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CLIMATOLOGICAL PREDICTION OF CUMULONIMBUS CLOUDS IN THE VICINITY OF THE YUCCA FLAT WEATHER STATION

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I. INTRODUCTION

The objective of this report is to collect climatological information relating to the occurrence and prediction of cumulonimbus clouds (CB) in the vicinity of the Yucca Flat Weather Station in a single document for ready reference. The annual and daily cycles are first described in terms of relative frequency, i.e., the empirical equivalent of probability expressed either as a percentage or decimal fraction. This is followed by a look at the persistence of days with CB activity and an evaluation of the predictive value of various climatological indices.

II. THE DATA BASE

The data base pertinent to this report consists of a catalog of thunderstorm and CB days derived from the hourly surface observations made approximately on the hour and the 12Z rawinsonde observations at the Yucca Flat Weather Station from January 1962 through December 1975. The sequence of hourly observations is treated as being serially complete even though there are brief periods (as long as two weeks) of missing data. After an examination of the missing days, it was concluded that these days could be considered to be free of CB activity without any serious consequences or loss of accuracy.

A thunderstorm day is defined as a day on which thunder was heard as evidenced by an entry in column 82 of meteorological form MFI-10B. A CB day is defined as a day on which CB were observed as evidenced by an entry in columns 22 through 35 of MFI-10B. The relatively rare days (12 days in 14 years) on which thunder was heard or lightning (not qualified as distant) was recorded in column 13 of MFI-10A were also counted as CB days even though there was not an entry of CB in the cloud columns of MFI-10B. This provides assurance that all actual, as well as potential, thunderstorm days are included in the count of CB days. In some applications the 8 days on which distant lightning was recorded in column 13 but CB were not recorded, were also counted as CB days.

III. THE ANNUAL CYCLE

The annual cycles of CB and thunderstorm days are portrayed in Figure 1 in terms of the relative frequency of occurrence of the specified degree of activity during a 15-day period centered on a selected day. The count of CB days includes all days on which thunder, lightning or distant lightning were recorded. Except for the amplitude of the annual cycle, both curves are very similar with a peak in the frequency of convective activity in early August and a secondary peak in early June. It would be interesting to speculate why this secondary peak is so pronounced; however, it is beyond the scope of this report to attempt to provide a physical basis for the observed facts. The reader is left to rely on his imagination until appropriate evidence can be compiled to support further conjecture.

IV. THE DAILY CYCLE

The daily cycle of CB activity is given for selected combinations of months for the May through September period of greatest frequency in Figure 2 in terms of relative frequency of occurrence by time of day. Distant lightning was not counted as an occurrence of CB in this application. The cycle is rather smooth with peaks near 1500 PST in both the May/June and July/August periods. There is, of course, a rather pronounced difference in the amplitude of the daily oscillations for the two periods.

The daily cycle of thunderstorm activity is shown for selected combinations of months in Figure 3 by the relative frequency with which a portion of a thunderstorm period is part of a half-hour time increment. A thunderstorm has by definition a minimum duration of 15 minutes and an absence of thunder for more than 15 minutes terminates a thunderstorm. The thunderstorm curves of Figure 3 are not as smooth as the CB curves of Figure 2, but they do rise rapidly after 1000 PST and fall off rapidly after 2000 PST. The remarkable difference is the absence of a well-defined peak in the thunderstorm frequency. In fact, there is a strong indication of a double maximum which suggests that even though convective activity is at its peak during midafternoon as indicated by the CB observations, there is a pronounced change in the intensity of the activity with peaks shortly after noon and near sunset. Speculation concerning the reasons for this pattern is not within the scope of this report; however, one should keep in mind that for about 2 to 3 hours following 1500 PST the attention of the observer is distracted by activities related to making the 00Z rawinsonde observation which has been part of the daily routine since October 1966. One should also keep in mind that a storm (CB) must be within hearing range for thunder to be recorded, i.e., within 10 to 15 miles.

V. PERSISTENCE

It is interesting to examine the day-to-day persistence of CB activity before looking at the predictive value of various climatological indices derived from the 12Z sounding. The evaluation of persistence follows a procedure taken from a copy of a manuscript prepared by Smith (1962). The procedure uses overlapping runs of occurrences to more properly evaluate the likelihood of shorter runs by considering them as part of longer runs; e.g., a run of 4 days contains 2 runs of 3 days, 3 runs of 2 days and 4 runs of 1 day. The effect of using overlapping runs as opposed to runs of exactly a given length can be seen in Figure 4. The upper curve is derived from the expression for the probability of successive occurrences of the event; i.e., a run of n CB days, which is

$$P_n = N_n/N$$

in which

N = number of observations = 1708 days
n = length of run
N_n = number of overlapping runs of length n

The probability of a run of CB days continuing for m additional days after having persisted for n days is

$$P(m|n) = N_{n+m}/N_n.$$

This relationship was used to graph the persistence of CB days during the warm season (May-September) in Figure 5. The curve for $m = 1$ hovers around .70 out to about $n = 9$; i.e., once a run of CB days has started the probability of the run continuing for an additional day is about .70 regardless of the length of run. The erratic behavior of the curve beyond $n = 9$ can be attributed to the infrequent occurrence of long runs. There were no runs of exactly 13 to 17 days in the sample and only one run of 18 days. The highly persistent character of CB days is also evident in the curve for $m = 3$. Once a run has started, the probability of the run continuing for an additional 3 days (roughly .35) is greater than the probability of a CB day occurring (.28 as read from the graph at $n = 0$, $m = 1$).

A comparison of the observed number of runs with the number of runs expected under the assumptions of (1) no persistence and (2) a constant probability of .70 of a run continuing for an additional day once started is given in Table 1. Calculation of the expected number of runs is based on the logic of Brooks and Carruthers (1953). Slight errors are introduced because three of the observed runs started on May 30 and one run carried over to October 1 but all calculations are based on N = 1708 days. It is readily apparent in Table 1 that the assumption of no persistence is unrealistic. The assumption that the probability of a run continuing is a constant .70 yields a distribution of expected number of runs of exactly n days which is not significantly different from the observed distribution. This suggests that persistence will be a more formidable opponent for forecasts expressed in probability terms than the climatological relative frequency of occurrence which is often used and generally referred to as simply climatology.

VI. PREDICTORS DERIVED FROM YUCCA 12Z SOUNDING

A variety of indices have been derived from the Yucca 12Z sounding and related to the occurrence of CB days in terms of relative frequency as a function of index value. They are used as predictors in a purely climatological sense since none of the input parameters are predicted values. They are predictive in the sense that the time period used to establish the occurrence of CB extends 20 hours beyond the time of the 12Z sounding.

Randerson Z-index. This index was derived by using multiple linear regression techniques to select the most significant subset of parameters from the Yucca 12Z sounding without a significant loss in the proportion of total variance explained. The predictors offered for selection consisted of height (pressure at the surface), temperature, dewpoint, dewpoint depression, u-component and v-component of the wind at the surface and at 50-mb intervals from 850 to 500 mb. The selected predictors were then offered to a discriminant analysis routine to generate a linear discriminant function which maximizes the difference between the means of observations which fall into two groups. The relative frequency of CB days was then graphed as a function of index value and serves as the key to a probabilistic prediction of convective activity conditional upon the availability of the morning sounding. A comprehensive discussion of the Z-index has been provided by Quiring (1974a).

K-value. The relative frequency of CB days as a function of the Yucca K-value at 12Z was adapted to the NTS by Quiring (1974b) to provide a probabilistic forecast based on a widely used index for comparison with the Z-index. The data base used in this development was the same as that used for the Z-index.

Precipitable Water. The relative frequency of CB days at Yucca as a function of precipitable water at Yucca at 12Z was developed by Quiring (1975). This parameter is considered by some to be a key element in convective activity. This is a reasonable expectation because the humidity parameters were among those most highly correlated with the occurrence of CB days. The data base for this development differs from that used with the Z-index and K-value by addition of data for May and 1972.

Verification. The relative performance to be expected of the various climatological indices derived from the Yucca 12Z sounding is essentially known from the statistics of the sample from which they were generated. The Brier P-score (Brier, 1950) is generally accepted as a measure of forecast performance and the expected score can be easily determined if the relative frequency of occurrence of the predictand and the correlation between the predictor and predictand are known (see for example the appendix to Klein, 1971). Please note that it is standard practice for the National Weather Service to use 1/2 the P-score as originally formulated when there are only two forecast categories; i.e., the event either occurs or it does not occur and only the forecast of the probability that the event will occur is verified. The other half of the forecast, the probability that the event will not occur, is not verified. This practice has been adopted for purposes of this paper so that the possible range of the P-score is from 0 for perfect forecasting to 1 for maximum error.

The correlation coefficient for the multiple linear regression equation used to select the predictors for the Z-index discriminant function is .6395. Since the distributions of the predictand values from the regression equation and the discriminant function as seen in Quiring (1974a) are almost identical it is assumed that the regression equation correlation is applicable to the Z-index even though the coefficients for the discriminant function were developed from a restricted sample drawn from the data base. The correlation coefficient of .6395 for 9 predictors is down from .6550 for 44 predictors remaining after inversion of the matrix of 54 predictors from the Yucca 12Z sounding which were offered for selection. Further elimination of predictors would have resulted in a significant loss in the reduction of variance. No single parameter, or combination of less than 10 parameters, from the Yucca 12Z sounding will yield a higher correlation. The 800-mb dewpoint was the single parameter most highly correlated ($r = .5432$) with the predictand and was thrown out by the matrix inversion.

A correlation coefficient of .5078 is available for the K-value from an earlier computer run in which the predictors offered for selection were correlated with the number of hours with CB as opposed to the final selection run in which the predictors were correlated with the occurrence or nonoccurrence of CB (either +1 or -1). The differences between correlation coefficients for parameters common to both runs are generally small and the correlation coefficient of the K-value from the earlier run is assumed to be valid for the scale of the predictand used in the final run and subsequently used for verification purposes.

Table 2 presents P-scores for four seasons (June - September) of forecasts assuming the availability of varying degrees of knowledge at the time the forecasts are made. The least information available to the forecaster that is considered is the relative frequency of occurrence of CB based on the historical record; i.e., the climatological probability which is often used for comparative purposes and referred to as either climatology or a no skill forecast. The P-score for this level of information is designated as P_C in Table 2 and, as expected, has the poorest scores (highest values).

One might expect that if the forecaster had knowledge of the annual cycle as seen in Figure 1 he could change his probability forecast from day to day and possibly improve his score. This has been done for the annual cycle based on data for 1962-1971 and is designated P_{CA} in Table 2. The improvement, if any, is slight as seen in the score for the 4-year period.

The earlier evidence presented with regard to persistence of CB days suggests that if the forecaster has knowledge that yesterday was or was not a CB day he should be able to improve his score by forecasting yesterday's condition to persist. The score designated P_P in Table 2 is based on a forecast probability of CB today of .70 if yesterday was a CB day and zero otherwise, without regard to length of run. The improvement over the climatological relative frequency is substantial and consistent from year to year.

With the morning Yucca sounding available one might expect the forecaster to improve his score even more. Precipitable water performed only slightly better than persistence for the four seasons; however, the K-value and Z-index provided successively more substantial improvement. The improvement shown for the 4-year sample pretty well follows expected performance. Very little additional information can be extracted from the Yucca 12Z sounding as seen by the maximum possible score of .117 in the expected column of Table 2. This score would be obtained if all 54 parameters available in the Yucca 12Z sounding were used in the prediction equation. The improvement of the scores for the 1972-75 sample relative to the expected scores would appear to be attributable to some extent to the less frequent occurrence of CB days during this period. There are, of course, other factors which must be considered in such an evaluation, but this goes well beyond the scope of this paper.

There is another aspect of the verification of probability forecasts which is at least as interesting as the measure of relative goodness of forecasts. The P-score not only provides this measure of relative goodness, but can be partitioned into at least two parts which have been referred to in the literature as reliability and resolution. This can be accomplished both mathematically and graphically, and some of the pertinent literature is worth noting for the record; e.g., Root (1962), Sanders (1963), Curtiss (1968), Murphy (1972), and Sadowski (1973). Reliability is a measure of the extent to which the forecast probability agrees with the relative frequency of occurrence of the forecast event for given probability categories. Resolution is a measure of the extent to which the forecasts are distributed away from the climatological probability. Both properties are essential to good probability forecasting and according to Sadowski (1973), the contribution of resolution to the Brier Score is roughly 50 times the contribution of reliability and is, therefore, the real payoff in probability forecasting. The ratio is not quite this great for the 1972-75 probability of CB forecasts for the NTS, but still substantial, as seen in Table 3. The sum of the two components does not agree in all cases with the P-score tabulated in Table 2; however, this can be attributed to the coarse categorization (.10 intervals of probability) used in computing the components.

The resolution of the probability of CB forecasts for June-September 1972-75 is shown graphically in Figure 6 for the Z-index, K-value and precipitable water. The relative frequency of CB days during this period was .248 so that if resolution had been perfect, the proportion with probability 1 would have been .248. Even though this degree of perfection is not achieved, the trend is in the right direction. The proportion of the forecasts is greatest near 0, falls off rapidly to a minimum near the relative frequency of CB days for the sample and fluctuates at higher forecast probabilities without reaching a maximum at probability 1. There are not enough forecasts in the highest probability categories. It appears that it is easy to forecast no CB, but difficult to forecast CB with certainty. The relatively higher frequency of forecasts in the four highest categories by the Z-index is very likely a major factor contributing to the better resolution shown in Table 3 for this index.

Reliability of CB probability forecasts is shown in Figure 7. All of the indices tend to overpredict at low probabilities and underpredict at high probabilities. The changeover point is at a probability of about .40 for the Z-index, .20 for the K-value and near .10 for precipitable water. A least squares fit weighted for the number of forecasts represented by each of the plotted points suggests that the reliability of the Z-index and K-value is essentially equal and that precipitable water is the least reliable of the three indices, which is confirmed by the numbers in Table 3.

VII. CONCLUSIONS

The performance of the various climatological indices as predictors of CB activity in the vicinity of Yucca Flat is essentially as expected. There is a strong suggestion that the performance of the indices derived from the Yucca Flat 12Z sounding can be attributed mainly to the high degree of persistence of CB days. Precipitable water as an index of the probability of CB activity is little better than persistence. The K-value and Z-index are essentially equal with respect to reliability of the probability forecasts in that the relative frequency of occurrence agrees favorably with the predicted probability over the full range from 0 to 1. The contribution of reliability to the Brier Score is small. The Z-index is distinctly better than K-value with respect to resolution; however, both indices fail to predict often enough at the high end of the probability scale.

The Z-index is very near the limit of success that can be achieved with climatological indices derived from the 12Z sounding; i.e., climatological in the sense that the index is based strictly on observed values. If one accepts the correlation coefficients from the multiple linear regression which selected the observed parameters used in the discriminant function to generate the Z-index, and there is not compelling reason not to, the Z-index accounts for 41% of the variance of the predictand in comparison with 43% for the combination of all 54 parameters offered for selection. This means, of course, that there is still 59% of the variance of the predictand which is not explained by the Z-index. This should provide some incentive for investigating the merits of introducing predicted parameters into the prediction equation. It is conceivable, however, since we are dealing with an air mass phenomenon in the summertime, which implies slow change, that there is very little hope of improving on the climatological probability provided by the Z-index. One would hope, however, that the skill and ingenuity of the forecaster with the aid of satellite pictures and the vast array of prognostic charts available to him daily would prevail in the long run. In other words, the forecaster should be able to take the guidance offered by the climatological indices and subjectively adjust the forecast probability in a manner consistent with the synoptic situation and the numerical predictions and produce a better probabilistic forecast.

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Table 1. Comparison of observed number of runs of exactly n days with expected number of runs assuming persistence and no persistence.

n	Observed	Persistence P = .70	No Persistence P = .28
1	55	43	247
2	30	29	69
3	18	22	19
4	13	13	5.3
5	11	12	1.4
6	7	6	< 0.5
7	3	5	
8	4	4	
9	1	2.4	
10	4	1.6	
11	1	1.1	
12	2	1.0	
13	0	0.5	
14	0	< 0.5	
15	0		
16	0		
17	0		
18	1		

Table 2. P-scores for June-September, 1972-1975 for various climatological predictors.

Index	1972	1973	1974	1975	1972-1975	Expected
P_C	.228	.174	.176	.177	.188	.204
P_{CA}	.229	.129	.148	.217	.181	-
P_P	.167	.107	.088	.112	.119	-
P_W	.159	.130	.082	.098	.117	-
P_K	.146	.118	.062	.094	.105	.152
P_Z	.127	.075	.053	.074	.082	.121
Rel Freq of CB Days	.342	.214	.218	.221	.248	.286
			Maximum to be Expected			.117*

$$P = \frac{1}{N} \sum_{i=1}^{n} (F_i - O_i)^2 = \text{P-score} = 1/2 \text{ Brier Score}$$

F_i = forecast probability of occurrence

O_i = 1 if the event occurs, 0 otherwise

N = number of forecasts

$$E(P) = f(1-f)(1-r^2) = \text{expected value of } P$$

f = climatological relative frequency

r = correlation coefficient

$$E(P_C)_{k=2} = \frac{1}{2} (1 - \sum_{j=1}^{k} f_j^2) = f(f-1)^2 + (1-f)(f-0)^2$$

f_j = relative frequency in forecast category j

k = number of forecast categories

(Continued following page)

*Maximum possible score based on correlation coefficient of .6550 for 54 parameters from 12Z sounding used as predictors in regression equation.

Table 2. (Cont'd)

P_C = P-score for constant forecast of climatological relative frequency (.286)

P_{CA}= P-score for climatological relative frequency adjusted for annual cycle

P_P = P-score based on persistence (dependent data set 1962-1975)

P_W = P-score based on precipitable water (dependent data set 1962-1972)

P_K = P-score based on K-value

P_Z = P-score based on Z-index

Table 3. Comparison of the contributions of reliability and resolution to the P-score for selected indices for the period 1972-75.

	Z-index	K-value	Precipitable Water
Reliability	.005	.006	.020
Resolution	.077	.101	.097
Sum = P-Score	.082	.107	.117
Ratio (Resolution/ Reliability)	15	17	5

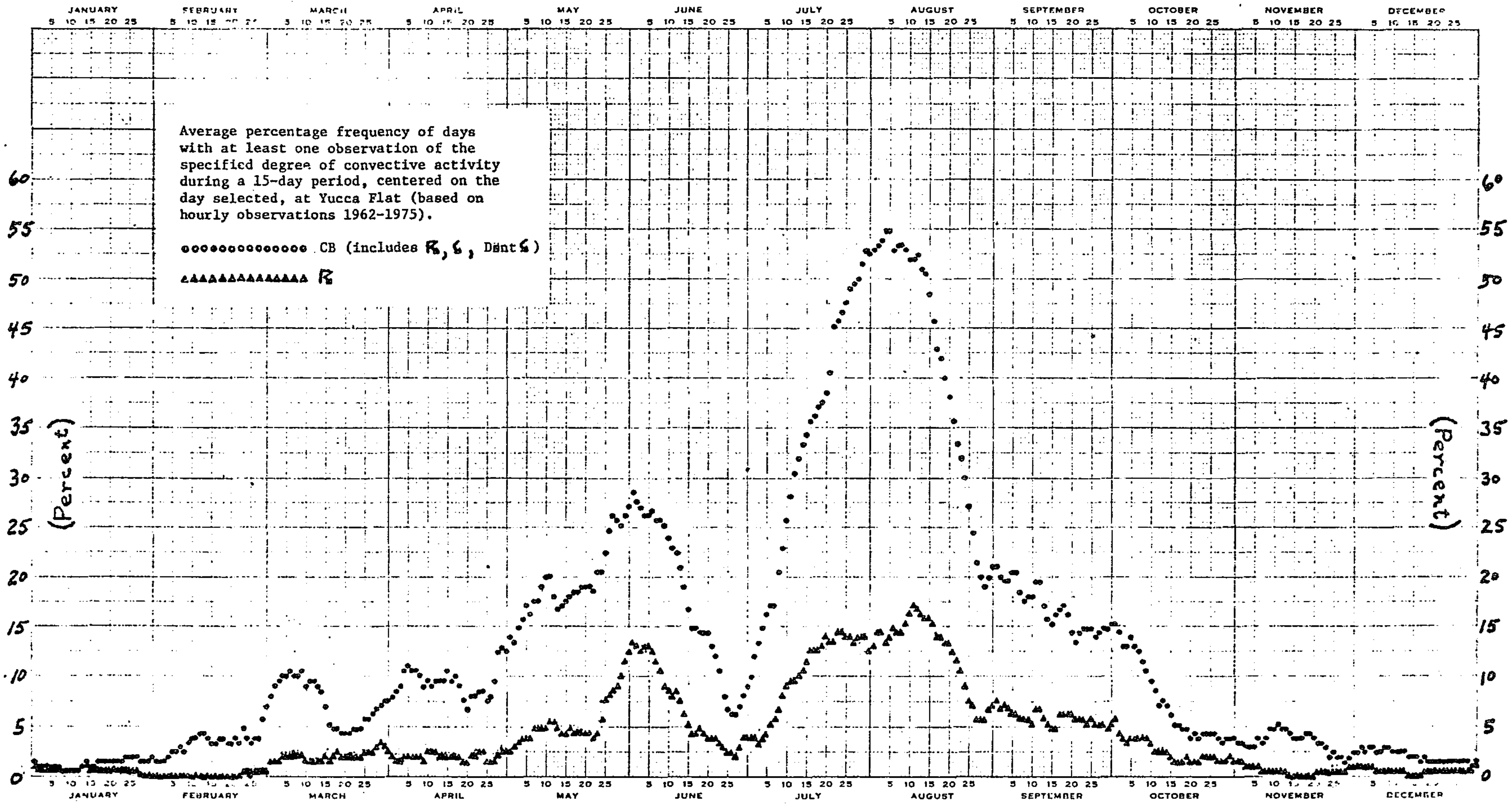

Figure 1. Annual cycle of CB and thunderstorm days (1962-1975).

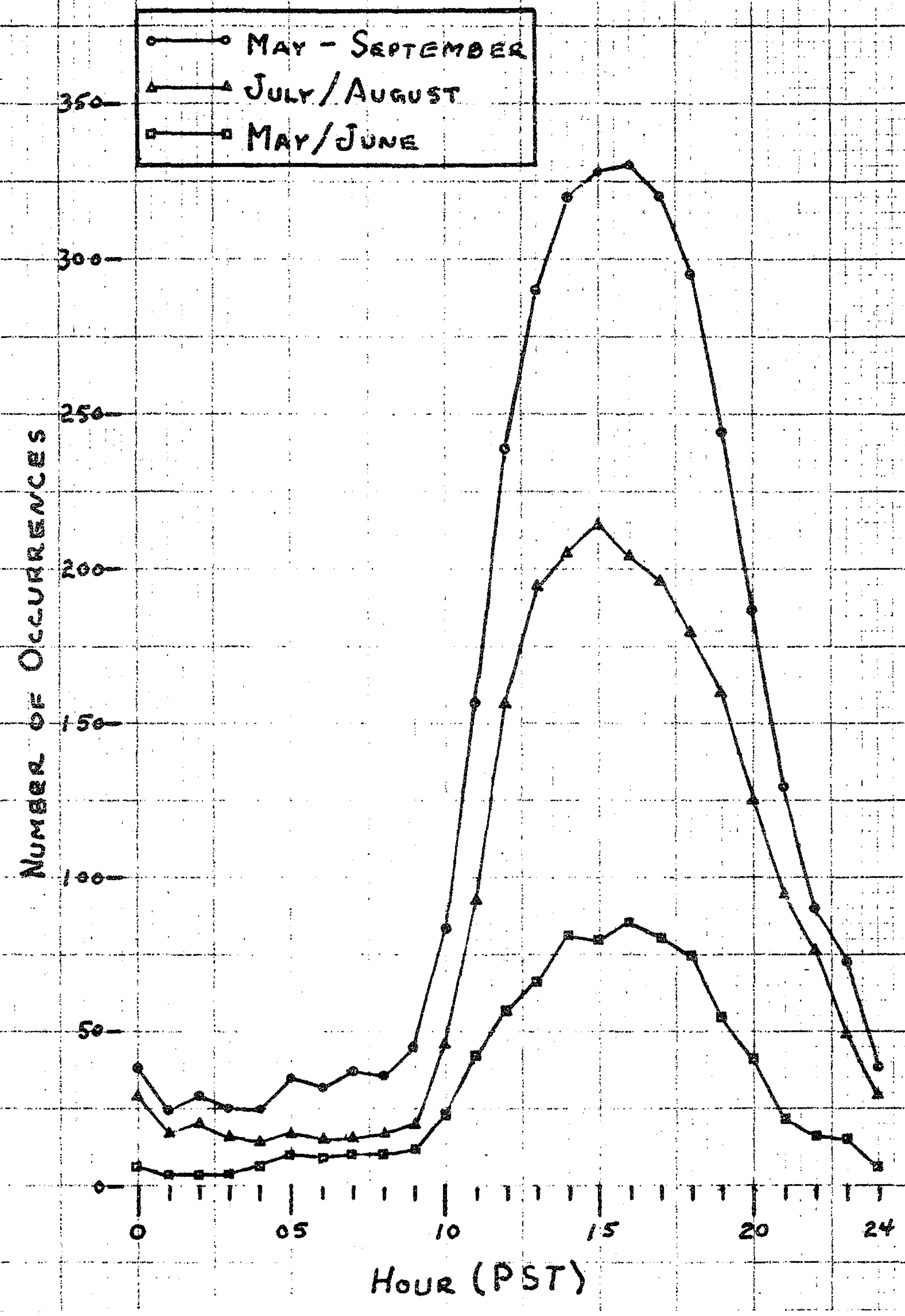

Figure 2. Daily cycle of CB activity during the warm season (May-September) based on hourly observations 1962-1975. Distant lightning by itself not counted as an occurrence of CB.

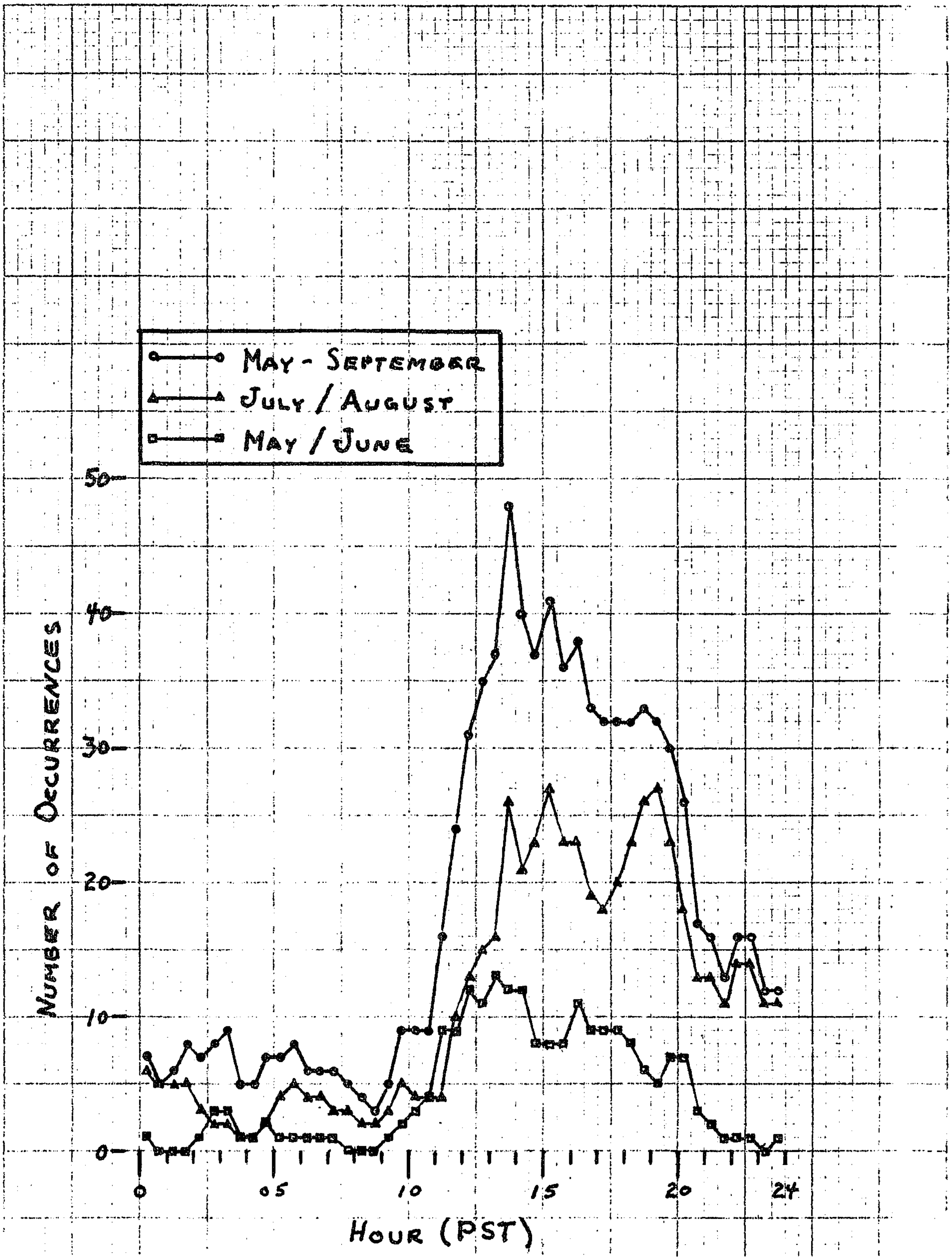

Figure 3. Daily cycle of thunderstorms during the warm season (May-September) based on duration of thunder data during 1962-1975.

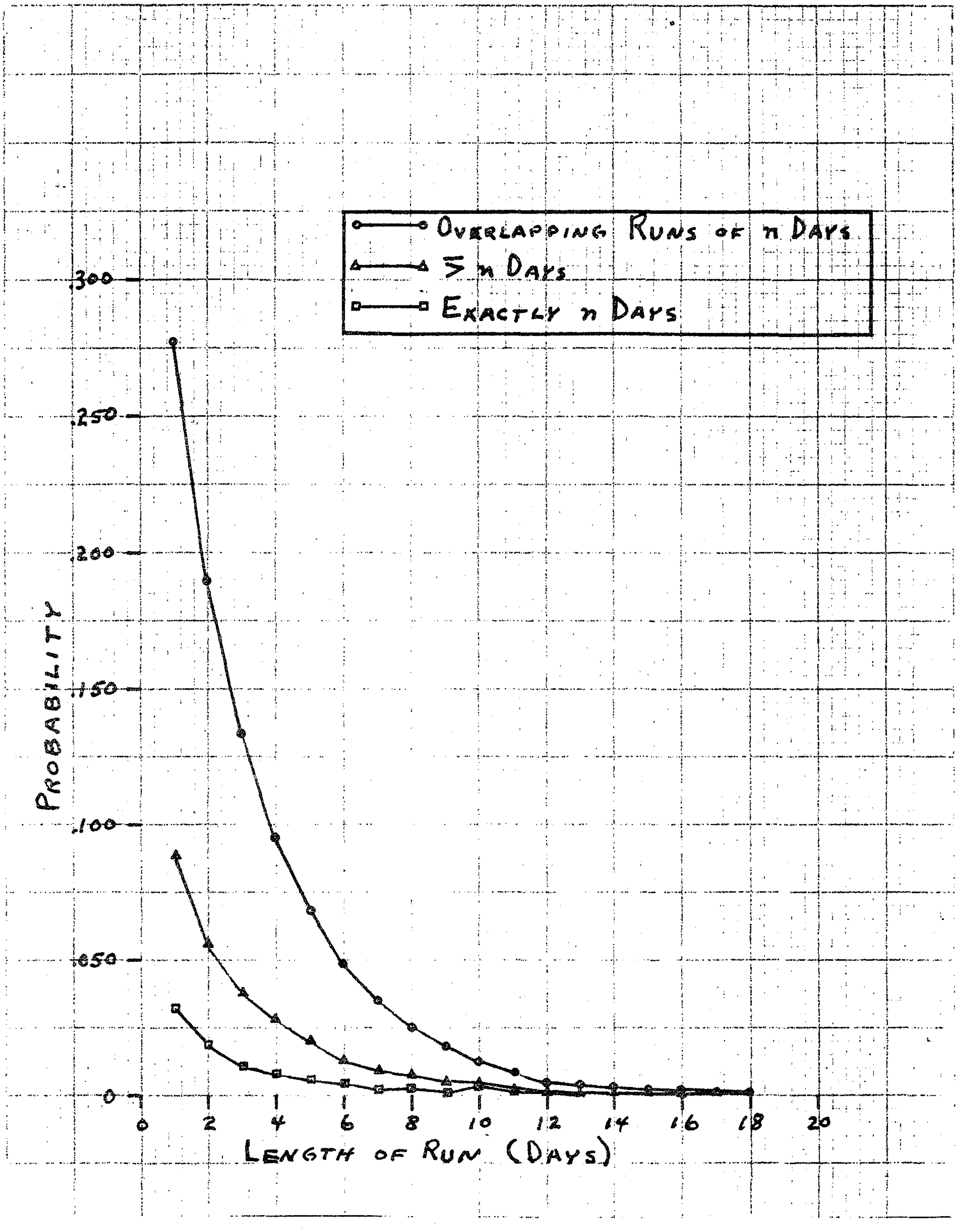

Figure 4. Probability of a run of CB days of a given length during the warm season (May-September) based on data for 1962-1975.

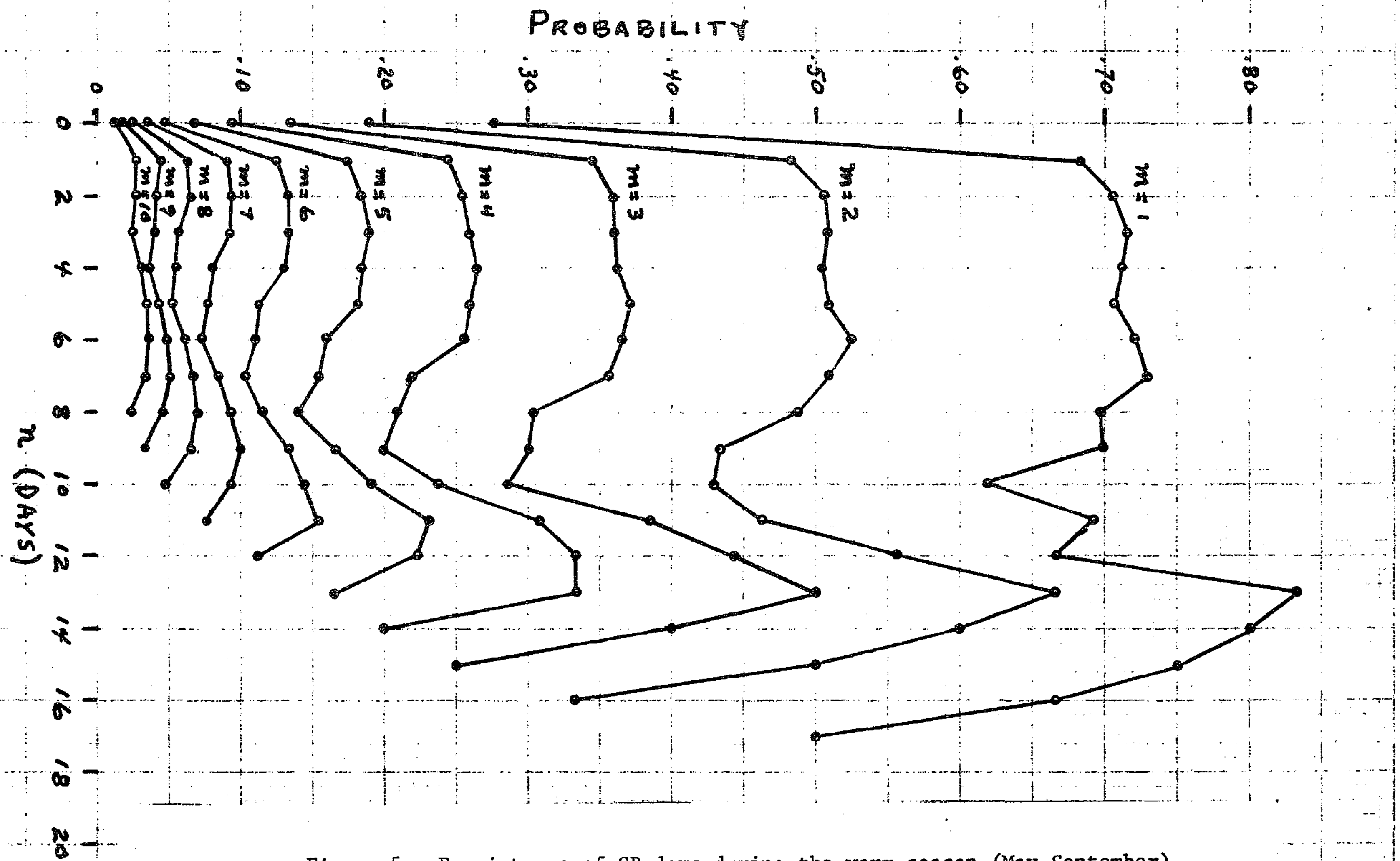

Figure 5. Persistence of CB days during the warm season (May-September), based on data during 1962-1975, expressed as the probability of CB continuing for m additional days after having persisted for n days. $P(m|n) = N_{n+m}/N_n$.

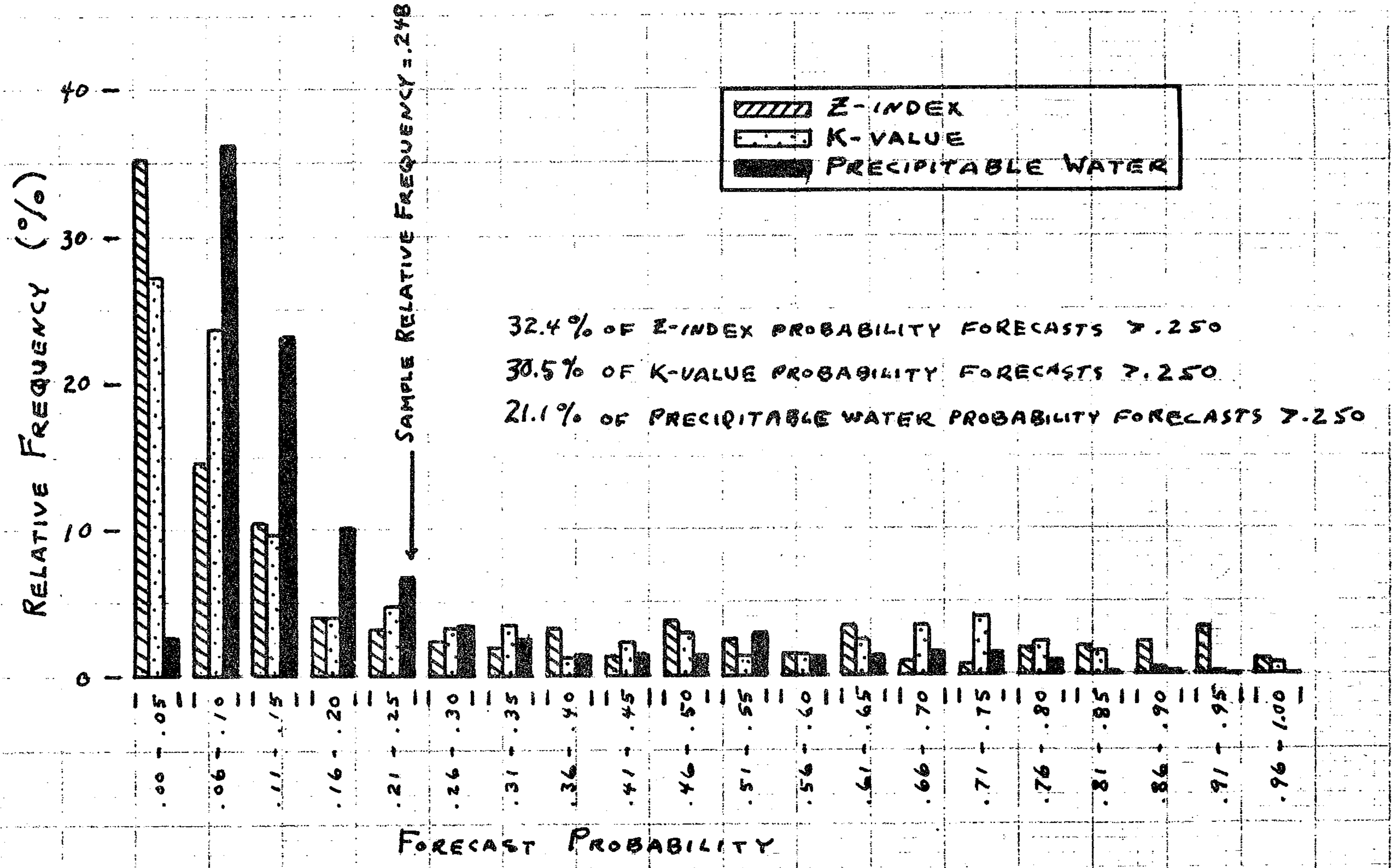

Figure 6. Resolution of the probability of CB forecasts for the NTS for June-September, 1972-1975.

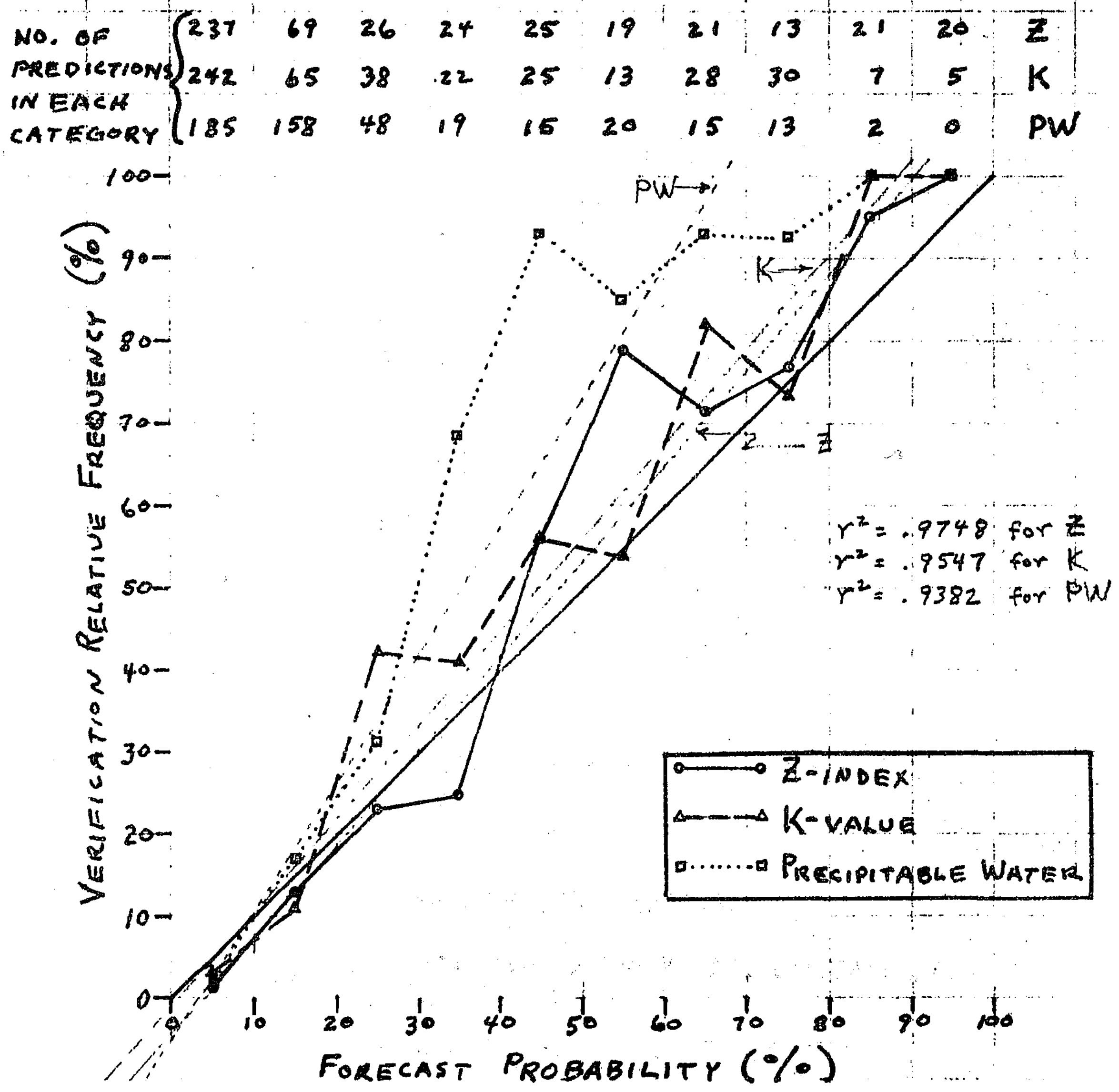

Figure 7. Reliability of the probability of CB forecasts for the NTS for June-September 1972-1975.

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