

SUMMARY OF SEVERAL RADAR ECHO STUDIES FOR
WEATHER MODIFICATION APPLICATION IN ILLINOIS

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Abstract. Information is provided on the spatial and temporal distribution characteristics of squall lines and squall areas, which are the primary warm-season rain producers in Illinois and the Midwest. The distribution characteristics of individual echoes (single echoes) were also determined with respect to important echo properties, such as duration, average area, total area, average and maximum rain rates, and total rain flux. Next, a similar study was made of initially equivalent pairs; that is, pairs likely to be selected as target and control convective entities in cloud seeding experiments. Differences were evaluated through computation of the frequency distribution differences between selected pairs for key echo properties, such as listed above. A fourth study investigated the relationship between echo height and echo characteristics pertinent to evaluation of cloud seeding experiments.

1. INTRODUCTION

Most weather modification research has utilized radar as a primary evaluation tool, and this will continue to be a most important research and operational tool in the future. Total water yield from cloud seeding and its distribution in time and space must be measured in assessing the feasibility and utility of weather modification, and this can best be accomplished through radar observations. Dense raingage networks are also most desirable in weather modification experiments, but installation, operation, and data reduction are very expensive on large-scale projects, and they provide less total information than radar for evaluation purposes.

In optimizing the use of radar in evaluation of weather modification experiments, knowledge of the natural distribution characteristics of radar echoes for the region of study is important to reliable interpretation of the results. Consequently, before undertaking the experimental phases of a weather modification experiment, it is very important to pursue a study of echo climatology in the target region. If no echo data of substance are available, data from other areas with similar precipitation climate should be procured for establishing an echo climatology. One should always have the best information available on the characteristics of the natural rain-producing entities (echoes) before undertaking an experiment. This paper reports on one such effort, made in conjunction with extensive weather modification research in Illinois.

As part of the pre-experimental phase of the Illinois weather modification research, several radar echo climatological studies were made during the 1982-1986 period. Studies were limited to July and August when weather modification needs in Illinois agriculture would normally maximize. The purposes have been to: provide background information on the characteristics of convective storm system in Illinois which will be useful in the planning of future weather modification experiments under the ongoing research program known as PACE (Precipitation Augmentation for Crops Experiment); help determine the feasibility and utility of radar echo observations in evaluating cloud seeding effects; provide

input to the selection of seedable clouds and/or storm units in seeding operations; and, assist in the development of optimal forecasting techniques for future experimental operations. The echo studies were based on radar data from NE Illinois collected during 1977-1979 in conjunction with hydrometeorological research (CHAP project) in the Chicago area (Changnon et al., 1980), 1978 operations at Champaign, and 1975 data collected in the St. Louis area as part of the METROMEX research (Changnon et al., 1977). Findings should be generally applicable to the Midwest and other areas of similar precipitation climate.

The data used in the studies were from PPI photographs of the reflectivity factor (Z) of two Water Survey radars usually referred to as the HOT and CHILL (Dzurisin, 1983). Both were 10-cm sets with peak transmitter power of 600 kw and a pulse width of 1 μ s. The pulse repetition frequency was 974 Hz for the CHILL and 650 for the HOT. The beam width was 1° for the CHILL and 1.6 for the HOT. Minimum discernible signal was -103 dbm for both radars. Some differences also existed in the contour intervals of radar reflectivity. However, the foregoing differences should not compromise the compatibility of the two sets for the climatological studies. These studies were concerned essentially with the characteristics of Z that defines the various precipitation factors (intensity, duration, areal extent, volume, and cloud height) useful as analytical tools in weather modification experiments. The HOT radar was operated in SW Illinois with the METROMEX research on inadvertent weather modification in 1975 and with the CHAP project in NE Illinois during 1977-1979. The CHILL radar was operated at Champaign (central Illinois) during 1978.

The results presented here are based primarily on the CHAP data for which detailed measurements of echo characteristics had been made and computer-processed for 86 storms, as part of this earlier research project. The echoes were separate rain-producing convective cloud entities that were usually multicellular, easily identifiable on the radar scope, and represent the type of cloud entities that would be treated in cloud seeding experiments and operations in the Midwest. Since individual cells (intensity centers) within

multicellular entities can not be treated as independent samples in cloud seeding experiments, cell analysis was not undertaken in this echo climatology study for PACE, except for a study of maximum echo heights described in Section 5.

2. INITIAL STUDY - LINES, AREAS, AND ISOLATED ECHOES

Dzurisin (1983) made a study of radar-portrayed squall lines, squall areas, and isolated convective entities, based on data from all three sources (NE, SW, and central Illinois). Data from the HOT and CHILL radars were combined to increase the sample size.

Only echo systems developing and reaching the decaying stage within radar range were used in the study. These were considered to be the convective systems most amenable to treatment in cloud seeding experiments, in view of the need to treat convective entities in the early stage of development established in the FACE experiments (Gagin et al., 1985) and supported by PACE pre-experimental studies of Midwestern cumulus characteristics. Furthermore, complete life histories were available for these echo systems, and they included most of the convective systems detected within radar range in the sampling periods (Dzurisin, 1983).

Essentially, an echo line was defined as a group of echoes with length at least twice the width and extending for 20 nautical miles or more. An echo area had to include a minimum of four echoes not lying along a single line. An isolated echo system was any group of less than four echoes separated from other echo systems. The above definitions yielded 155 areas, 262 lines, and 256 isolated echo systems for the Dzurisin analyses.

2.1 Line Characteristics

On the average, a line lasted 62 minutes, but 65% had durations of 30-75 minutes, and less than 10% persisted for two hours or more. The standard deviation was 50 minutes.

The average distance of line travel was 17 nautical miles (nm) and most traveled less than 40. About 20% were stationary. The average line length was 64 nm and the average width was 5 nm. Individual echo diameter was usually less than 5 nm. The average area encompassed by lines was 530 nm² with 55% having less than 400 nm². During their lifetime, however, the moving lines frequently produced rainfall over areas of 5000-15,000 nm².

Lines moved most frequently from the NW (45%), followed by W and SW (27%); 22% were stationary. Within lines, individual echoes moved from the SW most often (49%), followed by W and NW (36%).

Comparison of day and night lines revealed no significant differences in the echo parameters examined. In summary, a typical Illinois squall line in July-August extends 65 nm, is 5-10 nm wide, oriented NE-SW, and travels approximately 20 nm from the NW before decay. It lasts approximately one hour, travels at an average speed of 20 knots, with individual echoes moving from the SW.

2.2 Line Evolution

In over 80% of the cases, the greatest number of distinct echoes occurred within the first 45 minutes after development, and peak intensity

occurred within the first 18 minutes. These findings emphasize the need to treat seedable clouds in the early stages of convective development to optimize operational results. Multiple echo lines occurred in 70% of the cases (183 of 262 sampled). Also, in 80% of the cases, lines occurred in the presence of other echo formations (areas or other lines).

2.3 Line Dissipation

Echoes dissipated on the ends in 80% of the cases. Usually, complete and rapid dissipation did not occur. Rather, transformation into another system took place; this was squall areas most often (53% of the lines).

2.4 Area Characteristics

Areas tend to last longer than lines in the convective storms of July-August in Illinois. The average duration of radar-portrayed squall areas was 129 minutes compared to 62 minutes for lines. Thus, areas tend to last over twice as long. However, there is a wide variation in area durations, as indicated by the sample standard deviation of 124 minutes. Of the 155 areas sampled, 63% lasted less than 150 minutes, but a few persisted for over five hours.

The average number of separate echoes in an area was 7, and 79% had less than 10. Area echoes tend to be larger than line echoes. Typically, area echoes had diameters of 5 to 10 nm, whereas line echoes were usually less than 5 nm. Average area encompassed by squall areas was 383 nm² compared to 530 nm² for lines. Separate area echoes tend to move most frequently from the NW and W. Translation of the areas was not investigated because they do not have distinct geometric forms, and there is extreme difficulty in determining the motion components due to formation and decay of the separate echo entities.

2.5 Area Evolution and Dissipation

It was found that 62% of the echo areas formed from scattered echoes and 38% from existing lines. The greatest number of areas echo developed in the first 40 minutes of area formation. Maximum reflectivity occurred in 25 minutes compared to 18 minutes for lines. Analyses showed that when echo areas dissipated, they divided into isolated echoes 64% of the time, and became lines 36% of the time.

2.6 Summary

In general, it was determined that during their lifetime echo lines in Illinois during July-August most frequently produce rainfall over areas of 5000-15,000 nm². They appear to be distinctly different from classical frontal squall lines in duration, areal extent, and translation speed. However, they are similar in orientation and with respect to individual echo movements within the lines. No discernible difference was found between day and night lines with respect to the variables studied.

The study revealed that echo areas in July-August are typically more extensive and last longer than lines. They most frequently form from isolated echoes. Similar to lines they reach maximum intensity quickly. No discernible difference was detected between the day and night echo areas (similar to lines). This does not necessarily mean there are no differences; it

merely indicates no substantial differences between the variables studied in this sample - duration, movement, areal extent, configuration, and time of maximum intensity (reflectivity).

3. CHARACTERISTICS OF INDIVIDUAL ECHOES (SINGLE ECHOES)

During 1984-1986, considerable effort was devoted to the climatology of individual (single) echoes, based on the 86-storm sample processed as part of the earlier CHAP research. This data was collected with the HOT radar, located at Joliet, Illinois, which scanned an area of 42,000 km² (16,900 mi²) over NE Illinois and Lake Michigan (Changnon et al., 1982). This area was represented by 64 x 64 grid points with 3.25-km spacing (2 mi) in reflectivity computations. The reflectivity (Z) was range corrected and converted to grid values by averaging neighboring bins (Hsu, 1985). The radar-indicated rain rate (R) was obtained from the relation between reflectivity (Z) and rainfall rate (R) derived at the Water Survey, in which: $Z = 300 R^{1.35}$. The radar was operated at elevation angles ranging from 0.75° to 5.4°. Echo entities were isolated and matched from scan to scan manually. The rain rate at each grid had to be 4 mm/hr or more for inclusion in the study, and there had to be three or more contiguous grid points which met the rain rate criteria for an echo to qualify as an echo entity. Thus, the echo entity included all contiguous points with $R > 4$ mm/hr.

3.1 Method of Analyses

In the single-echo climatological studies, analyses were limited to those echoes having a duration of 8 minutes or more (at least two radar scans). It was assumed that echoes of shorter duration would not meet operational and seedability criteria in future PACE experiments. Of the 86 storms, 32 were eliminated because of various data problems (Hsu, 1985). In the 54 remaining storms, a total of 1334 echoes were sampled. However, only 560 of these met the echo study criteria (durations ≥ 8 min., rates > 4 mm/hr).

In the analyses, determination was made of averages and maxima for various echo characteristics. In all cases, statistical computations were based on the real numbers as opposed to transformation values. Frequency distributions were determined for each selected parameter, and the "best-fit" statistical distribution identified. Computations of the mean, standard deviation, and coefficient of variation indicated a large degree of natural variability in the echo parameters as illustrated in Table 1. For example, the coefficient of variation for total rain flux, a most important parameter in assessing weather modification experiments and operations, was 13.06. The lowest coefficient (relative variability) apparently occurs with average rain rate of echoes during their lifetime. First-echo average area is somewhat more variable than for echoes in general (2.66 vs. 2.17). First-echo mean rain rate is considerably more variable than the mean rate for all echoes of the sample combined.

In evaluating fitting procedures, the exponential, normal, log normal, extreme value 1 and 2, and Weibull distributions were tried (Hsu, 1985). In general, it was found that the

extreme value distribution-type 2 fit best with average and maximum values of the various parameters. The log normal distribution was better for parameters involving data totals, such as total rain flux and total area encompassed by an echo during its lifetime. The first-echo variables were also fit best by the extreme value distribution.

3.2 Results of Analysis

Initially, frequency distribution curves were derived for echo duration of 8 minutes or more for all echoes combined and for various synoptic storm types. From these curves, Table 2 was obtained. This table provides a convenient means of comparing the several frequency distributions derived from the stratified data.

Table 2 indicates no large differences between the median values of the synoptic storm types. The median duration ranges from a high of 19 minutes for air mass storms to 16 minutes for cold fronts. In view of the variation in sample size among the synoptic types (26 to 264), these differences are not considered significant from a practical standpoint. It is obvious that the "all echo" distribution is strongly influenced by squall areas which constituted about 47% of the total echo sample.

The major differences in the distribution curves occur in the upper 20% of the observations. The values are less reliable in this range than in those that follow, since they are based on a relatively few observations. For example, the 5% to 20% portion of the air mass curve is based largely on 5 observations. With squall area echoes, approximately 50 observations largely determined the upper 20% of the curve. As a result of the findings in Table 2 which shows little difference among the synoptic types, it was decided to limit the rest of the individual echo analyses to the distribution characteristics of all echoes combined. This will provide the best available first approximation of the pertinent characteristics of Illinois rain echoes for PACE applications.

The upper part of Table 3 provides a summary of the frequency distribution for each of the six echo characteristics analyzed. The lower portion shows ratios of various frequency values to the median. This provides a simple measure of the natural variability inherent in each echo parameter, among those echoes meeting our criteria for inclusion in potential seeding experiments.

Table 3 indicates a high degree of variability among the selected type of radar echoes. The most pronounced departures from the median occur at the upper end of the curves. Mean rain rate has the smallest relative variability among the 6 echo parameters and total rain flux has the largest. Total flux is an especially important parameter in assessing cloud seeding, because it is a measure of the total output of the storm entity (echo) at the ground.

Table 4 summarizes results of the analyses of the frequency distribution of echoes having durations of 15 minutes or more. Findings are similar to those for durations of 8 minutes or more shown in Table 3. Thus, the least variability among observations occurred with mean rainfall rate and the largest with total rain flux. The degree of variability is greater for some parameters in the

15-minute group (mean rate, mean maximum rate, mean area), whereas it is greater for others in the 8-minute sample (duration, total area, total flux). Overall, differences are relatively small and inconsistent between the two groups.

3.3 Conclusions

This study has provided additional information on echo climatology in Illinois (and the Midwest) which should be useful in the planning, operational, and evaluation phases of future PACE experiments. Among echo parameters studied, the natural variability tends to be least in mean rainfall rate and greatest in total rain flux (total water output). The degree of natural variability is an important factor that must be taken into consideration in various phases of the PACE research, but especially in evaluation of the cloud seeding experiments.

4. CHARACTERISTICS OF INITIALLY EQUIVALENT ECHO PAIRS

The single-echo sample was used to form a population of "initially equivalent pairs". Equivalence was based on an operational point of view; that is, pairs likely to be selected as "target" and "control" convective entities in cloud seeding experiments. For our study, the equivalent pairs had to (1) be separated by a minimum distance of 20 km and a maximum separation of 150 km, (2) initiate within less than 1 hour of each other within 100 km from the radar, (3) both have a duration of at least 8 minutes, and (4) both have a radar-indicated rain rate of 4 mm/hr or more.

Hsu (1985) initially tested four scenarios of equivalent pairs. The first scenario involved "completely independent" pairs; that is, a second pair for target-control comparisons was not selected until 5 minutes after both echoes in the first pair had dissipated. In the second scenario, a second pair was chosen 60 minutes after the first-pair history ended, due to one or both echoes dissipating. A definition was used in the third and fourth scenarios, in which a second pair was selected 10 minutes and 5 minutes after the first-pair history ended. Various echo parameters were measured for each equivalent pair.

A large number of echo statistics were derived from these data which should be useful for experimental planning purposes, and these are summarized by Hsu (1985). Examination was made of such echo parameters as mean and maximum rainfall rate, distance between members of the equivalent echo pairs, echo area and differences in echo area between pairs, duration and differences in duration of pair members, rain flux characteristics, and first echo properties.

Huff (1986) then used the large compilations of statistical information derived by Hsu to investigate further the distribution characteristics of echo pairs which had been selected as potential target-control entities in weather modification experiments. This was done for the Hsu data sets having mean rain rates of 4 mm/hr or more and durations of 8 minutes or more and 15 minutes or more, respectively. All selected pairs were independent - that is, no echo was used in more than one pair. Both echoes in each pair had to be detected within one hour or less of each other within a 60-nautical mile radius of the CHAP radar used in the study. There were a total of 219

pairs in the 8-minute sample after eliminating those which did not meet all the criteria established for inclusion on the study. The number was reduced to 143 pairs in the acceptable 15-minute data sample.

Differences were computed for mean rain rate (R), mean maximum rain rate, (R_m), mean area (A), total area (A_t), total rain flux (F), and echo duration (D). The differences were originally grouped by synoptic storm type, but later combined into two groups, since the distribution of differences among the individual types showed no distinct trends. However, total sample size and variation in the sample size among storm types could have masked significant difference. For example, in the 8-minute sample of 219 pairs, the number ranged from 11 for air mass storms to 106 for squall zones.

Frequency distributions were derived for each of the six echo parameters listed above for the two synoptic groups. One group included air mass and three frontal storm types, and the other contained squall lines and squall areas. Frontal types were cold front (CF), warm fronts (WF), and stationary fronts (SF). This division was based primarily on examination of the ranked data and individual frequency curves obtained with each synoptic type.

4.1 Results of Analyses for 8-Minute Pairs

Figure 1 shows the frequency distribution for total rain flux differences between echo pairs. Rain flux is probably the single most important measurement in radar evaluation of cloud seeding undertaken to enhance natural rainfall for agricultural and hydrological purposes. Figure 1 indicates that pair differences tend to be considerably larger with squall line and squall zone storms (SL + SA), but are frequently large among both synoptic groups. For example, at the 50% probability level (median), squall-type storms have a pair difference that is 2.62 times the air mass-frontal value (AM + CF + SF). Comparative curves for the other five radar parameters were provided by Huff (1986), but all show a trend for relatively large differences between "initially equivalent" pairs. Tables 5 and 6 show the variability distribution of echo pair differences, as determined by the ratio of selected probability level values to the median of the distribution. The greatest variability was exhibited by total rain flux and the least by average rainfall rate. With the exception of A_t , relative variability for each echo parameter was greater with the squall line and squall area storms than with the air mass and frontal combination. This is especially evident for total rain flux. This parameter is dependent on A_t , R , and D , and, hence, incorporates the variability inherent among these three echo properties.

Table 7 shows correlation coefficients between echo pair differences for each of the six parameters analyzed. Coefficients of 0.50 or more (25% or more of the variance explained) are underlined. Differences in total water output of the raincells, as measured by F , is most closely related to differences in A_t , followed by A and then D . The correlation between F and R is insignificant, accounting for only 4% of the variance. A_t accounts for 83% of the variance, A for 46%, and D for 34%. The foregoing results suggest that differences in total water output from convective

storm systems are largely controlled by variation in the area and duration of convective entities rather than by rain intensity. This finding is supported by results of the METROMEX surface raincell studies (Huff, 1977). The correlation between F, A_t , and D was stronger when all echoes with durations ≥ 8 minutes were analyzed, compared with the longer lasting echoes having durations of ≥ 15 minutes (discussed later). Table 7 also indicates that differences in average rain rate and mean maximum rain rate (average of peak rates for all observations during echo lifetime) are related strongly only with each other. Of the two parameters, maximum rate correlates somewhat better with F, A_t , A, and D than does average rate. Duration is most strongly correlated with A_t and F.

4.2 Results of Analyses for 15-Minute Pairs

The same analysis procedures employed with the 8-minute pairs were used in the study of pairs lasting 15 minutes or more. In the 15-minute sample, there was a total of 143 echo pairs meeting the established criteria, and the number of samples ranged from 6 for air mass storms to 77 with squall areas. As expected, findings were very similar to those obtained with the 8-minute sample. Thus, the frequency distributions fit the log probability distribution well, with the exception of total rain flux which showed a slight curvature on the log probability scale. The greatest natural variability was indicated by total rain flux, and the smallest by mean rain rate. Correlation coefficients showed rain flux differences most closely related to differences in echo area and duration of echo. Correlations between total rain flux and average rain rate differences were insignificant, accounting for only 4% of the variance compared with 56% for total echo area and 26% for echo duration. Table 8 shows correlation coefficients for the 15-minute pairs.

4.3 Conclusions from Echo Pair Studies

These studies have provided much useful information relative to the distribution characteristics of initially equivalent radar echoes that is pertinent to the evaluation of weather modification experiments and operations. Pair differences for the most important echo parameter, total rain flux, were found to be most strongly related to differences in echo area and duration, and poorly related to echo rain rate differences. This is in agreement with METROMEX findings concerning surface raincells obtained from a 52,000-km² dense network of recording raingages. That is, the total water output of the raincells was strongly linked to cell area and duration and only weakly related to rainfall rate.

Great natural variability among radar echo properties was found. Among the six echo parameters studied, frequency distributions indicated maximum variability in total rain flux and least in average rain rate among the initially equivalent pairs of echoes.

5. RADAR ECHO CELL STUDIES

A limited investigation was made of the relationship between maximum echo cell height and five radar echo parameters pertinent to evaluation of cloud seeding. Echo cell in the following discussion refers to separate intensity centers, of which several may exist in an echo entity (which, in turn, may be part of an echo line or area). The parameters included total rain volume of the cell (RVOL), maximum reflectivity (ZBMAX), maximum echo area (ABMAX), cell duration (DUR), and maximum

rainfall volume rate (RVRB). This study was done to verify a similar study done for PACE by Gagin and associates at Hebrew University and to extend their study somewhat. Gagin et al., (1985) had indicated from studies of the Florida FACE experiments that maximum echo cell height could be used to evaluate cloud seeding effects and to establish sampling requirements for statistical verification at various confidence levels. Their study of a limited sample of the Illinois CHAP data for 118 echoes in 3 storms indicated the technique could also be applicable to Illinois.

It should be understood that the single echo cells analyzed in the Gagin study are not equivalent to the radar echo entities used in the Illinois studies described previously. The echo entities usually consisted of several cells in combination (multicellular echoes). In practice, specific cells may be treated, but the output from the total convective entity is most important. A specific cell within a convective entity cannot be considered an independent entity statistically, since what happens to it will affect neighboring cells in a multicellular entity.

From our study, it was concluded that because of the small sample size and natural variability involved, the Gagin regression equations should be used only as a first estimate in establishing the relationship between maximum echo height (HMAX) and the other radar parameters. Major changes in the initial regressions are likely to occur when a large number of storms are incorporated into the calculations. Furthermore, it is quite possible that substantial differences in the regression relations may exist among different storm types. In essence, the methodology may be acceptable, but the results have limited utility at this time.

Table 9 shows the correlation coefficients (r) and variance explained (r²), between HMAX and the five related echo parameters. The correlation coefficients are slightly lower than those contained in the Gagin report (Changnon et al., 1986). Although these correlations appear quite strong, they do not adequately reflect the relatively large variability about the regression lines (equations) relating HMAX to the various echo parameters.

Despite the relatively small sample size, we investigated the HMAX relations further by stratifying the height data into three groups. These were maximum heights of 7 km or less, 7.1-9.9 km, and 10 km or greater. However, erratic results were obtained because samples were too small and the parameter variability too great to establish any worthwhile relationships.

5.1 Frequency Distribution of Echo Cell Parameters

The frequency distribution of selected echo cell (intensity center) parameters in the 3-storm sample of 118 echoes was determined. Figure 2 shows the frequency distribution of HMAX, the independent variable in the Gagin equations. This indicates that the distribution is closely approximated by the log normal distribution. If representative of the HMAX population (questionable), Fig. 2 indicates that radar echo cell tops in northern and central Illinois will exceed 15 km about 1% of the time, 10 km about 15% of the time, and 7.5 km about 50% of the time. This curve provides some initial guidance for PACE planning purposes.

Table 10 shows the frequency distribution ratios for total rainfall volume and maximum cell height derived from the CHAP data sample. Ratios to the median are shown for selected values along the two frequency curves derived from the sample of 118 cells. Thus, the ratio at the 5% level is 30.57 for RVOL compared with only 1.65 for HMAX. The great variability among echo cell volumes in the 118-echo sample results in much uncertainty about the representativeness of regression curves derived from the data. The need for a much larger sample is obvious, if the cell evaluation technique is to be employed in future weather modification experiments under PACE.

5.2 Comparison of Echo Pairs

Following the same procedures used in our study of echo entity equivalent pairs, the sample of 118 echo cells was grouped into pairs. In selecting the pairs, the cells had to be separated by a minimum of 10 km, and to have developed within less than one hour of each other. With these basic requirements, cells closest to each other in time of occurrence were paired. A total of 56 pairs met the requirements.

Frequency distributions were then determined for each echo parameter. Results are summarized in Table 11 which was abstracted from the frequency curves and illustrates the wide range of values making up the frequency distribution in each case. The greatest range in pair differences (natural variability) is with total rain volume and the least with maximum echo height. The purpose of Tables 11 and other cell analyses was to obtain a quantitative measure (first approximation) of natural differences that may exist between individual echo cells which could conceivably be selected as target and control entities in cloud seeding experiments.

The natural variability illustrated in this limited study of echo cells is indicative of what must be accounted for in planning and evaluating seeding effects when radar is a primary selection and/or evaluation tool. Although large variability among the echo cells was indicated for the several echo parameters, the degree of variability was somewhat less than found in our more complex echo entity pairs.

6. GENERAL SUMMARY

Several studies of the climatic properties of radar echoes in Illinois were made during 1982-1986 in conjunction with the pre-experimental phase of an extensive weather modification research program in Illinois. Radar is a primary tool in the operation and evaluation of weather modification research project; hence, knowledge of the natural echo climatology of the target region is important in the planning, operation, and eventual evaluation of cloud seeding projects, particularly when convective precipitation augmentation is the major objective.

Initial studies of the natural distribution of Illinois radar echoes during convective precipitation were largely concerned with the dimensions, movement, evolution, and dissipation of squall lines and squall areas, which produce most of the warm season rainfall in the state, and the Midwest, in general. Results indicated that a typical echo line in July-August, when the need for rainfall augmentation most often occurs, extends about 65 nm, is 5-10 nm wide, oriented NE-SW, travels approximately 20 nm from the NW before decay, lasts about 1 hour, travels at an average speed of 20 knots, and has individual cells

moving from SW. Squall areas tend to last longer than lines, having an average duration of 129 minutes compared to 62 minutes for lines. Also, area cells tend to be larger than line cells. Squall areas develop most frequently from isolated echoes, and secondly from existing echo lines.

The next echo study was oriented toward the characteristics of individual echoes (single echoes as opposed to lines and areas). Analyses were limited to echoes having mean rain rates of 4 mm/hr or more and durations of 8 minutes or more. These were considered to have dimensions making them potentially suitable for successful treatment. Averages and maxima were determined for various echo characteristics, frequency distributions were determined for each selected parameter, and the "best-fit" statistical distributions identified. This study helped to establish the distribution characteristics of pertinent precipitation factors such as echo area, rain intensity, echo duration, total rain flux, and other properties useful in evaluation of seeding experiments. Quantitative information relating to the natural distribution of important radar echo parameters is essential to evaluation, and this study provided useful knowledge on the subject. Most of the echo distribution parameters were fit satisfactorily by the log normal distribution. Among the echo parameters investigated, natural variability was found to be greatest with total rain flux and least with mean rainfall rate.

The third echo study was concerned with characteristics of initially equivalent echo pairs, in which equivalence was based on the operational point of view; that is, pairs likely to be selected as "target" and "control" convective entities in cloud seeding experiments, because of similar structural properties and acceptable spatial separation. All selected pairs were independent, had mean rain rates of 4 mm/hr or more, durations of 8 minutes or more, and had to be detected within one hour of each other within a 60-nautical mile radius of the radar. Pair differences were computed for 6 important verification parameters that included mean and maximum rain rate, mean area, total area encompassed during echo lifetime, total rain flux, and duration.

Frequency distributions were derived for each parameter after grouping according to synoptic storm type to obtain quantitative information on their distribution characteristics. The greatest variability in pair differences occurred with rain flux and the least with mean rain rate. Greater variability was exhibited by squall line and squall area echoes than by air mass and frontal related echoes. Differences in total rain flux, a most important verification parameter because of its close relationship to total water output (rainfall) at the surface, was found to be most closely related to differences in total echo area (83% of variance explained), followed by mean echo areas and duration. Insignificant correlation was obtained between rainfall rate and total flux (4% of variance explained).

A limited study of echo cells within the normally multicellular echo entities was made to investigate the relationship between maximum cell height and other radar parameters, which has been recommended as a cloud seeding evaluation technique by Gagin and associates (1985). Although this study provided some useful information on the subject, the sample was too small to arrive at any reliable

conclusions in view of the great natural variability among the various radar parameters both within and between storms.

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Table 1. Coefficient of Variation of Selected Radar Echo Parameters from CHAP Operations.

<u>Variable</u>	<u>Coefficient</u>
Echo Duration	1.04
Total Rain Flux	13.06
Total Area Encompassed	4.37
Average Area	2.17
Maximum Area	2.58
Average Rain Rate	0.63
Maximum Rain Rate	1.28
First-Echo Average Area	2.66
First-Echo Mean Rain Rate	3.97
First-Echo Maximum Rain Rate	1.41

Table 2. Frequency Distribution of Echo Duration by Synoptic Storm Type (Durations \geq 8 Minutes, Mean Rain Rate $>$ 4 mm/hr.).

<u>Cumulative Percent of Observations</u>	<u>All Echoes</u>	<u>Air Mass</u>	<u>Cold Front</u>	<u>Static Front</u>	<u>Squall Line</u>	<u>Squall Areas</u>
5	77	51	44	76	110	82
20	34	31	27	38	42	34
50	18	19	16	18	18	17
80	11	11	11	11	11	11
95	8	9	8	8	8	8
N	554	26	67	111	86	264

Table 3. Frequency Distribution of Echo Properties. All Echoes Having Durations ≥ 8 Minutes and Mean Rain Rate > 4 mm/hr.

Cumulative Percent of Observations	Duration (minutes)	Mean Rain Rate (mm/hr)	Mean Max. Rain Rate (mm/hr)	Mean Area (n. mi ²)	Total Area (n. mi ²)	Total Flux (mm x n. mi ²)
1	128	40	185	772	10,960	4.3×10^5
5	77	21	72	167	2,070	4.0×10^4
20	34	13	30	53	465	4.5×10^3
50	18	8	15	27	158	1.1×10^3
80	11	6	9	18	70	4.1×10^2
95	8	5	6	12	42	2.3×10^2

Ratio to Median						
1	7.11	5.00	12.33	28.59	69.36	390.91
5	4.28	2.63	4.80	6.19	13.11	36.40
20	1.89	1.62	2.00	1.97	2.94	4.09
50	1.00	1.00	1.00	1.00	1.00	1.00
80	0.61	0.75	0.60	0.67	0.44	0.27
95	0.44	0.60	0.40	0.44	0.27	0.21

Table 4. Frequency Distribution of Echo Parameters.. All Echoes Having Durations ≥ 15 Minutes and Mean Rain Rate > 4 mm/hr.

Cumulative Percent of Observations	Duration (minutes)	Mean Rain Rate (mm/hr)	Mean Max. Rain Rate (mm/hr)	Mean Area (n. mi ²)	Total Area (n. mi ²)	Total Flux (mm x n. mi ²)
1	137	42	217	824	28,940	5.0×10^5
5	93	23	100	200	2,410	7.1×10^4
20	43	14	36	63	625	7.7×10^3
50	25	9	16	30	235	1.9×10^3
80	18	6+	9	18	108	7.8×10^2
95	15	5	7	13	62	4.6×10^2

Ratio to Median						
1	5.48	4.67	13.56	27.47	123.00	263.16
5	3.72	2.56	6.25	6.33	10.25	37.37
20	1.72	1.56	2.25	2.10	2.66	4.05
50	1.00	1.00	1.00	1.00	1.00	1.00
80	0.72	0.67	0.56	0.60	0.46	0.41
95	0.60	0.56	0.44	0.43	0.26	0.24

Table 5. Variability of Echo Pair Differences about the Median in Air Mass and Frontal Echoes Having Durations ≥ 8 Minutes.

Prob. (%)	D	R*	R _m	A	A _t	F
10	5.05	3.75	3.89	6.11	9.20	9.62
20	2.86	2.38	2.52	3.27	4.33	4.38
30	1.95	1.68	1.76	2.11	2.47	2.50
50	1.00	1.00	1.00	1.00	1.00	1.00
70	0.52	0.57	0.43	0.48	0.40	0.48
90	0.20	0.25	0.19	0.17	0.11	0.18

* R - Mean Rain Rate; R_m - Mean Max Rain Rate;
A - Mean Area; A_t - Total Area Encompassed;
D - Duration; F - Total Rain Flux

Table 6. Variability of Echo Pair Differences about the Median in Squall-Line and Squall-Area Echoes Having Durations \geq 8 Minutes.

Prob. (%)	D	R*	R _m	A	A _t	F
10	6.00	4.16	8.59	7.17	9.20	58.82
20	3.27	2.56	4.08	3.79	4.32	13.53
30	2.08	1.75	2.45	2.27	2.48	4.41
50	1.00	1.00	1.00	1.00	1.00	1.00
70	0.48	0.53	0.41	0.44	0.40	0.35
90	0.16	0.23	0.11	0.13	0.11	0.09

* R - Mean Rain Rate; R_m - Mean Max Rain Rate;
 A - Mean Area; A_t - Total Area Encompassed;
 D - Duration; F- Total Rain Flux

Table 7. Correlation Coefficients of Differences Between Independent Pairs of CHAP Radar Echoes Having Durations of 8 Minutes or More.

Echo Parameter	Echo Duration	Avg. Rain Rate	Mean Max. Rate	Avg. Area	Total Area	Total Flux
Total Flux	0.58	0.19	0.43	0.68	0.91	1.00
Total Area	0.63	0.13	0.37	0.80	1.00	0.91
Average Area	0.35	0.19	0.46	1.00	0.80	0.68
Avg. Rain Rate	0.15	1.00	0.77	0.19	0.13	0.19
Mean Max. Rain Rate	0.29	0.77	1.00	0.46	0.37	0.43
Duration	1.00	0.15	0.29	0.35	0.63	0.58

Table 8. Correlation Coefficients of Differences Between Independent Pairs of CHAP Radar Echoes Having Durations of 15 Minutes or More.

Echo Parameter	Echo Duration	Avg. Rain Rate	Mean Max. Rate	Avg. Area	Total Area	Total Flux
Total Flux	0.51	0.21	0.34	0.66	0.75	1.00
Total Area	0.43	0.11	0.28	0.89	1.00	0.75
Average Area	0.30	0.19	0.41	1.00	0.89	0.66
Avg. Rain Rate	0.22	1.00	0.88	0.19	0.11	0.21
Mean Max. Rain Rate	0.29	0.88	1.00	0.41	0.28	0.34
Duration	1.00	0.22	0.29	0.30	0.43	0.51

Table 9. Correlation Coefficients (r) and Variance Explained (r²) Between HMAX and Related Echo Parameters.

Parameter	r	r ²
RVOL	0.69	0.47
ZBMAX	0.53	0.28
ABMAX	0.74	0.54
DUR	0.40	0.16
RVRB	0.70	0.49

Table 10. Comparison of Frequency Distributions of Selected Echo Parameters in Gagin CHAP Sample.

Frequency (%)	Ratio to Median	
	Maximum Height	Total Rain Volume
5	1.65	30.57
10	1.49	14.33
20	1.28	5.85
30	1.18	3.02
50	1.00	1.00
70	0.86	0.40
90	0.69	0.14
95	0.61	0.07

Table 11. Variability of Echo Pair Differences About the Median for Selected Echo Parameters.

Prob. (%)	Max. Height	Max. Z	Max. Area	Duration	Total Rain Volume
					Ratio to Median Values
5	2.92	3.53	3.02	4.74	22.43
20	1.86	2.10	2.03	2.74	3.58
50	1.00	1.00	1.00	1.00	1.00
80	0.37	0.43	0.37	0.24	0.28
95	0.12	0.19	0.14	----	----

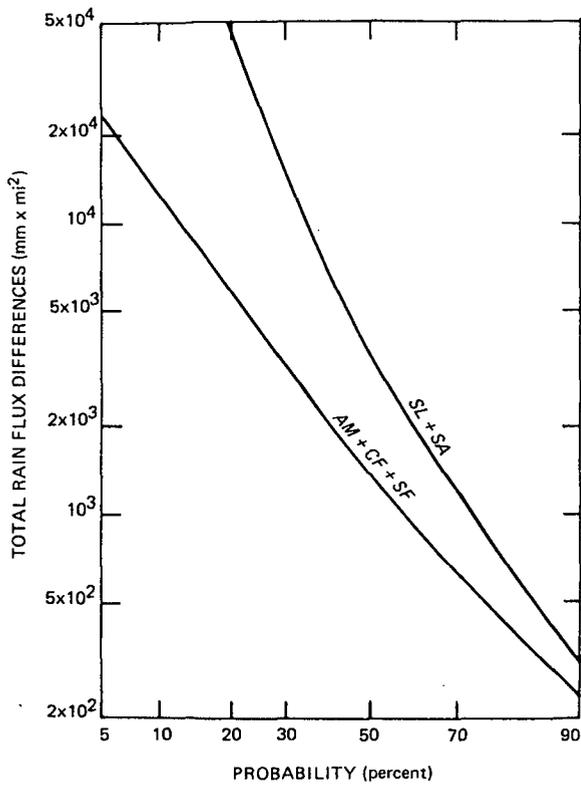


Fig. 1. Frequency distribution of total rain flux differences between echo pairs.

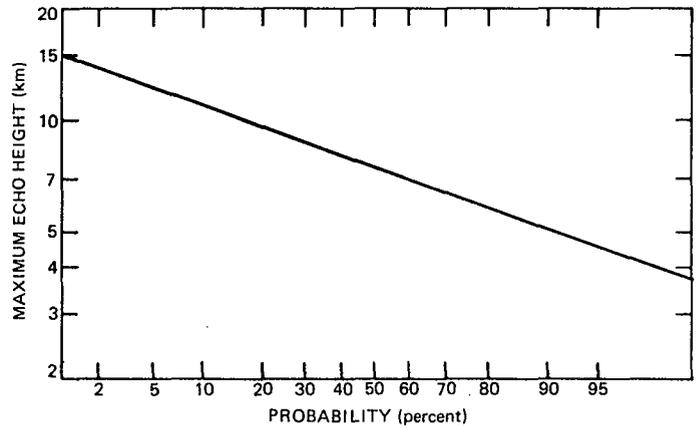


Fig. 2. Frequency distribution of maximum heights in radar echo cells from 3-storm CHAP sample.