larger than in period 3, so that there is a decrease from period 1 through period 3 and then an increase during the last two periods. This increase in the latter two periods is due to the elimination of some of the drier cyclones, since they had passed off the coast, and the deepening of the two coastal cyclones. Indications are that with the exception of the South Atlantic cyclones, the precipitation mean would decrease steadily with time for all southern cyclones. For the South Atlantic cyclones, on the other hand, the precipitation increases as the cyclones move up the coast and deepen.

During this study the position of the heaviest precipitation relative to the cyclone track was determined. This was accomplished in the following manner. The position of every cyclone during period 2 was plotted on its corresponding period 1 grid, the position during period 3 on the period 2 grid, and so on. Each plotted position was then connected by a straight line with the position in the central box, giving a six-hour track. A perpendicular line was drawn from the center of the box of maximum rainfall to the cyclone track. The length of this perpendicular line and its distance from the center was measured in degrees and then plotted as a point on a graph. On the graph, the distance along the cyclone track was the abscissa and the

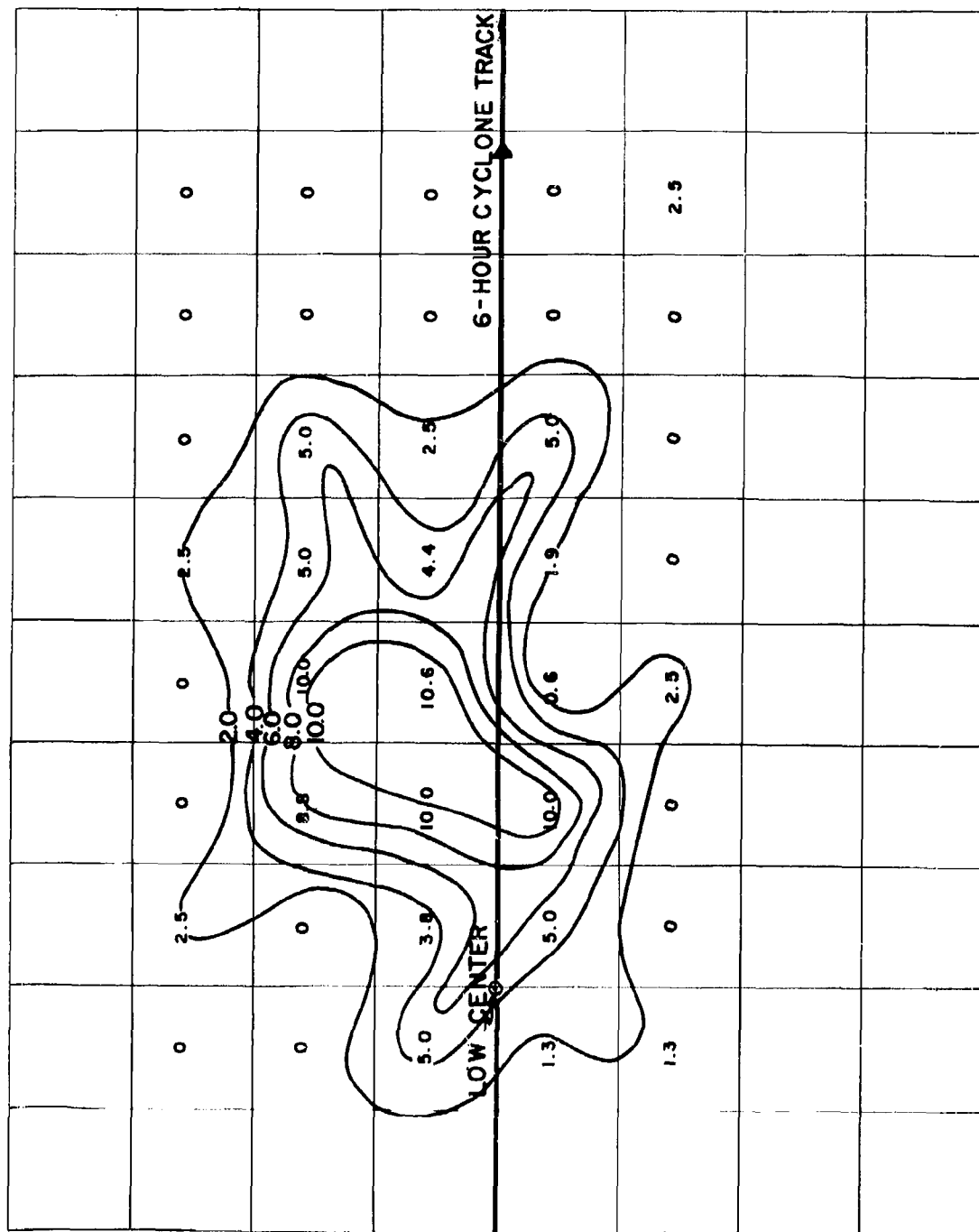


Fig. 7. Isopleths of frequency (percent) of location of precipitation maxima in southern storms relative to the cyclone track. One degree grid.

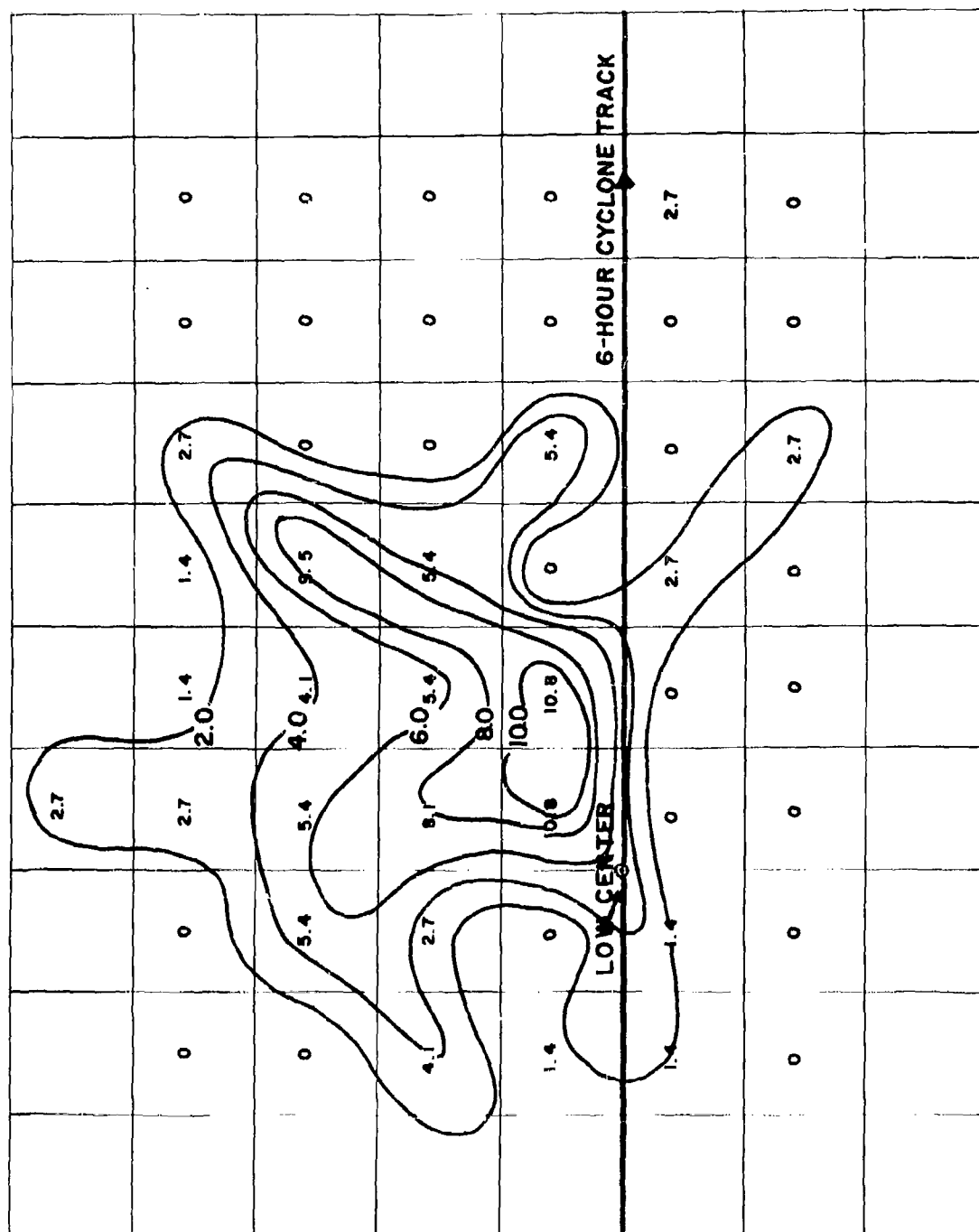


Fig. 8. Isopleths of frequency (percent) of location of precipitation maxima in western storms relative to the cyclone track. One degree grid.

perpendicular distance, the ordinate. The percentage of points located in each degree square was determined and these values were isoplethed (figures 7 and 8). The results show that the maximum precipitation points are scattered over a large area to the left of the cyclone track for both southern and western cyclones. The cyclone does not necessarily move toward the area of heaviest precipitation. Therefore, this is not a good basis for forecasting cyclone movements. The only definite statement that can be made is that the cyclone will move to the right of the area of maximum precipitation.

The results of the statistical analysis demonstrate that a satisfactory precipitation model can be constructed when a sample of sufficient size has been selected so that a stable mean can be obtained. However, these models are of doubtful value for forecasting precipitation amounts because of the large standard deviation. The standard deviations obtained for the small samples that were used in this study were of about the same magnitude as the mean. Even in the overall composite maps where the 90% confidence intervals were narrow, indicating that the mean was fairly stable, the standard deviation was of the same magnitude as the sample mean. In a normal distribution, 68% of the values lie between plus and minus one standard deviation around the mean, 95% between plus and minus two standard deviations around the mean. For example, in the overall composite map of southern cyclones the mean was 0.69 inches and the standard deviation 0.67. Therefore 68% of the values in the distribution would lie between 0.02 and

1.36 inches, and 95% would lie between 0 and 2.03 inches. The conclusion is that there is too much variation in precipitation amount from cyclone to cyclone to permit reliable forecasts to be made from models.

It should also be pointed out that the large standard deviation of cyclone precipitation is one of the most serious problems in the evaluation of cloud-seeding experiments. Since the standard deviation is so large, the effect of seeding cannot be verified immediately after one or several experiments. An accurate verification would require that every favorable situation be seeded over a fairly long period of time, and then a comparison be made in the average precipitation with an unseeded period of similar length.

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