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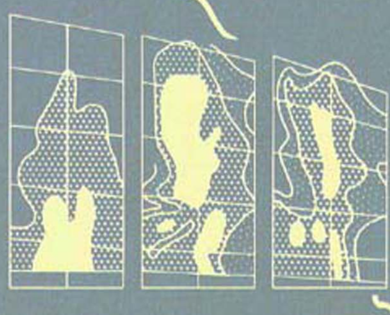
Design of an Experiment to Suppress Hail in Illinois

by STANLEY A. CHANGNON, Jr., and GRIFFITH M. MORGAN, Jr.



ILLINOIS STATE WATER SURVEY
URBANA
1976

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Design of an Experiment to Suppress Hail in Illinois

by STANLEY A. CHANGNON, Jr., and GRIFFITH M. MORGAN, Jr.

Title: Design of an Experiment to Suppress Hail in Illinois.

Abstract: This report presents an optimum design for a hail suppression experiment in Illinois. It is a final report for the 2½-year project DESH (*D*esign of an *E*xperiment to *S*uppress *H*ail) funded by NSF-RANN and the State of Illinois. The design is based on 9 years of hail research geared to hail modification planning. DESH studies of 3-cm and 10-cm radars, surface hail measurements, weather analysis and objective forecasting techniques, aircraft measurements of cloud properties, seeding technologies, and evaluation techniques are reviewed in detail. The hail suppression experiment design includes the modification hypothesis and related seeding technologies, the statistical-physical design and evaluation, operational requirements, and impact monitoring and public interaction efforts. The advisability of conducting such an experiment at this time is discussed.

Reference: Changnon, Stanley A., Jr., and Griffith M. Morgan, Jr. Design of an Experiment to Suppress Hail in Illinois. Illinois State Water Survey, Urbana, Bulletin 61, 1976.

Indexing Terms: agricultural meteorology, climatology, cloud physics, cloud seeding technology and evaluation, economic aspects (weather), forecasting techniques, hail, mesometeorology, meteorological networks, severe weather, social aspects (weather), weather modification, weather radar.

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CONTENTS

CONTENTS (Continued)

PAGE

CONTENTS (Concluded)

Design of an Experiment to Suppress Hail in Illinois

by Stanley A. Changnon, Jr., and Griffith M. Morgan, Jr.

INTRODUCTION

This report concludes a 2 1/2-year project dealing with the development of an optimum design of a hail suppression experiment in Illinois. The ultimate goal of the project was to advise the Illinois government and citizens as to the desirability of hail suppression in Illinois, and to provide the proper experimental design. Importantly, this project for the Design of an Experiment to Suppress Hail (DESH) was based on data and results from prior hail research that began in 1967, some of which was aimed at this goal. This report serves also as the final report of National Science Foundation (RANN) grants GI-37859 and ERT 73-07770. This effort was funded by the state of Illinois and the Weather Modification Program of the Foundation. The authors were the Co-Principal Investigators of the NSF grants.

After 10 years of various kinds of specialized hail research projects (1957-1966), the Illinois State Water Survey began in 1967 a research program aimed partially at developing a design for a hail suppression experiment in Illinois (figure 1). Such an experiment in Illinois was considered to have viable prospects within a national framework, since the Illinois hail climate is

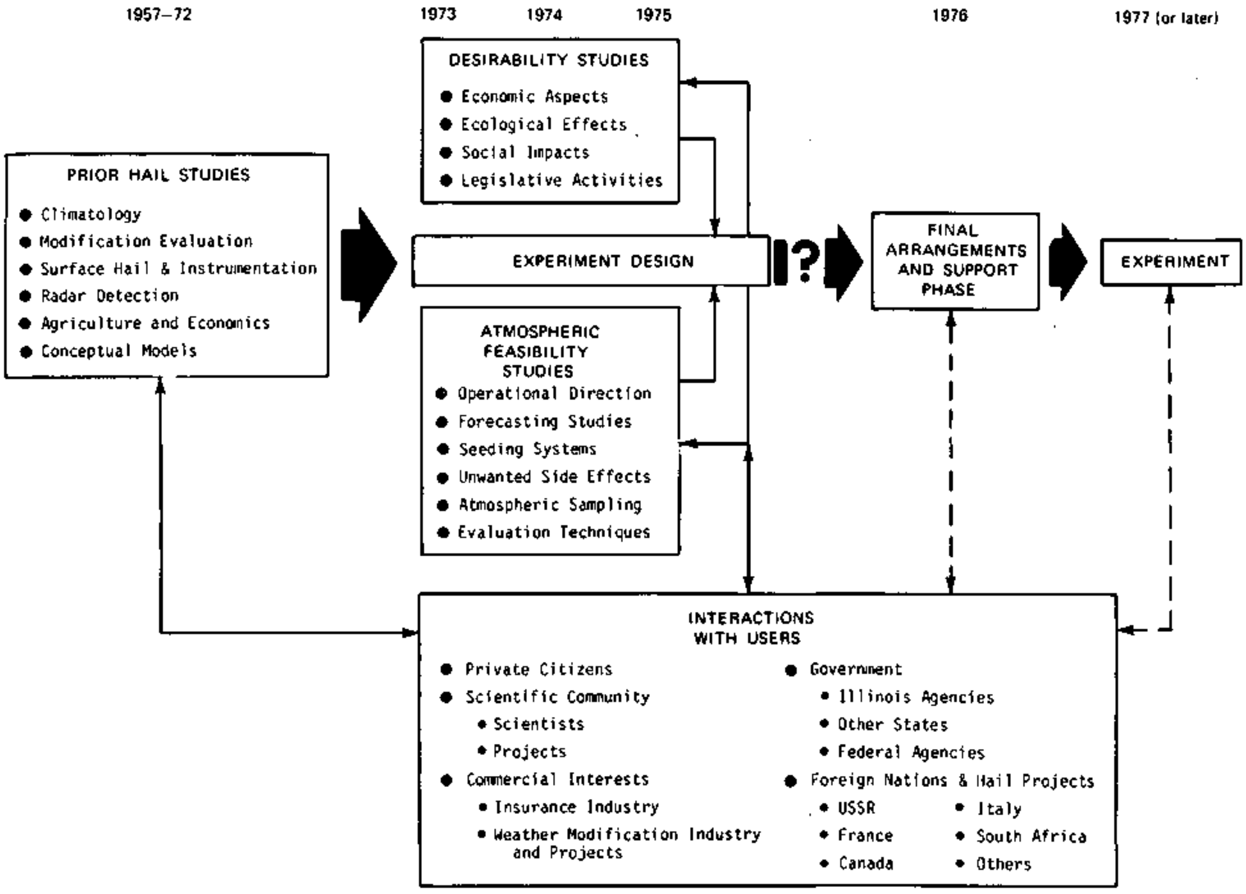


Figure 1. Flow diagram for Illinois hail suppression program

representative of that throughout the Midwest and the crop-hail losses in the Midwest rank second nationally only to those of the Great Plains (Changnon, 1972). More crop-hail insurance is sold in Illinois than in any other state, and Illinois ranks seventh nationally in total hail losses per year. In 1973 Illinois led the nation in crop-hail losses with a total of $40 million.

DESH comprised a series of interlocking studies that incorporated a 'building block' and 'stop-go' approach. In the logical sequence of such a program, as shown on figure 1, the initial studies were those critical to answering prime unknowns about midwestern hail, and thus essential to proper planning of the later studies of the current design program. The major initial studies and the years they were pursued were:

1) Ascertaining the potential economic benefits of hail suppression (1969-1972)
2) The gathering of basic surface hail data to understand its time-space variability, suitable size and shape of experimental area, and damage-producing characteristics (1967-1972)
3) Developing instruments to provide desired measures of surface hail (1967-1972)
4) Investigating the utility of 3-cm wavelength weather radars to detect hailstorms in field operations and for suppression evaluation (1967-1969)
5) Analyzing historical hail data to ascertain the optimum statistical design, best evaluation techniques, and the probable length of a well-designed program (1967-1970)
6) Conceptual modeling of hailstorms (1969-1972)

All of these initial studies were performed under a combination of state, private industry, and National Science Foundation sponsorship (NSF GA-482, GA-1520, GA-4618, GA-18909, GA-43005, and GA-16917). These studies provided *a)* the information desired, and *b)* importantly, the information that indicated that a suppression experiment in Illinois was possible within a scientific framework and desirable within an economic framework. Other important information areas essential to a properly designed experiment were not then available, but became the subjects studied in the 30-month DESH project. These included:

1) Investigation of seeding systems and determination of the technology needed for Illinois types of hailstorms
2) Evaluation of potential adverse side-effects from hail modification (increased severe weather, decreased rainfall)
3) Study of hail forecasting techniques for operational utility
4) Evaluation of 10-cm radar for monitoring of hail production in storms for operational seeding decisions
5) The ascertainment of public attitudes toward weather modification so as to develop a proper social framework for the experiment
6) Chemical monitoring of background amounts of potential seeding materials in Illinois rainwater and hailstones so that measurements during an experiment can be used to evaluate possible effects on the ecosystem, to examine the efficacy of the seeding system, and to discern possible differences in the hailfall characteristics of seeded and nonseeded storms
7) Atmospheric sampling of Illinois hail-producing cloud conditions with respect to their moisture and nuclei flux, updraft characteristics, and relevant cloud nuclei to guide decisions on seeding agents and techniques
8) Numerical modeling of single and multiple convective clouds for prognostic and diagnostic (evaluation) utility

Fortunately, two other major atmospheric research programs developed in Illinois in the 1971-1972 period: one was the study of inadvertent modification of rain and hail at St. Louis, and the other concerned the development of a rain enhancement experiment in Illinois. The St. Louis METROMEX program with NSF, ERDA, AEC, EPA, and state support provided much of the information needed under study areas 7) and 8) above. The rain enhancement program (Changnon, 1973) with the Bureau of Reclamation support provided some of the information needed in studies 6), 7), and 8). The drastic decrease of support for this project in 1974 restricted the large cloud and updraft data sample and more work is needed.

The Survey also developed, over a 2-year period, a model state law (Ackermann et al., 1974) concerning the permissive control of weather modification activities in Illinois. This law was enacted in September 1973. These efforts and other research programs have provided information needed for DESH in Illinois.

Therefore, DESH concerned study areas 1), 2), 3), 4), 5), and 6). Items 1-4 were largely handled through a simulation approach since they direct themselves to the final and largely operational aspects of the envisioned experiment. Item 5 included a 1974 survey and study of public attitudes on potential hail suppression in Illinois plus a variety of communications of results and recommendations to the public and the government. Item 6 involved a rainwater and hailstone sampling effort during 1974 to measure silver content.

This report contains three principal sections. The first is a comprehensive review of the research results for DESH. This includes the results of the radar effort, the surface hail studies, weather analysis and forecasting study, aircraft measurements of cloud properties, etc. [It will be noted that a mixture of U.S. and metric units of measure appears in this report because of differences in the way the data were collected for the various studies.] Part 1 also includes a description of the public attitude research. The user relationships, project publications, project personnel, and a summary of achievements and recommendations for future research are presented in Appendix F. The activities in DESH were focused in a project work plan (Changnon et al., 1974) presented in figure 2.

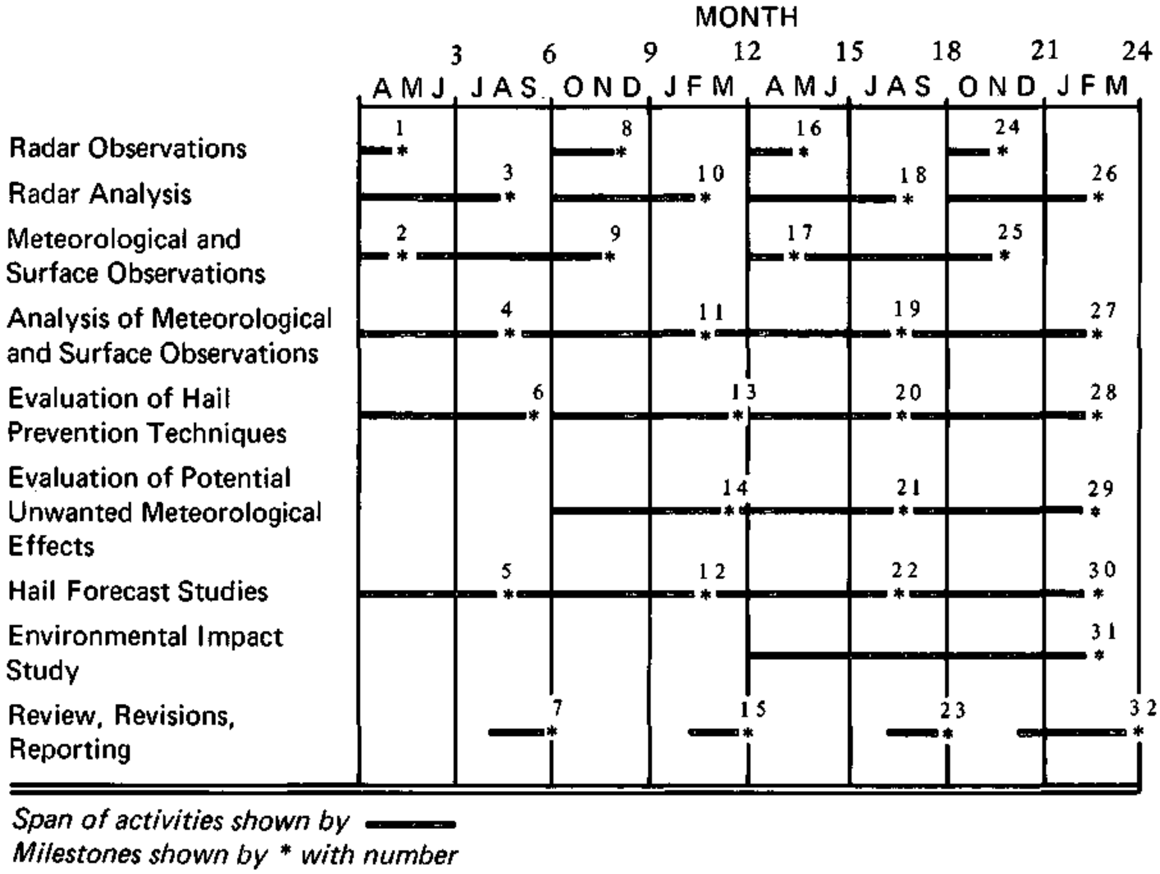
The second major section of this report concerns the recommended design of an experiment to suppress hail in Illinois. The approach to this 'proof of concept' type of experiment includes discussion of the modification hypothesis and seeding technologies, the statistical-physical design, the operations, and the impact efforts.

The third major section is an analysis of the advisability of an experiment at this time in Illinois. This is followed by Appendices that list all the hail-related publications of the Water Survey and a variety of other relevant material.

Acknowledgments. This research has been performed under the general direction of Dr. William C. Ackermann, Chief of the Illinois State Water Survey. Several senior project staff made signal contributions to this report including the preparation of portions of certain sections. Gary L. Achtemeier contributed significantly to the Weather Analysis and Forecasting Studies section. Herbert Appleman made major contributions to the section on Suppression Hypothesis and Seeding Technologies, and Ronald C. Grosh contributed to the sections on radar. Paul T. Schickedanz was heavily involved in the section on Evaluation of Hail Suppression, and Neil G. Towery made major contributions to the sections on field activities and cloud properties. Floyd A. Huff prepared a section on the frontal climatology of central Illinois. The involvement of Sigmund Krane and Eugene Haas of the Human Ecology Research Services, Inc., in the public attitude surveys and their interpretation is deeply appreciated.

The assistance of Eugene A. Mueller, Edward Silha, and Roy Reitz in carrying out radar operations is also noted.

Field operations, analyses, and data processing were carried out by Ronald Alsup, Oscar Anderson, Jennie Coppenbarger, Edna Anderson, and Catherine Jackson, along with numerous student analytical assistants (see staff list in Appendix F). Artwork was prepared by the Water Survey Graphic Arts staff under the direction of John Brother. The final manuscript was edited by J. Loreena Ivens, Survey Technical Editor, and the camera-ready copy was prepared by Suzi L. O'Connor, Editorial Assistant.



Changes:

1) Fall 1974 radar operations (Milestone 24) were eliminated as unnecessary.

2) Fall 1974 field operations (Milestone 25) were deemed unnecessary and networks were shut down.

Figure 2. DESH work plan diagram

The advice and assistance of Thomas J. Henderson of Atmospherics Incorporated and of Larry G. Davis of Colorado International Corporation are deeply appreciated. G. K. Mather and his staff in South Africa were extremely helpful in supplying useful data and information.

The assistance of the Crop-Hail Insurance Actuarial Association and the Country Company in supplying data and advice is gratefully acknowledged. The untiring efforts of our 300+ volunteer hail observers also contributed to the project.

Part 1. Results of DESH

A. RADAR-HAIL DETECTION AND FORECASTING

INTRODUCTION

There are many ways that radar must be employed in hail suppression experiments and operations, and these are basically related to operational activities and evaluation activities. The major uses of the radar data, either in real time or in subsequent analyses, include-.

1) Delineating developing hailstorms for directing seeding activities
2) Counting hailstorms in seeded and nonseeded areas as part of an evaluation
3) Measuring hailstone sizes to decide on and evaluate seeding
4) Monitoring various physical changes in storms before and after seeding for evaluation
5) Determining the surface area covered by hail for evaluation and directing post-storm surveys
6) Ascertaining the in-echo volumes containing hail for direction of seeding activities

The radar analysis directed toward answering these potential goals for radar utilization included: *a)* a study of operational data from the use of two 3-cm radars operated in hail research projects in 1967-1969, *b)* analysis of the historical 3-cm data from the 1954-1965 period, *c)* study of data from a dual wavelength (3-cm and 10-cm) radar operated in 1973-1974, and *d)* analyses of radar data from National Weather Service equipment and associated atmospheric conditions.

3-cm RADAR STUDIES

Two forms of 3-cm radars, a CPS-9 (PPI) and a TPS-10 (RHI), were employed along with dense surface hail networks, to make detailed radar-hail studies in 1967-1969 (Changnon, 1972a). The studies performed could be grouped into four classes including: *a)* relationship between near surface reflectivities and hail, *b)* relationship of hail to reflectivities aloft, *c)* characteristics of hail-producing echoes, and *d)* detection of hail volume within echoes.

The radar-hail research of 1967-1969 had two goals. The primary goal was to study the potential detection of the in-storm hail volume. This was a very ambitious effort frought with difficulties and limitations inherent in 3-cm wavelength radar, but every effort was made to optimize the research through detailed echo analyses and elimination of intervening echoes. The other goal, the identification of hail echoes, was aimed at defining the common denominators in echo characteristics that are useful on a given storm day for indicating hailstorms.

Surface Reflectivities-Hail Relations

One major study concerned the relationship between surface echo reflectivity parameters and the areal extent of hail, as measured in the dense networks. The results from 15 storm periods revealed the correlation coefficient for the reflectivity areas and the hail areas to be +0.81. The maximum reflectivity values sampled on the different days gave the best correlations, and indicated a need to study the relationship for reflectivity areas and surface hail extent on a given day or storm basis. A poorer reflectivity-hail area relationship was derived from storm periods with very small hail, indicating promise for hail area detection when the hail is of 'significant' size, greater than 1/4 inch diameter. The results also indicated that storm gradients of reflectivity along the echo tracks were locales with the large areas of hail (hailstreaks).

Relationship of Hail and Reflectivities Aloft

The study of reflectivities aloft indicated that higher reflectivities did not conclusively imply hail at the surface. In most cases of hail it was possible to find a strong echo near or above the report of hail. However, there were 4 to 5 times as many cases of strong echoes (reflectivities greater than 10^5) not associated with any hail at the surface.

The primary maximum of high reflectivities ($\geqslant 10^5$) associated with hail was found to occur between 5000 and 20,000 feet above the freezing level. However, the high reflectivities in that zone and with hail accounted for only 5% of the total number of such high reflectivities. Most hail occurrences also had reflectivity cores somewhere below the freezing level, but only 5% were within 2 miles and 10% were more than 10 miles away from the surface hail. Seasonal studies showed that all spring (March-May) hail occurred with storms in which the reflectivity exceeded 35 dbz at 7000 feet or more above the freezing level. Summer and fall (June-October) storms that produced hail all had > 40 dbz at or above a level 10,000 feet above the freezing level. The results for comparing hail positions with reflectivity cores suggested that the hail was frequently occurring either in the front or the rear edge of the core in high reflectivity gradients.

Studies of thunderstorms that produced no surface hail established that *a)* there was not a typical profile of reflectivity for no-hail thunderstorms, and *b)* their reflectivity profiles were identical to many hail-producing thunderstorms. Data from the 5 days of the most damaging hail in the 3-year study period were employed to develop reflectivity maps for four different levels. The best results for the reflectivity data came from the level at 5000 feet above freezing level. However, even at this level only 40% of the hail with a reflectivity $\geqslant 10^{6.5}$ had hail, and for lower reflectivities, such as 10^5 and 10^6, only 10 to 15% of the reflectivities were related to hail.

The high reflectivities aloft also showed considerable variability in height and spatial location during short periods of time, *frequently less than 5 minutes.* High reflectivity zones or cores aloft often appeared to be present from 5 to 10 minutes and then not present or not readily identifiable 5 minutes later. These results indicated that operational radar sampling of storm volumes aloft should have a frequency of 10 minutes or less.

Hail-Volume Detection

The 1968-1969 research focused on detecting the hail volume. This was based on the fact that the 1967 results indicated that

1) There was a good relationship between the areal extent of relatively high reflectivity on a given day with areal extent of surface hail
2) There was a good relationship between hail areas and steep reflectivity gradients
3) There were frequent changes in echo volume just before hail time

The hail-echo volume analysis was based on a comparison of volume characteristics of hail and no-hail echoes taken on the same days. Although the sample size was limited by research support, useful results were obtained. The most promising results concerned the behavior of hail-echo volumes above -5° C and the occurrence of hail in gradients of higher reflectivity, whereas the least promising results came from comparison of hail with the magnitude of the reflectivities. Echoes that produced hail were relatively large above the -5° C level (more than two-thirds of the total reflectivity of $10^{4.5}$ volume was found at that zone). Hail-producing echoes also exhibited sizeable volumetric increases about the -5° C level, commonly during the 5 to 10 minutes before hail reached the ground. Conversely, no-hail echoes had low volumes above the -5° C level and never exhibited large increases in the low volume. Typically, the hail echo volume increases prior to hail were greater than 15 mi^3 for reflectivities of greater than 10^4 (a 50% increase), and greater than 5 mi^3 for reflectivities greater than 10^5 (a 60% increase). This study also indicated that 70% of all the hailfalls occurred in the forward edge of the storms and in high reflectivity gradients at or near the surface.

Characteristics of Hail-Producing Echoes

A fourth major effort was a study of the echo behavior, beginning at 'first echo time' through echo lifetime, to ascertain differences between hail echoes and no-hail echoes. This study showed that all of the tallest half of the first echoes became hailstorms on 50% of all hail days. The results clearly established that the top height of echoes at formation was an important parameter in ascertaining whether a storm will produce hail, suggesting that the roots of a hailstorm are tied to the initial strength of convection in developing clouds. In addition, the vertical extent (top to bottom) and reflectivities of first echoes that became hailstorms were much greater than those of no-hail echoes on a given day.

Development of echo models based on synoptic weather conditions also provided useful information. Comparison of hail-producing echoes with no-hail echoes provided forecasting guides relevant to a particular day. The average hail-echo tops ranged from 2000 to 5000 feet higher than the average of the no-hail echoes on any given day.

Comparison of echo characteristics on a seasonal basis also showed distinct differences. The echo characteristics of spring hailstorms differed considerably from those of the summer and fall. As might be expected, the spring hail echoes were smaller and more simple (single core) than the summer storms. Very few of the echoes in either season were sloping and were generally in the 'upright' configuration.

Summary

The 3-cm wavelength studies of 1967-1969 revealed useful information for both the operational needs and evaluation uses of weather radars in hail suppression projects.

A primary finding, largely for operational purposes, is that on a given day the relatively larger (higher) first echoes, including those with a greater depth from top to base and higher reflectivities, have a much greater likelihood of becoming hail-producing storms and should be monitored. On all hail days of a given period (season or years), at least 20% of the taller half of the first echoes will become hailstorms; and on 60% of all hail days, 60% of the taller echoes will become hailstorms. This is a powerful predictive tool Second, all hail-producing storms grew more than 5000 feet in height within 10 minutes above their first echo and had rates always 1000 feet per minute for 5 minutes, both useful predictors of hail-producing storms.

The 3-cm results showed that the magnitude of reflectivity aloft alone is not a good indicator of the occurrence of surface hail or of hail size. High reflectivities were generally associated with hail. All spring hail fell when reflectivities exceeded 35 dbz at 7000 feet above the freezing level, and all summer hail fell from storms when the reflectivities exceeded 40 dbz at 10,000 feet above the freezing level. However, many similar high reflectivities occurred at these heights without hail reaching the ground.

The third finding of utility is that the storms with more than two-thirds of their volume above -5° C are typically related to hail, and that hail typically occurs in 10 minutes after a sizeable (50%) increase in the volume above the -5° C level. This type of result might be useful in operations and evaluation, particularly if a paired storm design were used. The research on high reflectivity values well above the freezing level and on storm volumes pointed to a need to totally (3-D) scan each storm in less than 10 minutes for proper monitoring.

A fourth useful finding was that the hail shafts near the ground generally existed in steep reflectivity gradients. Coupled with this fact is that the hail is generally found to occur on the front or rear of the core in these gradients, with 70% of the hail falling in the front edge of the core.

Finally, there was a good association between high surface reflectivity area on a given day and the areal extent of hail at the surface. This should be useful in evaluation, particularly in areas of poor surface measurements.

10-cm RADAR STUDIES

Chill Dual Wavelength Radar and Related Studies

Atlas and Ludlam (1961) attempted to use multi-wavelength radars in the late fifties and early sixties to detect hail in thunderstorms. Unfortunately, the problem of radar hail detection proved to be theoretically complicated. Hailstones may be wet and spongy and have a variety of shapes, orientations, and roughnesses, all of which make generalizations difficult. Interest in multi-wavelength radar hail detection was regenerated in the late sixties when reports came from the Soviet Union indicating that reliable hail detection was being achieved with 3.2- and 11-cm wavelengths (Sulakvelidze, 1965, 1968).

Eccles and Atlas (1973) described a method for detecting spherical hail greater than 1 cm in diameter by taking the range (r) derivative of the ratio (y) of the powers returned at 10- and 3-cm wavelengths (dy/dr). They stated that 10-cm hail reflectivities will be greater than 3-cm hail reflectivities "for spherical hail of virtually any diameter greater than 1 cm and for any condition of wetness (with the exception of dry stones D ~ 4.7 to 5.2 cm) and for any size distribution . . . with few exceptions the same is true for any shape and orientation . . . and any degree of sponginess." The detection criterion is that $dy/dr < 0$. Normally, this condition is expected to exist on the far side of a hailshaft, while large positive values will occur on the near side. However, dy/dr is directly proportional to the one-way attenuation (A) and is also therefore a measure of liquid water content (Eccles and Mueller, 1971). As a result, regions of high liquid water content (LWC) could obscure the hail signal under some conditions. In addition, the relative strength of the noise introduced by the movement of scattering hydrometeors, compared with the signal generated by the hail, depends upon particle size spectra and motion and cannot be predetermined. Therefore, the susceptibility of the technique to sensitivity problems and large false alarm rates requires experimental determination.

A dual wavelength radar developed by the University of *Chicago* and the *Illinois* State Water Survey (CHILL) was the main observational tool of the field phases of DESH. One of the purposes of DESH operations involving the CHILL radar was to empirically verify the Eccles-Atlas criterion ($dy/dr < 0$) with data obtained during actual hail events and to determine suitable signal processing procedures to optimize the technique. The major use of this technique, if sound, would be in evaluation since the radar could presumably measure hail with greater detail than any possible network.

A day with much hail was selected for extensive study (3 April 1974). It was a day of widespread and severe hail in central Illinois and widespread severe convective and tornadic activity throughout the central United States.

Signal Processing

The CHILL signal processor-recorder can provide five or more types of output including doppler information. This study utilized only the block-averaged powers returned at the two wavelengths. The basic data were averaged over 64 pulses in 1 μsec range gates (150-m gate length).

This averaging time represented about 5 independent samples of the power returned at 10-cm wavelength and 15 samples at 3-cm. The 10-cm reflectivity (Z_{10}), when plotted as a function of range, presents a very noisy appearance (figure 3a). We believe that this noisiness is more the result of particle shuffling than real variations in precipitation concentration. For a less noisy signal, the logarithms of the power in consecutive range bins were added together (Range Adding) and averaged. Figure 3a shows the results of range adding 1 (the basic data), 2, 3, and 4 consecutive data points of 10-cm reflectivity to obtain block averages. The number of data points that remain after adding 4 consecutive range bins in this fashion is one-fourth of the original number, but the resulting curve is agreeably smooth.

Figure 3b shows the dramatic effect of range adding on dy/dr. The dy/dr points were obtained by range adding the 10- and 3-cm power values first, and then taking the ratio and derivative of the smoothed data. Without range adding (RA = 1), dy/dr was very noisy. The curves for RA = 3, 4 were much smoother. We confined our attention to RA = 4 because we believed the smoother curve was more statistically reliable. We also referred to dy/dr in terms of attenuation (A) because $1/2\ dy/dr = A$, and one-way attenuation is the more generally used concept.

Comparison of Radar Data and Hail Observations

Figure 4 shows five views of the 42 and 54 dbz echo contours of a storm which spawned several hailstreaks while passing over the ISWS meso-network on 3 April 1974. This storm produced a small tornado near Farmer City, Illinois (see arrow in figure 4d). The hail areas (stippled) were determined from a hailstreak and isochrone analysis based on data from the hailpad network without reference to the radar data. The hail areas were closely associated with the high reflectivity and notched areas (as in the tornado) on this day of complex, interconnecting, and rapidly changing echoes.

A smoothed analysis of a B scan of the digital 10-cm reflectivities observed at 1453 CDT, at 0.5° elevation between azimuths 266° and 285°, is shown in figure 5. Contours are drawn for 18, 40, and 50 dbz. Areas of strong negative A are stippled. The values of A shown are believed to have a probability of 0.01 or less of occurring from noise. These values correspond to an attenuation rate of -4 db/km or less. The probability estimate was determined from the formula for the variance of the attenuation distribution given by Eccles and Mueller (1971). They described their treatment as being 'very approximate,' so the threshold used here must also be so regarded. However, the region labeled hailstreak 2, where hail actually was falling during the period 1450-1500 CDT, encloses the main area of strongly negative A.

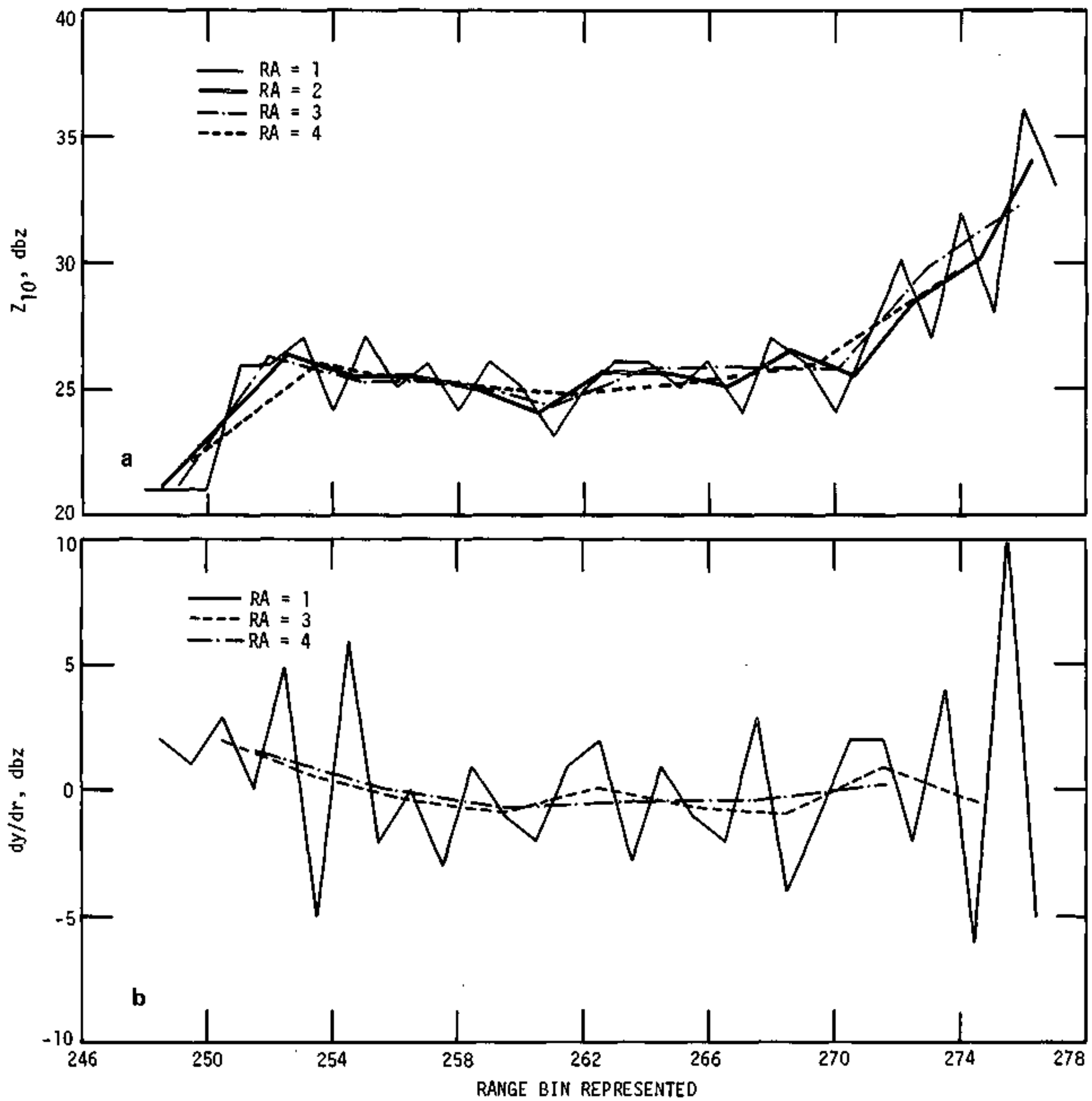


Figure 3. 10-cm reflectivity *(a)* and dy/dr *(b)* versus range for range adding of 1, 2, 3, or 4 consecutive bins

Not all of the significantly negative values are within the hailstreak isochrones shown, but most are close. Those that are not close are not of great areal extent and are not located over rain-gages (circles). We might well expect them to be real but simply not detected in the rain-hail network. Only the front one-third of hailstreak 2 is shown in figure 5. The front parts of both hail-streaks 1 and 2 consisted mainly of positive A values, as expected. We therefore find the agreement between the surface hail data and the A field to be encouraging.

Values of the 10-cm reflectivity, Z_{10}, the 3-cm power (P_3 db, arbitrary reference), y, and A for the 274° radial in figure 5 are plotted in figure 6 as functions of range. The region where the y curve (top) decreases most rapidly is marked by a steep negative gradient of Z_{10} . The mag-

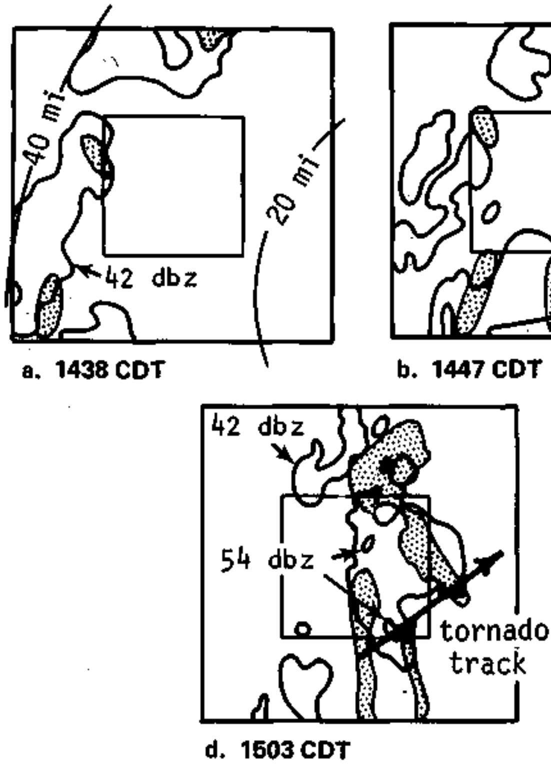


Figure 4. Contours of 42 and 54 dbz for storm over ISWS mesonetwork (large box), during 1438-1513 CDT (Smaller square depicts dense hailpad network within larger network; radar is about 20 n mi east of the networks)

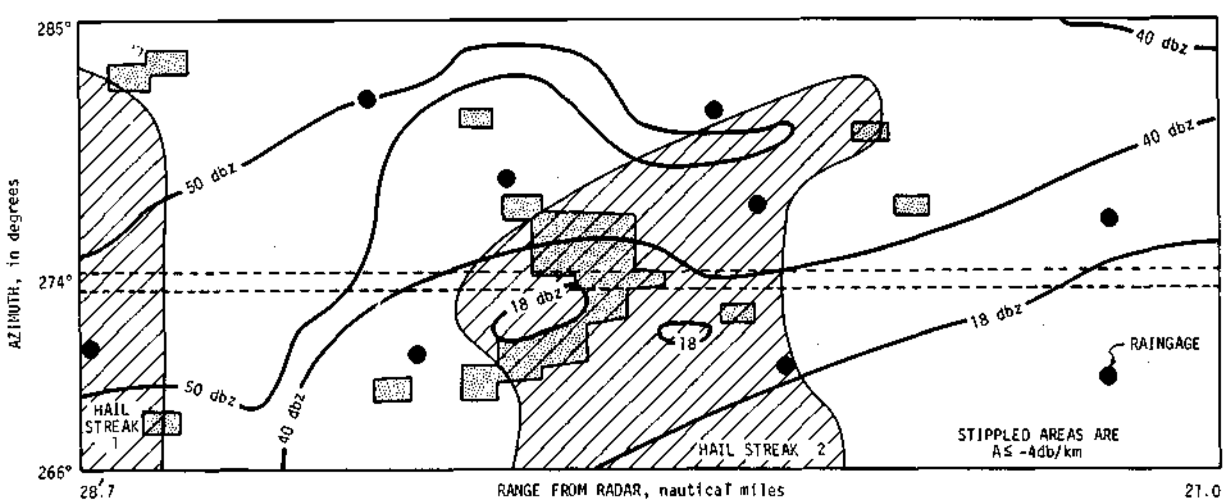


Figure 5. Analysis of B scan, showing 18, 40, and 50 dbz reflectivities (heavy line) with hailstreaks 1 and 2 cross-hatched (Azimuth 274° is shown in more detail in figure 6)

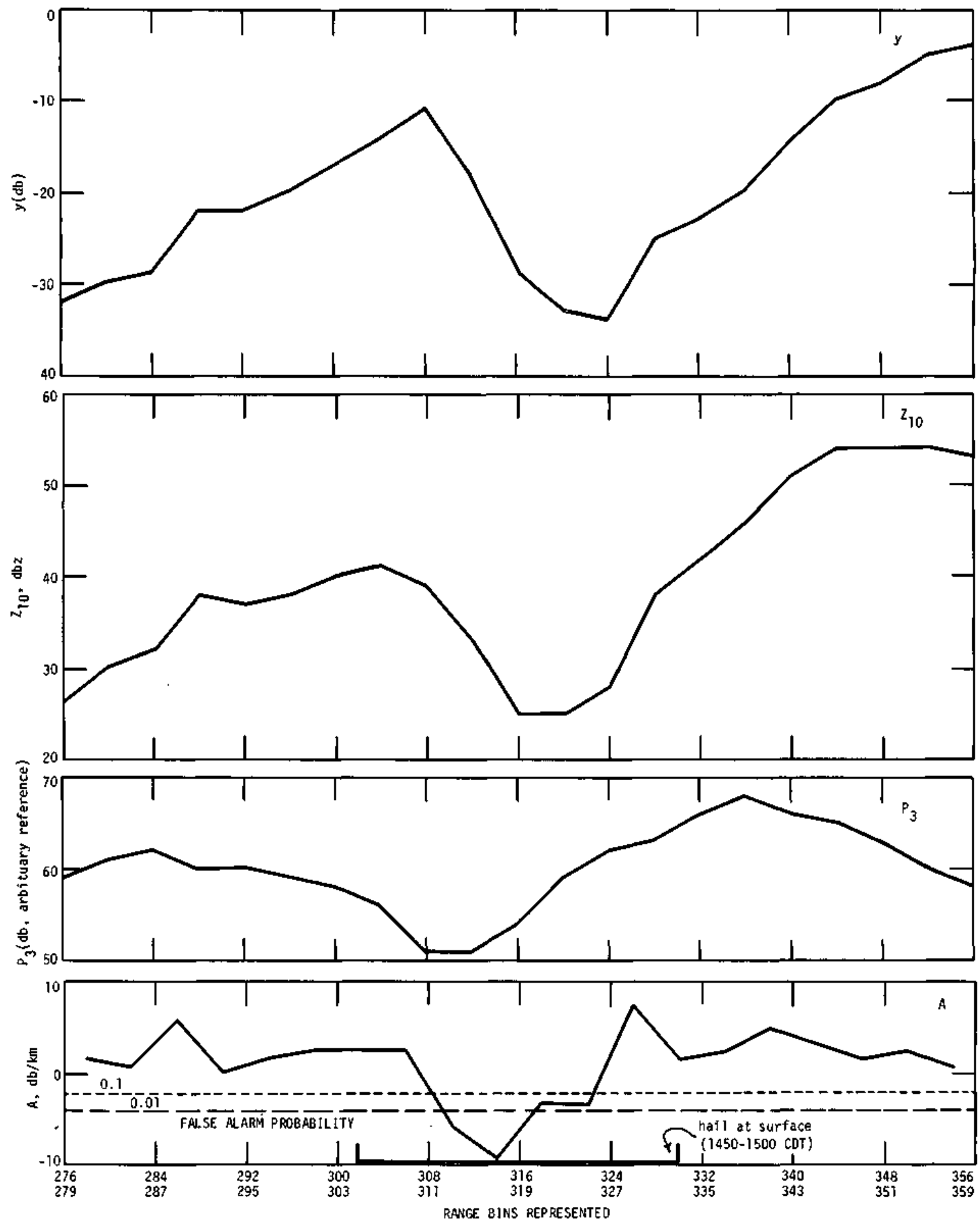


Figure 6. Y, Z_{10}, 3 cm power, and dy/dr plotted as functions of range for azimuth 274°

nitude of this gradient (14 dbz in 8 bins or approximately 12 db/km) is very similar to Z_3 gradients quoted by Changnon (1972) as having occurred near several hail events. This similarity lends credence to the possibility of single wavelength hail detection via large Z_{10} gradients. In the range interval where $A < 0$, the 3-cm power (the second curve from the bottom in figure 6) remained constant and then increased moderately. In conjunction with the sharp drop in Z_{10} and y, the A curve abruptly decreased to a minimum below -9 db/km. The A values corresponding to false alarm probabilities of 0.1 and 0.01 are shown as horizontal lines on figure 6.

Rainfall rates (30 minute average), at the time of figure 5, ranged between 18 and 44 mm/hr, and they correspond to a rain water content of roughly 1 to 2.5 g/m^3. Hailpads with hail had between 50 and 2200 $stones/m^2$, only a few of which exceeded 1.0 cm in diameter. Although hail was clearly widespread in the region examined, the large rainfall rates and predominately small size of the hail indicate that the Eccles-Atlas hail detection criterion performed in an acceptable manner.

A more thorough test of the techniques involving a larger number of observations including radar measurements from non-hailing storms is required.

Radar Estimates of Severe Storm Properties on 3 April 1974

On 3 April 1974 a record wave of severe weather swept 10 states of the eastern half of the United States (Fujita, 1974). The events of that day have been the subject of great interest as indicated by several special meetings.

The observations obtained by DESH operational personnel during and following the Illinois phases of the 3 April tornado outbreak were described in a special report (Changnon and Morgan, 1974). The major data set collected consisted of magnetic tape recordings of over 7 hours of storm observations by the CHILL dual wavelength radar. Some of the CHILL observations of this day were used in recently reported studies (Grosh et al., 1975; Jameson and Mueller, 1975; Jameson, 1975) relating mainly to evaluation of the CHILL hail detection and doppler capabilities.

Computer software for the utilization of the full dual wavelength information content of CHILL data to construct life histories of severe storms was not completed. A single wavelength (10 cm) approach was employed in order to arrive at descriptions of as many storms as possible.

Morgan and Mueller (1972) used digitized photographic recordings of radar data to generate maps of the vertically integrated liquid water (VIL or M*), and then to planimeter these to arrive at the total apparent storm liquid mass, M**. In the present study we chose to concentrate more on the distribution by height of the apparent liquid water and the total apparent liquid mass.

The integration procedure required defining restricted areas over which the recorded data would be manipulated. These 'boxes' were specified for each cell or storm, for each full volume scan of the radar. The specification of the boxes, which, because of the particular scheme used, must have sides oriented N-S and E-W, was not always easy and some allowance must be made for an edge of a storm being occasionally clipped by the box boundary or the boundary including a small piece of a neighboring storm.

All Z values were converted to liquid water content by the single relationship

$$M = 2.6 \times 10^{-3} Z^{0.6}$$

which is the same as was applied in Morgan and Mueller (1972).

The quantities derived for each full volume scan were:

1) The distribution with height of the apparent liquid water mass
2) The distribution with height of the volume occupied by echo
3) The total apparent mass, M**, within the volume above the box

4) The total volume of echo over the box
5) The profile of the highest value of Z as a function of height
6) The top (height) of the storm echo

The radar had a 1.0° beam width and was operated with the lowest elevation angle at 0.5° . It was apparent from the early attempts at determining 1) above that at this low, grazing angle there must have been considerable ground echo within the precipitation echo. All grazing angle data have been ignored in the analysis for this reason, and the base elevation angle is approximately 1.5° .

The derived quantities listed above were obtained for a giant hailstorm (which produced a large amount of hail over 3 inches in diameter), a tornado-bearing storm, and a second, lesser, tornado-bearing storm.

These results are still under review for possible errors due to processor noise, sidelobe effects on storm tops, or poor specification of the areas and volumes of interest.

The storm masses and volumes, shown in table 1, are much larger than those reported by Morgan and Mueller (1972) where the largest hailstorm mass was estimated at 1.5 megaton. The reasons for this must be: *a)* the wavelength used there was 3 cm with all the problems of attenuation, *b)* the probable presence in the 3 April storms of large masses of hail to which the 10-cm radar responds with very high returned power, and *c)* the sheer size of the 3 April storms. Very large apparent masses and volumes of these storms are characteristics which appear to be useful in identifying many very severe storms.

Table 1. Radar Estimates of Storm Parameters for 3 Storms on 3 April 1974

	*Peak mass, M** (megaton)*	*Max top (km)*	*Max volume (km^3)*
Farmer City tornado	7.96	15.6	3.02×10^4
Anchor tornado	19.3	17.0	3.03×10^4
Carlock giant hailstorm	13.3	14.43	1.44×10^4

Radar-Thermodynamic Hail Day Determination

The statistical evaluation of a hail prevention experiment can be performed in a blind 'black box' fashion by applying the chosen treatment to a randomly selected fraction of all thunderstorms affecting a fixed area. This is not economical since the fraction of all thunderstorms which produce hail is small and techniques are required for removing from consideration many of the storms which would not have hailed naturally. Predictors with which to improve this selection and identification process may include different types of data, but at the shortest time scales, which are the most crucial, the meteorological radar is the most efficient source of prediction information.

Attempts to define radar criteria for identifying hailstorms abound in the literature. Those criteria advanced are basically of two types, one concerned mainly with the height of the tops of radar echoes, and the other concerned with the maximum reflectivity values within echoes. The 3-cm radar investigations of 1967-1969 in Illinois found that growth of echo tops were as important as reflectivities aloft for hailstorm identification.

Hourly radar data from the NWS radar network coupled with surface temperature and humidity data from first order weather stations were studied in an effort to find criteria for separating hail days from non-hail days over a large area in central Illinois. This approach to the problem was dictated by the desire to have a large data sample involving 10-cm radar data coupled with atmospheric conditions.

Conceptual Framework

The approach taken was quite simple. The principal measurements involved were radar reports of storm top heights plus surface temperature and humidity measurements used to approximate the properties of clouds near their bases. During the warmest months of the year, radar echoes can on occasion reach surprisingly great heights without producing hail at the ground, whereas, during colder conditions during spring months echoes of rather modest dimensions are often associated with hail at the ground (Changnon, 1972). This suggests that the greater the amount of water vapor available at the base of the cloud, the stronger must be the updraft to produce hail of sufficient size to reach the ground without melting. An explanation for this was offered by Appleman (1960) who hypothesized that in clouds with warm bases, large drops (the presumed hail embryos) can form and fall out before freezing more readily than in clouds with cooler bases. For hail formation in warm-based clouds, a strong updraft (greater instability) is required in order to carry the large drops, which form in the deep warm part of the cloud, above the freezing level. An alternative explanation is that the deep, warm layer of the warm-based clouds causes the hailstones to melt as they fall through it.

Data

This study used radar and surface meteorological observations taken in an area of about 26,500 mi^2 in central Illinois during the warm seasons of 1971-1973. The study area is shown in figure 37 (page 61). Radar observations were obtained from microfilm records of the hourly radar facsimile charts (RADU). The radars closest to the study area were located at St. Louis, Evansville, and Chicago (or Marseilles in 1973). The RADU charts show outlines of the general echo areas and either the location and height of the tallest echoes or the average height of the cells within the general echo area. From these data, it was possible to estimate the height of the echoes in the study region on most occasions when echoes were present.

On the basis of the hail calendar (see figure 32) described in Section D, each day was declared a hail day, a non-hail day, or questionable. Questionable days were those on which only a few insurance claims indicated that there had been hail and were so classified because the date of hail damage is occasionally inaccurately reported to the insurance companies. Thirty-eight such questionable days were withheld from the analysis. Another day when hail was indicated by a NWS observer but no echoes were observed on the RADU charts was also deleted. The 430-day study period was reduced to 391 days and 78 were known hail days. The 1300 CDT surface temperature and dew point (T_d) data used were obtained from first order station data in the area.

The analysis centered on a combination of radar measurements of storm tops and estimates of the lower cloud thermodynamic properties derived from the surface measurements. It is instructive to look at the skill with which the single (radar or thermodynamic) variables predict hail or no-hail, and then that based on a combination of both variables.

Hail Probability as a Function of Surface Dew Point Temperature

Figure 7 shows the conditional probability of hail as a function of the 1300 CDT dew point temperature at a station (Springfield) near the center of the study area. The probabilities were determined by dividing the number of times hail occurred when the observed T_d was in a

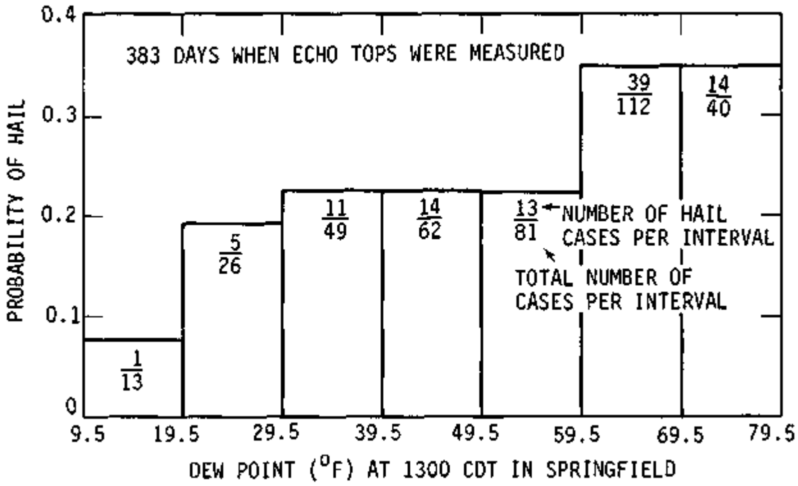


Figure 7. Probability of hail as a function of dew point temperature

particular 10-degree (F) interval by the total number of echo days with similar dew points. However, there is a marked increase in the probability of hail when $T_d > 60°$ F. The probability of hail is nearly twice as great when $T_d > 70°$ F as it is when $T_d < 60°$ F. It is clear, though, that T_d alone is not a strong hail predictor.

Hail Probability as a Function of Maximum Daily Echo Heights

Figure 8a shows the conditional probability for the occurrence of hail given the maximum daily echo top height (MxT). There is a rather strong trend and days with taller storms are much more likely to produce hail. The relatively large probabilities for taller storms suggest that MxT is a reasonably good predictor of hail.

Towery and Changnon (1970), Battan (1969), Dennis and Ziller (1967), Douglas (1963), Donaldson (1959), and Schleusener and Marwitz (1963) all showed that the probability of an individual convective cell being a hailstorm varies in some fashion with the height of the cell. Reinhart et al. (1968) and Donaldson (1961) showed that the probability of hail also depends partially on the reflectivity or intensity of the echo. The present study does not deal with reflectivity but this is not considered a serious omission since echo top height and maximum reflectivity are correlated (Altman, 1970; Donaldson, 1958). The dataon hail probability for radar cells presented by Battan (1969) for the mountainous Alazani Valley region of the USSR, by Dennis and Ziller (1967) for western Nebraska, by Douglas (1963) for Alberta and Texas, and by Donaldson (1959) for New England were compared with the hail day probabilities of the present study, as shown in figure 8b. The data of Douglas and Donaldson were read from graphs using 5000-foot intervals and the curves presented are somewhat smoother than the original data.

There were differences between the data collection procedures and definitions employed in arriving at these various radar hail prediction functions, but most of the differences are due to geographical and climatological factors. This can be seen from figure 8c where the echo height for which the hail probability is 0.5 has been plotted against the mean July dew point temperature for the five North American locations. This is a clear revelation of the importance of the sub-cloud moisture in understanding the dependence of hail probability on echo height. The general trend of the curve supports the assertion that warmer-based clouds must be taller to produce hail at the ground. The curve was drawn neglecting the Illinois value because the others were determined in a more directly comparable fashion, all being concerned with single cells. The Illinois value was based

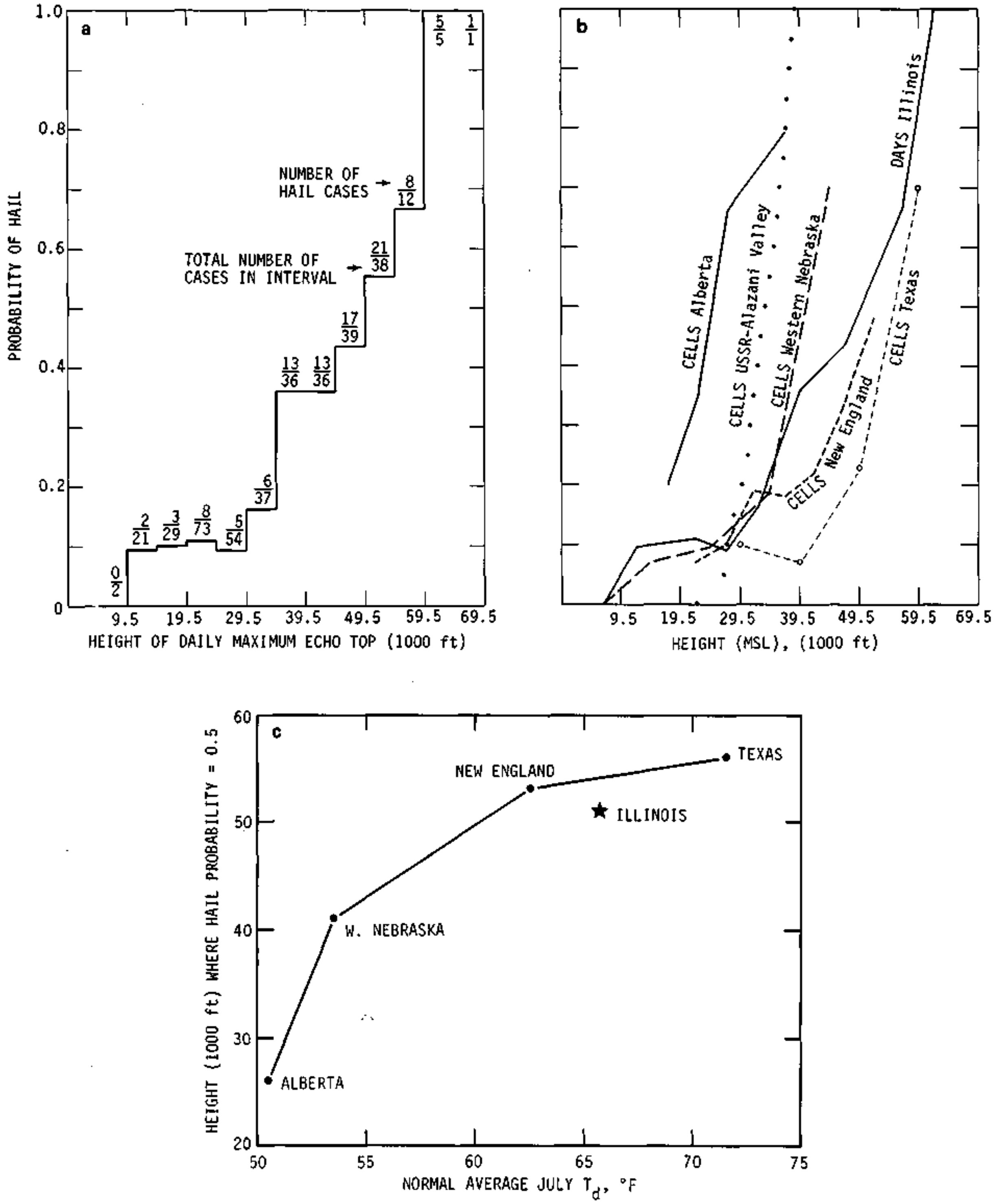


Figure 8. Probability of hail occurrence with given M×T *(a),* comparison of hail probabilities determined in various projects *lb),* and echo top height at which hail probability equals 0.5 versus average July T_d *(c)*

on the height of the tallest echo present in a large study area. Since more than one echo was usually present in the area of central Illinois on most of the days, the hail probability associated with a given height would be greater than that associated with a single Illinois cell of the same height. Conversely, the height at which the hail proabaility is 0.5 for all network storms would be lower than the corresponding individual cell height. Therefore, the Illinois data point in figure 8c should be expected to fall below the 'cell' curve as shown.

Hail Probability as a Function of the Maximum Daily Echo Height and the Warm Layer Thickness

The warm layer thickness (WLT), defined as the height interval between the cloud base and the in-cloud freezing level, was chosen as the parameter to represent the effect of the sub-cloud moisture on the cloud. The main justification for this choice is that it is a length, as is the radar echo top height. It is easy to show that under the assumption of unmixed pseudoadiabatic ascent the WLT is primarily a function of the cloud base temperature. Cloud base temperature also closely specifies the cloud base mixing ratio. These and other parameters such as surface dew point temperature, mean low level mixing ratio, wet bulb zero (the height or pressure level at which the environment of wet bulb temperature is 0° C) and the freezing level are strongly interlocked through functional dependence or empirical correlation and can be used somewhat interchangeably.

The WLT was calculated by graphically lifting a 1300 CDT surface air parcel (T, T_d) adiabatically to condensation (cloud base temperature and height) and pseudoadiabatically to a temperature of 0° C (in-cloud freezing level) and then determining the difference between the two heights. When the surface dew point temperature is near 0° C, the calculated WLT can be less than or equal to zero. Under these conditions the calculated WLT should not be thought of as a length, but as an index measuring the dry and cool surface conditions.

The conditional probability of hail for a given WLT was similar to that shown in figure 7 for a given dew point temperature. WLT and maximum daily echo top heights were combined in a manner parallel to the technique shown by Appleman (1960), where the positive area from parcel ascent, based on a proximity sounding (intended as an index of updraft development), was plotted against the cloud base temperature for hail and non-hail cases. In the present study the index of updraft development was the vertical echo development, a more direct and timely measure, and the cloud base temperature was supplanted by the closely equivalent WLT.

The relative frequency distributions of hail and non-hail days as a function of WLT indicated that on hail days the modal value of WLT was 11,500 feet, whereas that on non-hail days was 6500 feet.

Figure 9 is a plot of MxT versus the WLT for hail and non-hail days. For a given WLT, there is a tendency for hail to occur when MxT is large. For a given MxT, hail tends to occur with small WLT (cooler sub-cloud conditions). This supports the conceptual framework already described.

The stars on figure 9 represent hail days in northeast Colorado taken from the NHRE 1974 calendar of events. Only hail days were examined. MxT values were taken from RADU charts and WLTs were estimated from the daily weather maps. These stars are located in a rather well-defined region of small WLT ($\leqslant$ 8500 feet) with a few MxT above 50,000 feet. Colorado clouds are known for their high, cool cloud bases and appear in the diagram where expected.

Regressions of MxT on WLT were determined for the hail and non-hail data, and the curves are shown in figure 9. The subscripts H (hail) and NH (non-hail) have been used to identify the curves. The slopes of these regressions are significantly different (at the 0.1% level). This indicates that the relationship between MxT and WLT on hail days is different from that on non-hail days.

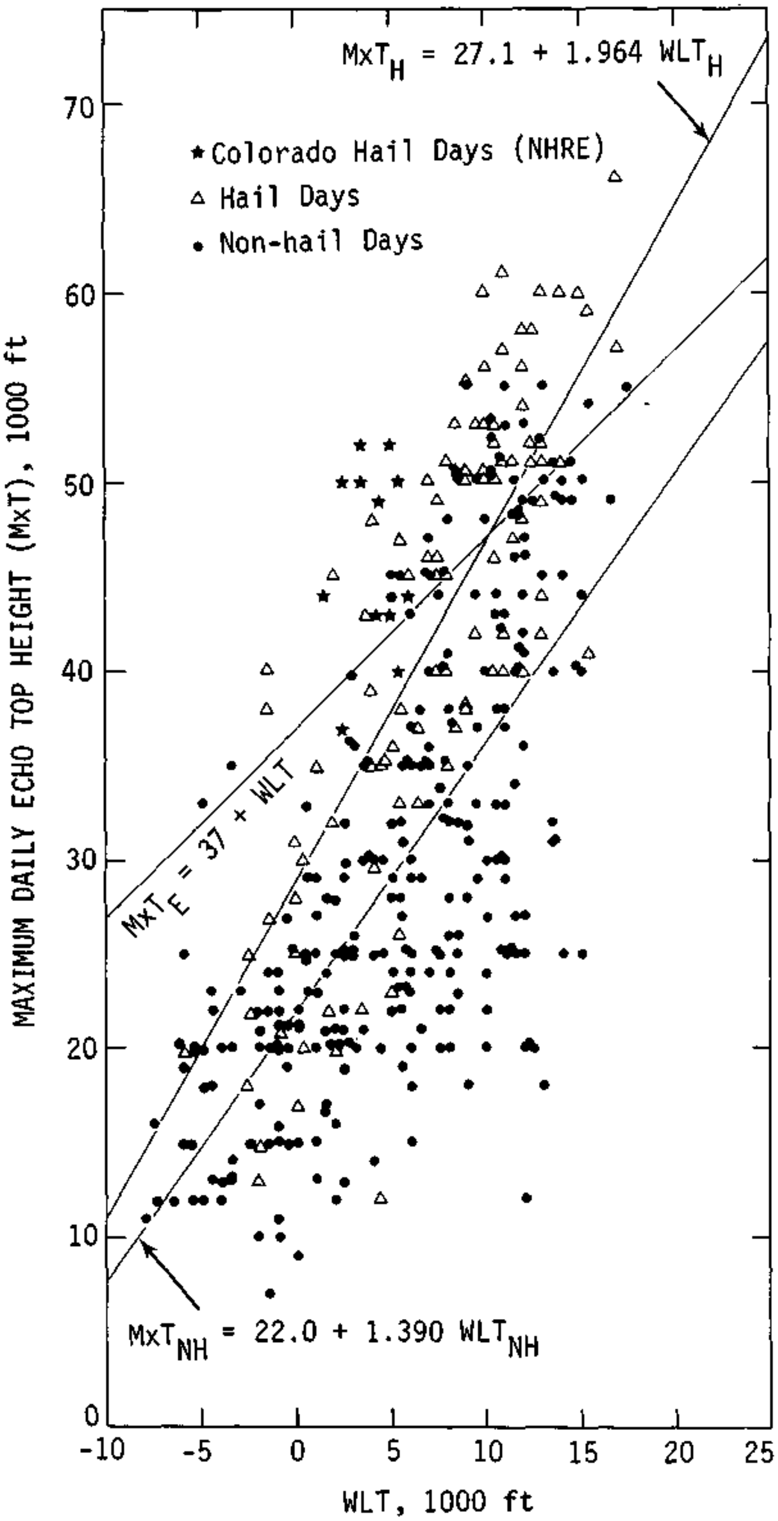


Figure 9. Maximum daily echo top height versus warm layer thickness for hail and non-hail days

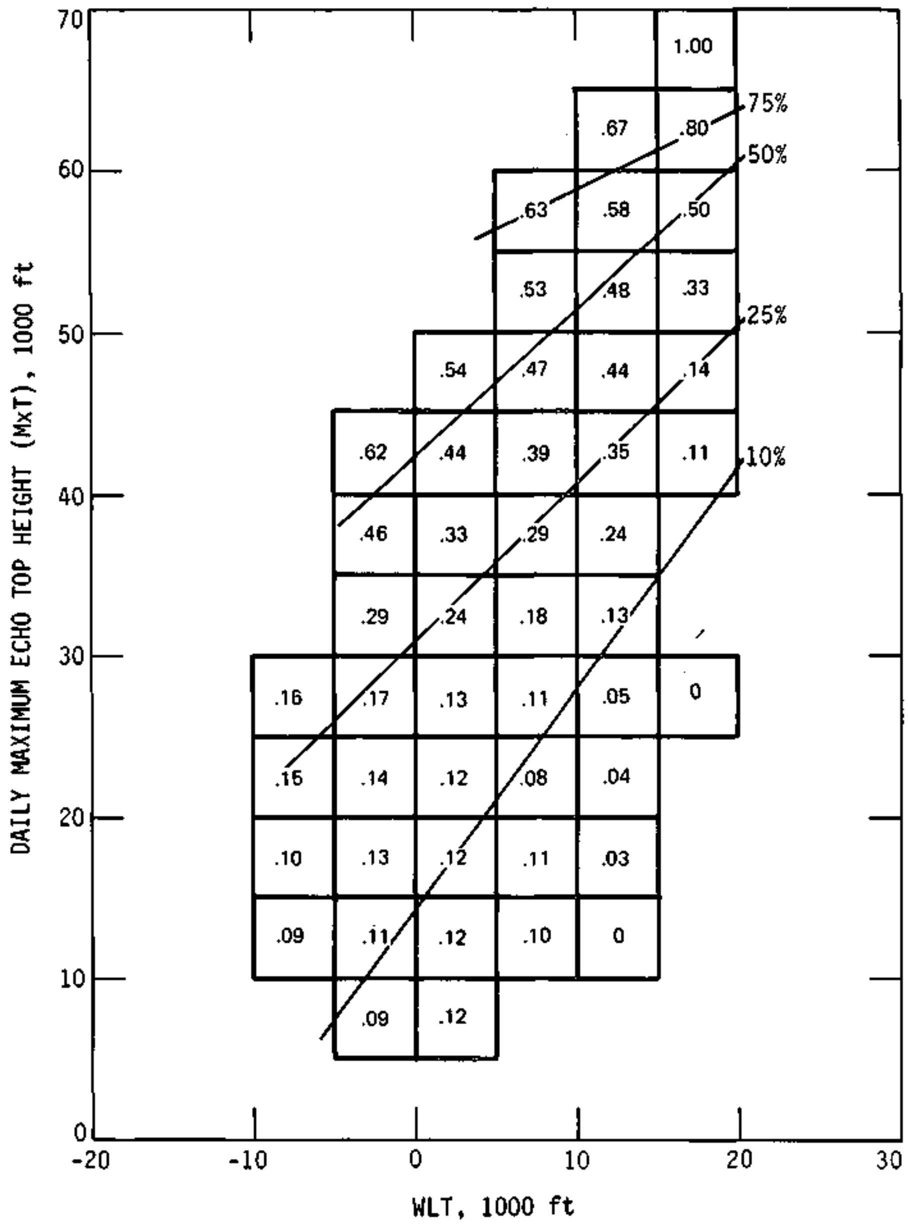


Figure 10. Hail probability as a function of warm layer thickness and daily maximum echo top height

The curves in figure 9 show that greater vertical development takes place on hail days than on non-hail days throughout the entire observed range of WLT, and that the difference becomes greater for warmer low-cloud conditions.

To examine the joint probability of hail as a function of the two variables, MxT and WLT, figure 9 was divided into 5000 x 5000 foot squares in which the hail and non-hail events could be summed. An estimate of hail probability was made in each square and smoothed isopleths of this were drawn (figure 10). The slopes of these isopleths are further support of the overall concept of this study.

In order to define a trial parameter for use in further analyses which combined radar and

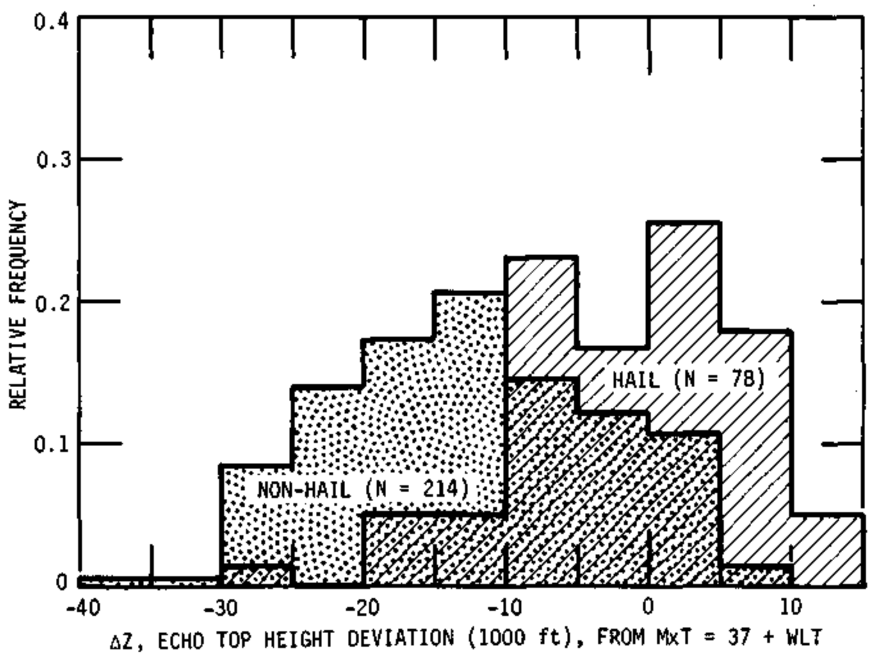


Figure 11. Relative frequency distribution of hail and non-hail days as a function of echo top height deviation

thermodynamic cloud properties, a line was fit to the data in figure 9. This line passed through the approximate location where the hail probability is equal to 0.5 (as determined from the 5000 x 5000 foot squares in figure 10). The equation for this line (shown on figure 9) is:

$$MxT_E = 37 + WLT \qquad (1)$$

where lengths are expressed in thousands of feet and the subscript E denotes the empirical nature of the line. If we let $M\times T_0$ be an observed daily value of MxT, the trial parameter ΔZ is defined as:

$$\Delta Z = MxT_0 - MxT_E \qquad (2)$$

The relative frequency distributions of hail and non-hail days as a function of ΔZ are shown in figure 11. A rather clear separation between the hail and non-hail cases is apparent. The principal mode of the hail cases is 15,000 feet to the right of that for the non-hail cases.

Figure 12 shows the conditional probability of hail for given ΔZ. Between 10,000 and 15,000 feet hail probabilities are nearly 100%, whereas between 5000 and 10,000 feet, hail probabilities are greater than 80%.

The performance of ΔZ as a predictor of hail is slightly superior to M× T. As a first trial this is very satisfying, since the bias of the sample favors the performance of MxT. MxT is favored because average storm top heights vary relatively little during the warm months which constitute the bulk of the sample. When a broad range of WLT is encountered, ΔZ would be expected to be a better predictor than MxT since ΔZ takes account of the variation of M× T with WLT.

Diurnal Behavior of Echo Tops

Figure 13a shows the average hourly echo heights for the hail and non-hail days of May, June, July, and August. Periods with no echoes, or those when no heights were given over the

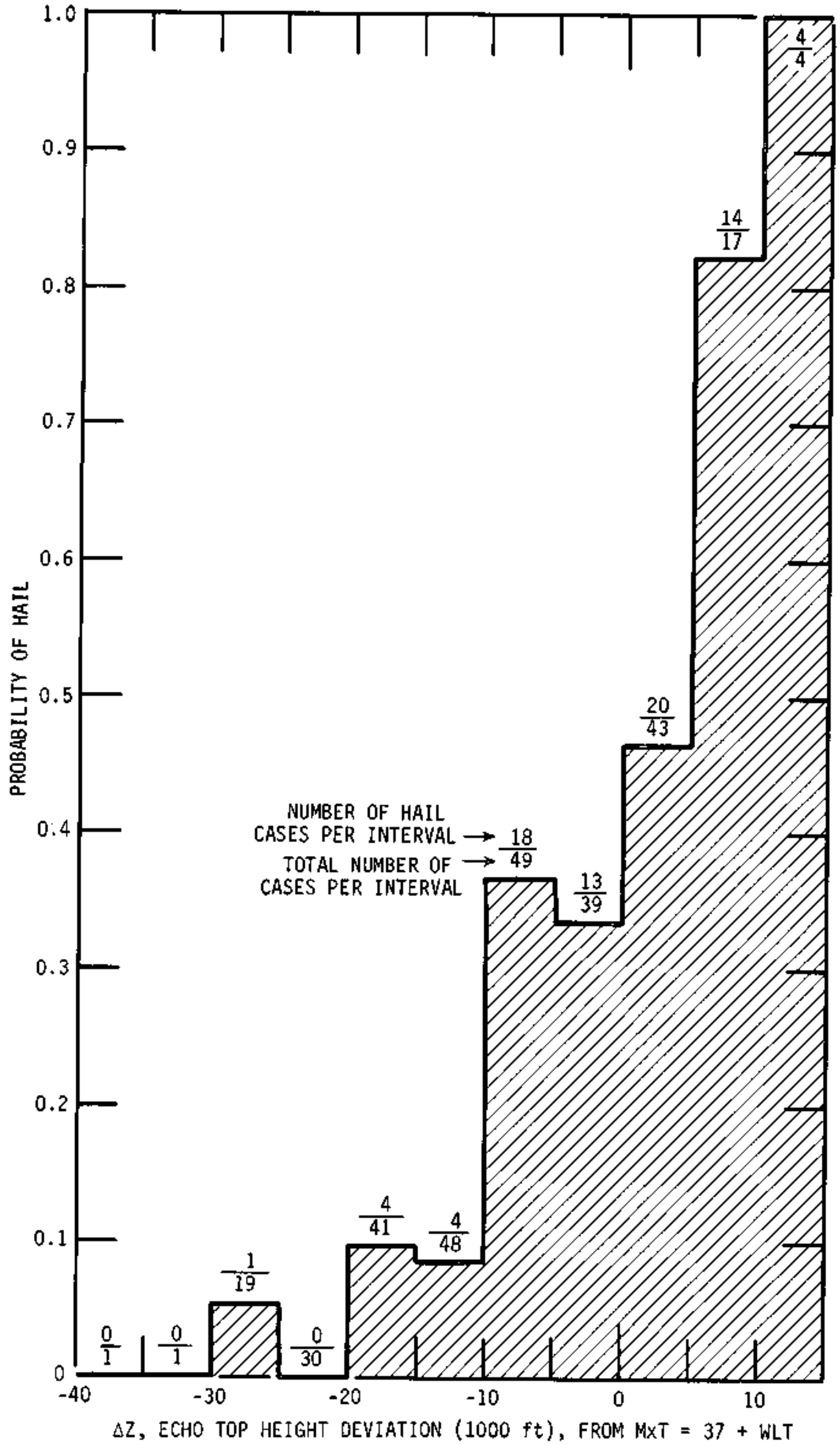


Figure 12. Probability of hail for given echo top height deviation

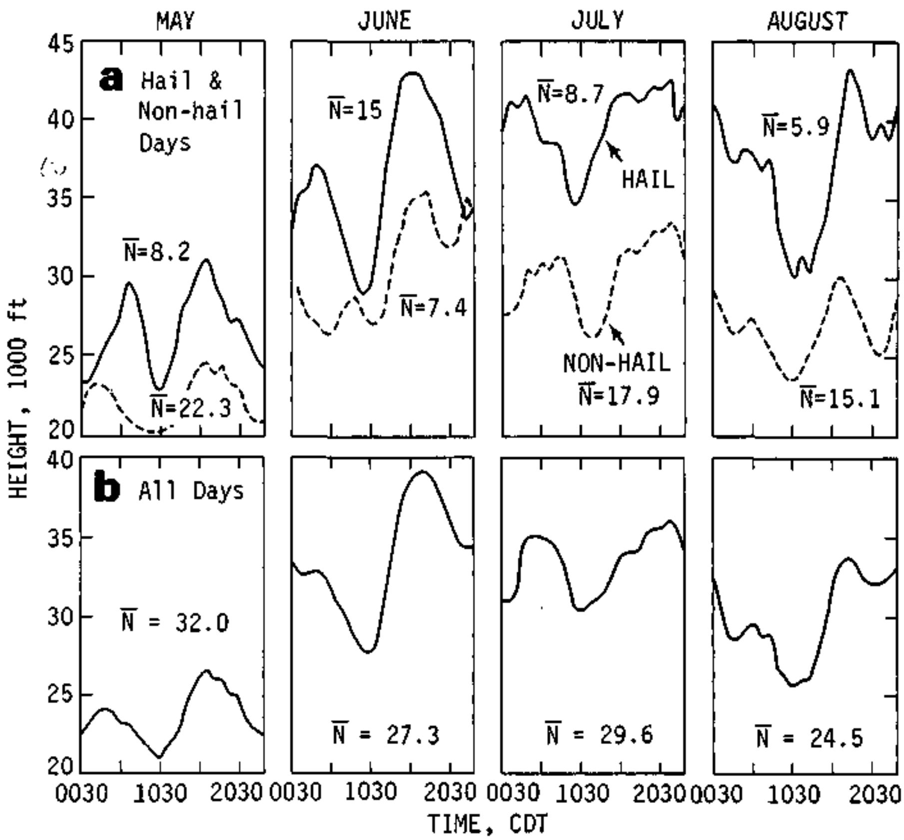


Figure 13. Average hourly echo heights for hail and non-hail days only *(a)* and for all days *lb)*

central Illinois study area, have been ignored. The values for three years have been averaged together and then smoothed with a 3-term running average. All of the ordinates for hail days are above the corresponding ordinates for non-hail days. Figure 13b is a similar plot, but all days (hail, non-hail, and insurance defined questionable days) have been used to obtain the average hourly heights for each month. The seasonal trend is again apparent. Echoes become much taller after May.

The curves in figures 13a and b show sharp and very distinct minimum hourly echo heights at about 1030 CDT. The primary maximum usually occurs about 1630 CDT, but tends to be broader than the minimum. Semi-diurnal oscillations are also apparent in the monthly plots with secondary maxima usually occurring at 0330 CDT and secondary minima at 2300 and 0130. August shows three reasonably distinct minima and maxima, but these are considered due to sampling deficiencies. August had the smallest average number of observations per hour of the 4 months ($\overline{N}$ = 24.5), while May had the largest number ($\overline{N}$ = 32.0).

In order to further reduce the effects of sampling on the daily curve, the hourly average echo heights for the months of June, July, and August were combined, by weighing the contribution of each month to a particular hour by the number of observations at that hour during the month. The months of June, July, and August were used for the averaging for two reasons. They are the months when the most damaging hailstorms occur in Illinois (Changnon, 1967) and the average MxT values for these months are very similar, within 4000 feet. The average diurnal curve for the three combined months is shown in figure 14. The nocturnal maxima in the monthly

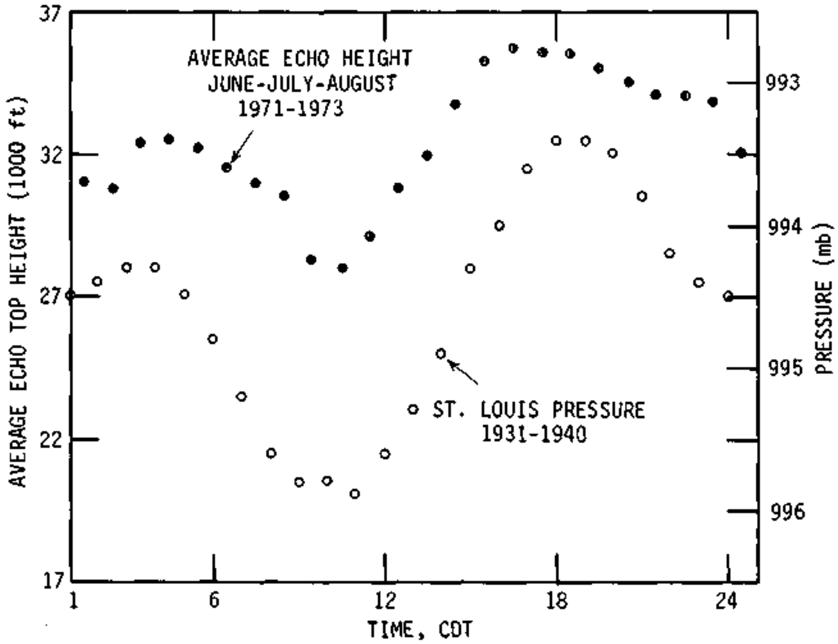


Figure 14. Average diurnal echo height curve for June-July-August combined, and comparison with pressure at St. Louis

curves have been greatly reduced by the averaging. The change from the 1030 minimum to the 1600-1700 maximum is 7700 feet, while the nocturnal range is now only 1700 feet.

Grantham and Kantor (1967) presented data on the probability of radar echoes occurring at various altitudes for the region within 100 miles of 31 NWS radar sites located mostly in the Midwest. Semi-diurnal variations were found in the monthly summer data for central Illinois and other nearby areas. For example, Kansas City had a distinct semi-diurnal variation. However, in the observations of the stations closest to the study area (Chicago, St. Louis, and Evansville), the nocturnal peaks did not occur in every summer month, and when they did occur they were much smaller than the afternoon peaks. This indicates that the semi-diurnal variation is of marginal importance in central Illinois. Conversely, Rasmusson (1971) indicated that in the western part of central Illinois the peak in thunderstorm frequency occurs at about 0200. Huff (1971) presented 10 years of rainfall rate data for central Illinois and Changnon (1969c) presented data for thunderstorms, both of which have nocturnal maxima. Thus, while the nocturnal peak of figure 13 is small, it is not clear that it is totally insignificant. In view of the marked nocturnal activity seen in figure 13, the 0300 maxima in figure 14 are hard to ignore.

The 1931-1940 average hourly pressures from nearby St. Louis are also shown in figure 14. The two curves are very similar. A shift of 1 or 2 hours makes the phases coincide. It may be that the essentially solar-driven semi-diurnal variations in the average pressure curve have convergent and divergent wind fields associated with them which are of sufficient strength to cause the semi-diurnal variation in the average maximum hourly echo heights. However, it may be that the semi-diurnal pressure wave is only a manifestation of other more meteorologically important phenomena. There is a tendency for higher frequencies of frontal passages to occur in the nocturnal hours than in the daytime in central Illinois (see Appendix E). The average pressure curve would reflect these activities as well as afternoon heating, and therefore it would be an index to both local and synoptic climatological frequencies. Since the pressure and echo top curves are so similar, it is assumed that the latter curve is reasonably stable.

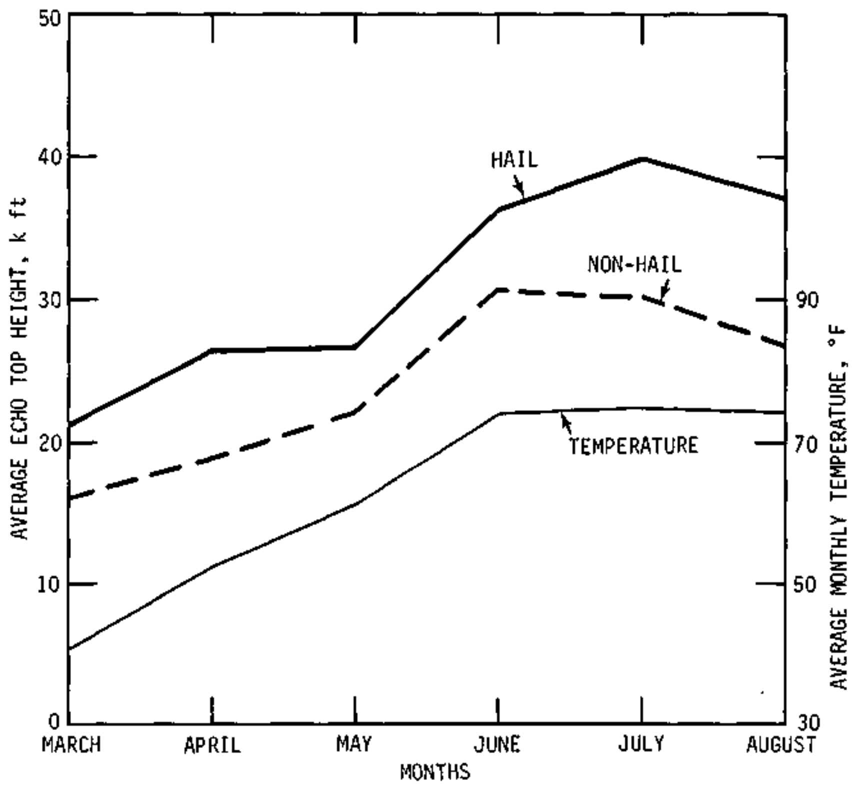


Figure 15. Seasonal variation of average maximum echo height, and comparison with monthly temperatures

Seasonal Changes in Echo-Top Heights

Figure 15 shows the seasonal variation of the average of the hourly maximum height of echoes on hail and non-hail days. The March and April values were from 1 year each, whereas the values for May, June, July, and August were based on 3 years of hourly observations. The average hourly values for a month were found by averaging all the hourly maximum echo-top measurements made at that hour during the hail or non-hail days of the month. The monthly averages were then computed by summing the hourly averages for the month and dividing by 24. The average monthly temperatures of the months studied are also plotted on figure 15.

The average height of hail echoes was greater than the non-hail average in all months. The average echo heights in the hail and non-hail cases increased from a low (22,000 and 16,000 feet) in March to peaks in July and June (40,000 and 31,000 feet, respectively). The average difference between the curves for hail and non-hail days was about 7000 feet. The heights of average non-hail day echoes in the warmer months were greater than the heights of the average hail echoes in the colder months. Figure 15 demonstrates that seasonal changes in the thermal structure of the atmosphere exert important influences on echo development and that identification of hailstorms from observations of top heights must take these influences into account.

Radar-Derived Indications of Hail Outbreaks

Maximum echo top heights (M× T) within 100 miles of the radar operations center near St. Louis were tabulated from the hourly RADU charts for the 6-hour period preceding hail on the 45 hail days in the METROMEX surface network. This was done to obtain information for identifying hail days during operations. The ΔZ values were determined for each hour from the tabulations and the hourly surface T and T_d observations made at St. Louis. Values of T and T_d for a given hour were converted to WLT, and hourly values of ΔZ were calculated from ΔZ = M× T - (37 + WLT), where M× T is the height of the tallest echo within 100 miles of the radar at any hour. If rain was affecting the surface observations at a given hour, an earlier unaffected set of T and T_d observations was used to obtain the WLT.

The frequency of various values of both M× T (hourly observations) and ΔZ for each of the 6 hours preceding hail in the St. Louis area are shown in figures 16 and 17. The top curve in figure 16 shows that for all storms echoes were present within 100 miles of a point close to the hailpad network 1 hour before hail time. Therefore, there should almost always be at least an hour's warning of this type before hail starts. Echoes were also present 6 hours before hail in over 70% of the cases.

In order to obtain a more certain indicator of hail, curves were plotted of the relative frequency at an hour of MxT of more than 30,000, 40,000, 45,000, 50,000, and 55,000 feet. There was a general rise in the frequency of all top heights as hail time was approached.

In only about 30% of the cases were echoes of 50,000 feet present the hour before hail. Tops of 40,000 feet were present the hour before hail in over 75% of the cases, and these appear to be a good indicator of hail. However, earlier results indicated that days characterized by M× T of 40,000 feet are less than 40% likely to be hail days. Figure 17 is similar to figure 16 except that relative frequencies of AZ are plotted. The ΔZ = -10,000 feet curve is very similar to the M× T = 40,000 feet curve. This chart is generally more useful than figure 16 because ΔZ takes account of the thermal character of the lower atmosphere. Figure 16 is shown because it would be easier to use operationally. During the summer (when most damaging hail falls) there usually are only small changes in WLT and the ΔZ and MxT values would be of about equal usefulness. ΔZ should be used as an indicator of hail during periods of changing weather when large moisture and thermal gradients exist.

Figures 18 and 19 show the frequency of occurrence of various MxT and AZ at or before a given hour prior to hail. Figure 18 shows that by 1 hour before hail time, echoes with tops ≥ 40,000 feet have been observed at least once in about 85% of the cases (a jump of 10% from figure 16). Echoes at 50,000 feet have been observed at least once in almost 50% of the cases, an increase of nearly 20% from figure 16. Figure 19 shows similar increases in the various AZ frequencies over figure 17.

Figures 16-19 show that *a)* large values of MxT and ΔZ are frequently observed during the 6 hours before hail time, and *b)* the frequency increases markedly as hail time is approached. All but two of the curves obtain their highest frequency in the hour encompassing the initiation of hail.

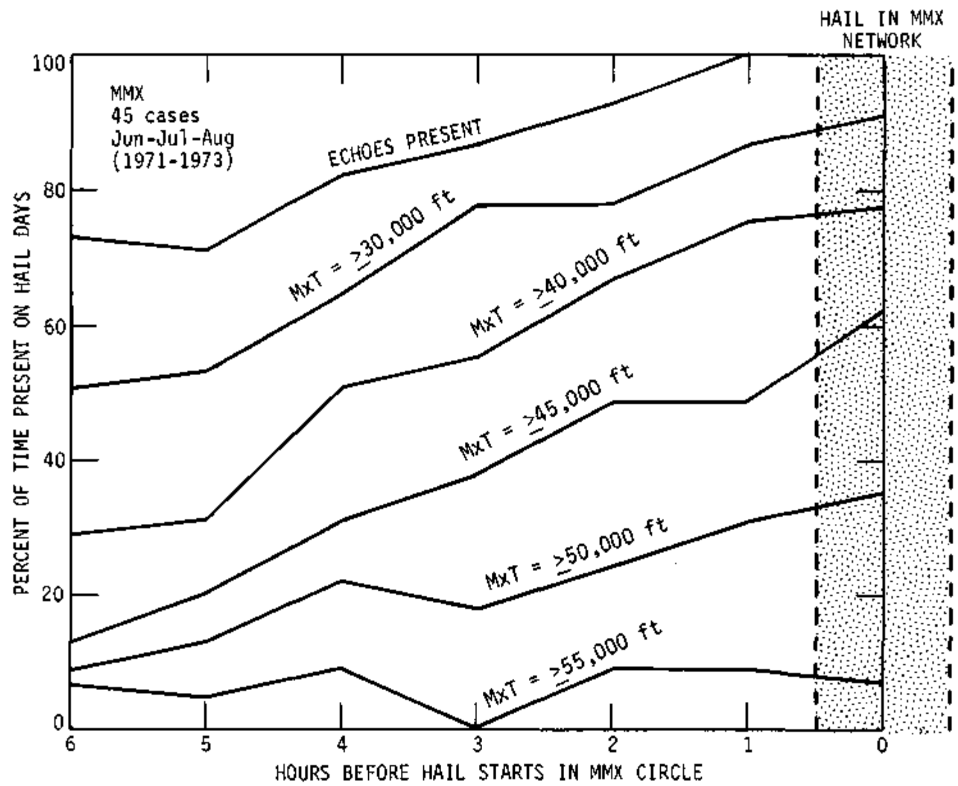


Figure 16. Frequency of various maximum echo top height values at given hours preceding hail

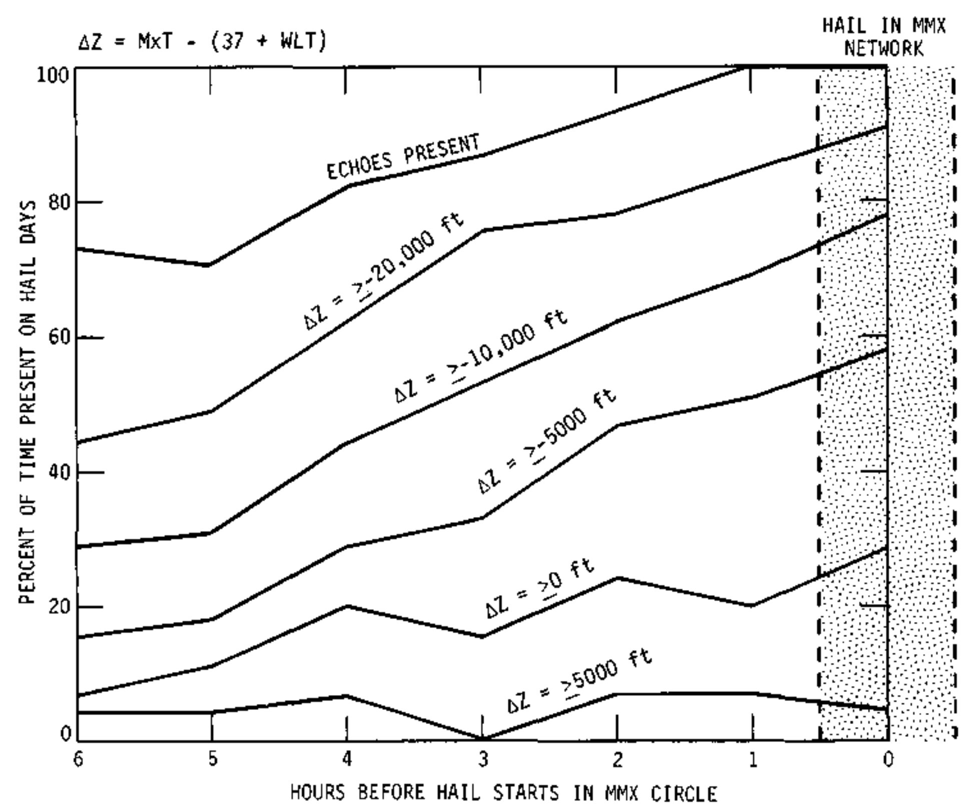


Figure 17. Frequency of various values of echo top height deviation at given hours preceding hail

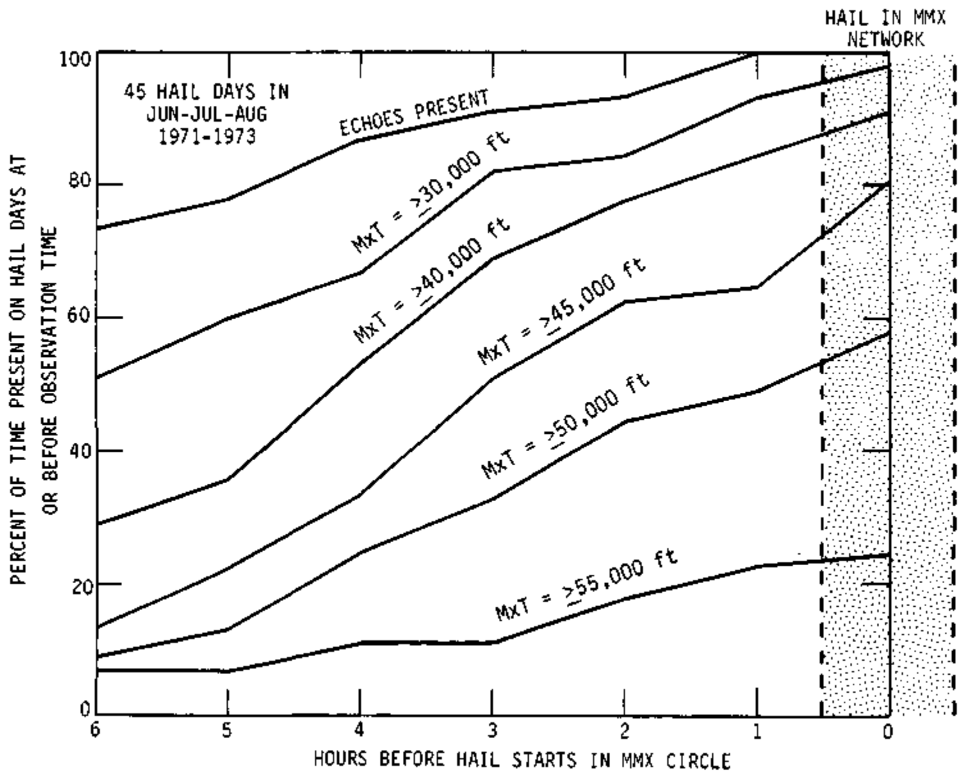


Figure 18. Frequency of various maximum top heights at or before given hours prior to hail

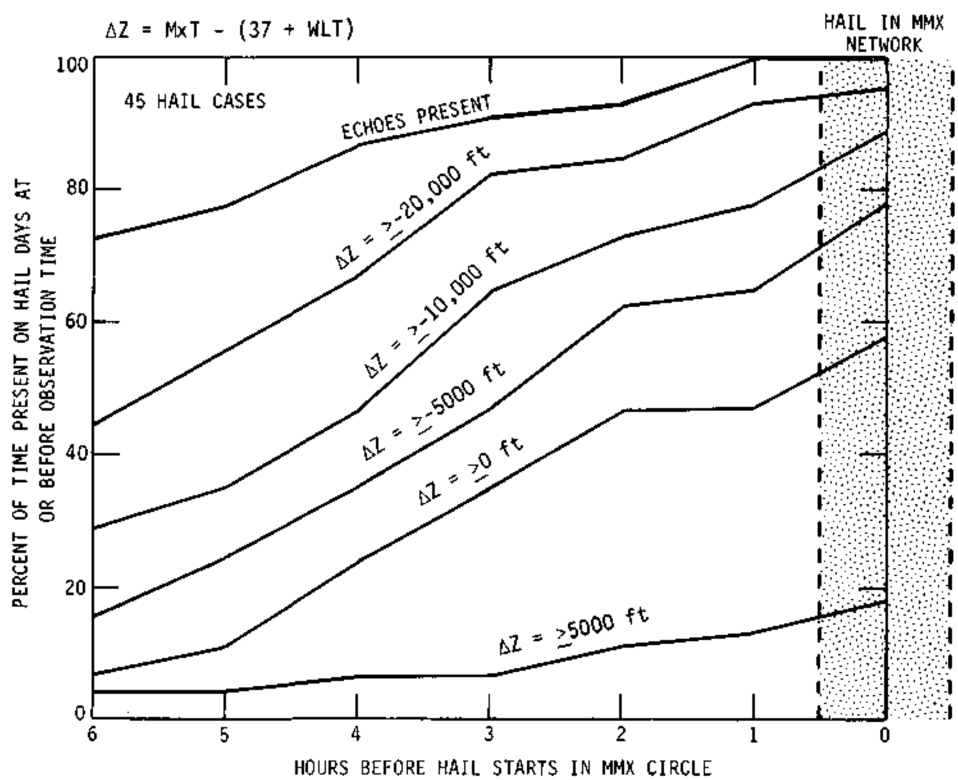


Figure 19. Percentage frequency of various maximum top height deviation values at or before given hours prior to hail

B. ESTIMATES FROM RADAR FOR OPERATIONAL PLANNING

Radar observations can supply information useful in planning the logistics of a hail suppression experiment. They allow specification of the material and personnel requirements and estimates of the costs for carrying out the chosen seeding treatment on all potential hail clouds in or threatening the protected area. Radar data will also make it possible to avoid weakening the statistical evaluation by failing to treat all hail-producing clouds on seeded days.

FACTORS PERTINENT TO LOW-LEVEL AIRCRAFT OPERATIONS

Cloud base height, low-level visibility, and the size of the cloud (echo) systems encountered on hail days all affect low-level aircraft seeding operations. If updrafts are to be seeded at cloud base, aircraft must be able to safely reach the updraft region. Cloud size, cloud base height, and visibility all play a role in determining the ease with which updrafts are located and then seeded.

Hail Day Cloud Base Heights

Cloud base heights (CBH) were calculated from the Springfield 1300 CDT surface temperature and dew point observations. The formula $CBH = 220 (T - T_d)$ was used. As a check on these calculations, low-level cloud base heights observed prior to hail in the METROMEX network were tabulated from the St. Louis WBAN forms for the 45 hail days during the summers of 1971-1973. Only CBH observations that clearly were not affected by recently developed precipitation were used in the St. Louis data.

The average cloud base height obtained from the Springfield surface data was 3400 feet with a standard deviation (a) of 1600 feet, whereas at St. Louis the observed average CBH was 3900 feet with a *a* of 1300 feet. The range of the Springfield CBH values was from 400 to 7700 feet, and that of St. Louis from 500 to 6000 feet. The difference between the two distributions appears small, the mean values differing by only 500 feet.

Figure 20 shows that the two distributions plotted in terms of relative frequency were quite different. There was a pronounced tendency for higher cloud bases at St. Louis where the mode was between 3000 to 5000 feet, as opposed to the 2000 to 3000 feet mode at Springfield. The distributions are skewed in opposite directions (which accounts for the similarity in the means). The differences may be due to inaccuracies that arise from the use of an empirical formula to calculate the CBH values, from erroneous observer reports, or from differences in observation time with respect to the hail event. For example, it is possible that the Springfield observations could have been more frequently influenced by rain than the St. Louis observations. Rain at the surface observation site would raise the relative humidity and cause calculation of lower cloud-base heights.

However, the St. Louis-Springfield difference may be real and due to thermodynamic effects produced by the St. Louis urban environment. Urban cloud-base heights are 1000 to 2000 feet higher than rural bases (Cataneo, 1974). A 5% decrease of the relative humidity (RH) could cause a CBH increase on the order of 500 to 900 feet, whereas a 10% RH decrease could cause a CBH increase of about 1000 to 1900 feet. Several authors have found the average RH in

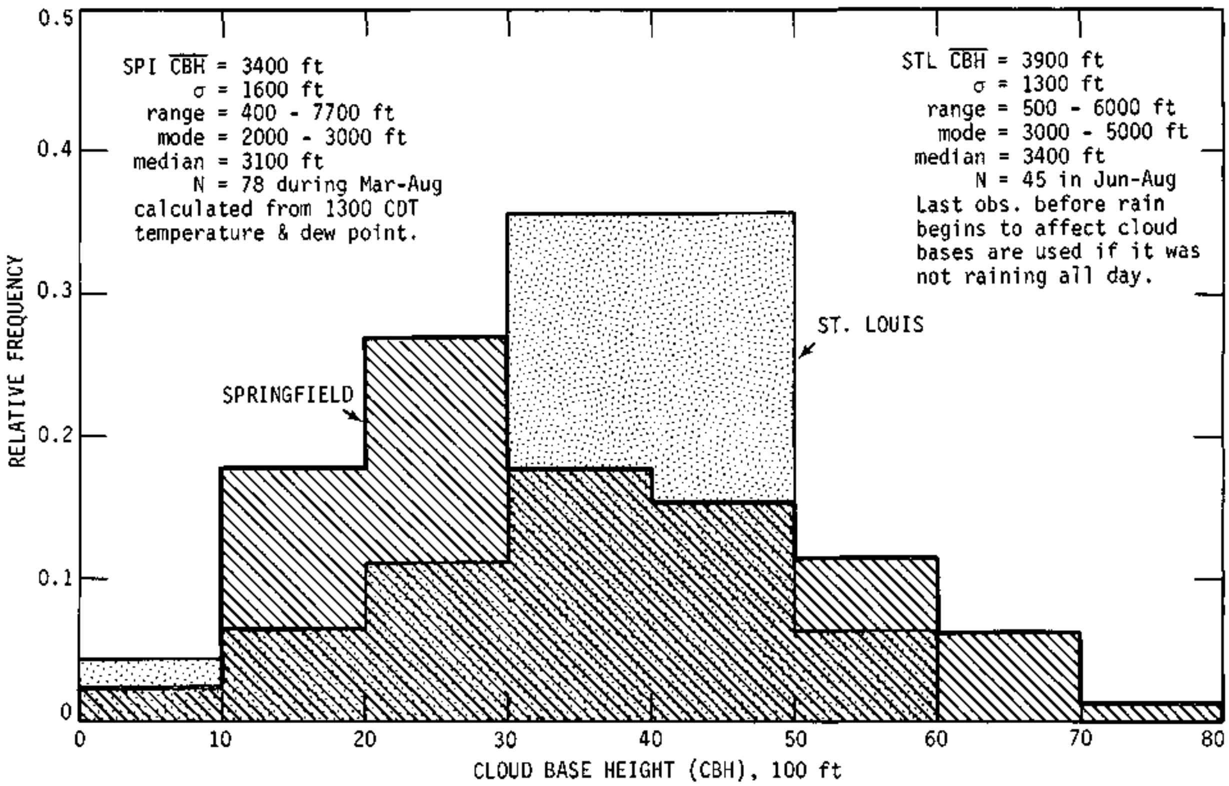


Figure 20. Distribution of cloud base heights at Springfield and St. Louis on hail days

urban areas to be 5% lower than rural values and instantaneous urban-rural RH differences can be much larger (Huff, 1973). Urban effects appear to be largely responsible for the St. Louis-Springfield differences in CBH.

The distributions have been plotted in a cumulative form in figure 21. About 90% of the CBH values in both distributions were ≥ 1500 feet. However, about 80% of the CBH at St. Louis and only about 50% of those at Springfield were ≥ 3000 feet. Since the CBH at St. Louis tended to be higher than rural CBH and the higher CBH values at Springfield may not be totally realistic, a compromise between the two curves of figure 21 might be appropriate. A conservative approach would be to use the Springfield curve in the more critical lower CBH region below the crossover point near 4500 feet, and then the St. Louis curve above it. This would also compensate for the localized urban influence at St. Louis and the too high CBH values calculated for Springfield.

Visibility

The St. Louis visibility observations made at the same time as the cloud-base height observations were also studied. The average pre-rain visibility on the 45 hail days was about 10 miles with a range from 1.5 to 15 miles. The relative and cumulative relative frequency distributions of St. Louis visibilities are plotted in figure 22. The relative frequency distribution is skewed since small visual ranges occur relatively infrequently. The cumulative distribution shows that about 96% of the time visibility exceeded 3 miles, the range required for visual (VFR) aircraft flight. Since urban areas such as St. Louis have 100 to 200% more days with poor visibility than rural areas (Peterson, 1969), an Illinois cloud seeding operation over a rural area will encounter fewer

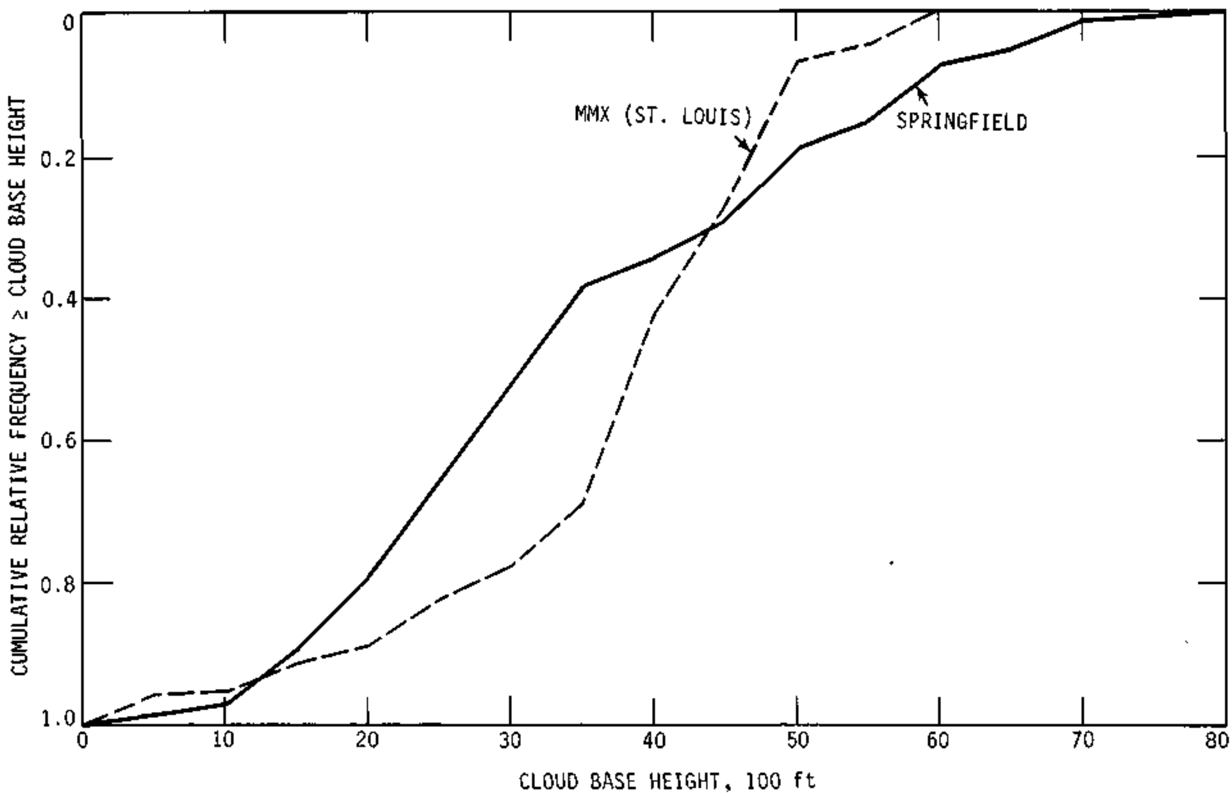


Figure 21. Cumulative relative frequency of cloud base heights at Springfield and St. Louis on hail days

visibility problems during daytime operations. About 30% of Illinois hail events occur at night (Changnon, 1969a) when maintaining VFR in flight is more difficult.

Echo-Cloud Dimensions

The sizes of echoes encountered over the network during hail conditions have a direct effect on the number of aircraft required to reach and adequately treat all significant cloud base updrafts. The size of the hail echoes should also provide a rough measure of seeding requirements for high flying aircraft or ground-based treatment systems (generators or rockets). Other factors which play a role in determining the number of aircraft needed for operations are the type of seeding treatment to be applied to potential hail clouds, the number of clouds the treatment must be applied to, and the period of time during which application must be made.

Echo circumferences were measured from Survey radar microfilm records to determine the size of hail-producing cloud systems in central Illinois which would have to be circumnavigated by seeding aircraft. Twenty cases were selected from 1967 operations when radar data included low elevation angles for periods when hail fell in the central Illinois hailpad network. All of the 1967 radar data had been obtained with a 3-cm radar. The circumferences of the 'main echoes' observed at maximum gain (27 dbz) during the network hail periods were determined from measurements of their lengths and widths with an assumed elliptical echo shape. Main echoes were defined as the smallest echoes with intensity cores which could be circumnavigated by seeding aircraft under the assumption that the main echo must be separated by at least 2 miles from much smaller nearby echoes to safely fly between them. [This is a somewhat narrower margin than that recom-

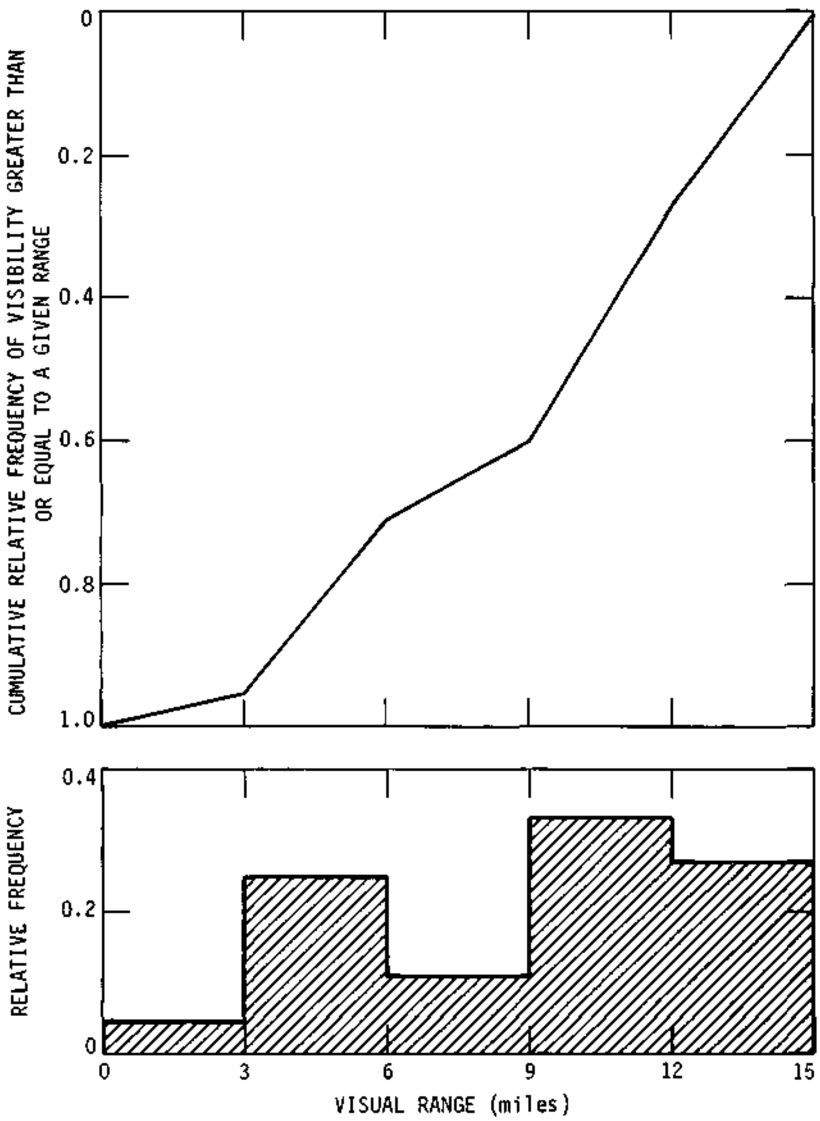


Figure 22. Relative and cumulative relative frequency distributions of visibilities at St. Louis on hail days

mended for commercial passenger aircraft (Foster, 1961).] Figure 23 shows the cumulative relative frequency distribution of the main echo circumferences. The median circumference is about 180 miles and 80% of the main echoes had circumferences less than 300 miles. The range of circumferences is 12 to 360 miles with an average of 200 miles.

The typical shape of the main echoes may be characterized by the horizontal aspect ratio (length/width). The median aspect ratio for the main echoes was 1.6 and the maximum was 5.2. Seventy-five percent of the main echoes had aspect ratios of less than 2.

Interpretation of the main echo data must include awareness that 55% of them had other main or smaller echoes within 3 miles, and all had echoes within 7 miles. Ninety-five percent of the cases had at least one other large echo (one dimension > 12 miles) within 10 miles. These other large echoes were not necessarily the closest echoes to the main echo, but serve as indicators of the extensive convective development present on hail days.

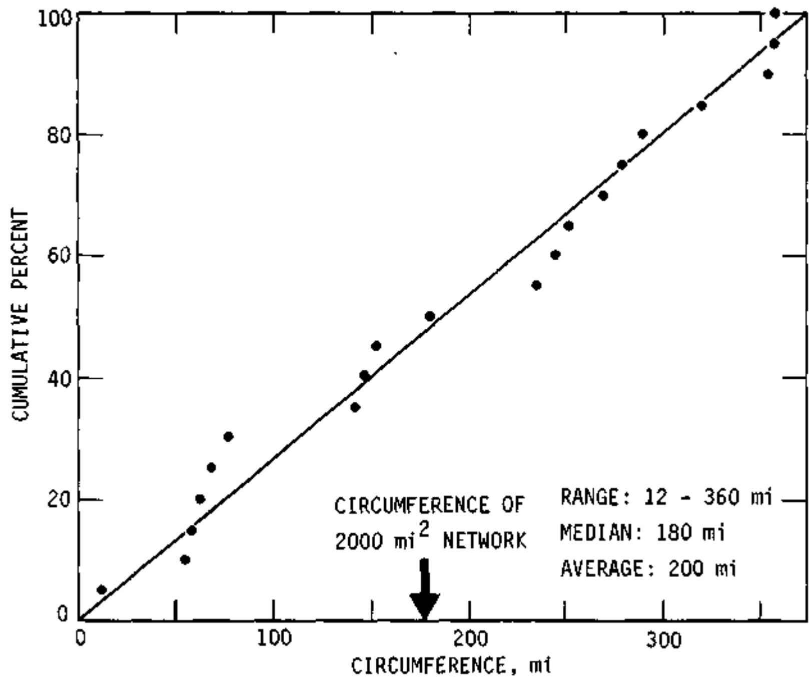


Figure 23. Cumulative relative frequency distribution of the circumferences of main echoes during hail periods

About 70% of the cloud base updrafts associated with Illinois hail echoes are located on the front side with respect to direction of movement of the cloud (Changnon et al., 1975; also see Section E, Cloud Properties, in this report). Cloud base seeding would require aircraft having the ability to maneuver around at least the front half (150-200 miles) of the main echoes in a reasonably short period of time. In some cases the main echoes will also have to be partially circumnavigated after (or before) seeding operations when aircraft are returning to (or approaching the cloud from) their base.

DURATION OF NETWORK STORM PERIODS

The length of time that potential hail-bearing clouds would exist over the network and would require seeding treatment was estimated from the duration of hail-associated maximum gain radar echoes over the network. Figure 24 shows the cumulative relative frequency of the duration of maximum gain echoes over the 2000 mi^2 network. About 90% of the 18 cases used had echo durations over the network of less than 9 hours, with the median duration being 5 hours and the average 5.5 hours. The range was from 2 to 10.5 hours. Since radar operations did not always completely coincide with the time echoes entered and left the 2000 mi^2 network, it was necessary to estimate durations in 12 cases. The estimates were obtained by extrapolation on the basis of echo velocities. Corrections added to the observed durations exceeded 1 hour in only two cases. Two cases were dropped from the sample because radar records were too short to allow extrapolation.

Another estimate of treatment duration can be obtained from the time hail actually fell in a network of a given size. Hail duration is an estimate of the minimum time required for treat-

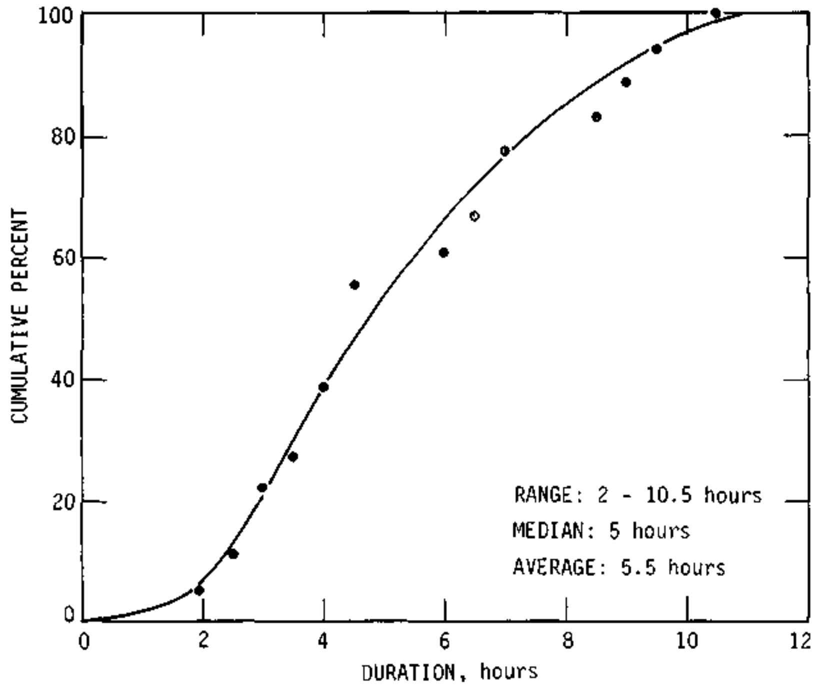


Figure 24. Cumulative relative frequency distribution of the duration of echoes for 18 hail days

merit, while the time maximum gain echoes are over the network is considered an estimate of the maximum required treatment duration. Changnon (1969a) found that in a 1600 mi^2 network 19 hail events had durations of 0.1 to 11.5 hours with an average duration of 2.4 hours. A 600 mi^2 network had an average hail duration of 1.1 hours.

On the basis of these estimates, and assuming that all echoes (regardless of reflectivity, echo top heights, etc.) are to be treated, one would expect the median treatment duration to be about 5 hours, but in a few cases as much as 12 hours. If some threshold (such as reflectivity) must be exceeded before seeding begins, the median treatment period will be reduced about 1 to 2 hours, but occasional long durations will exist.

FREQUENCY OF POTENTIAL HAIL CELLS

Radar reflectivity (Z) patterns were studied to provide information on the number of individual entities requiring seeding at one time. Figure 25 shows the cumulative relative frequency distribution of the maximum reflectivities (Zmax) observed during hail conditions in 1972-1973 in the 3800 mi^2 METROMEX surface network at St. Louis. The 10-cm wavelength radar was operated in an 0° elevation angle PPI mode. Thirty-one samples of radar data chosen such that they were within ±15 minutes of hail time in the surface network were selected at 30-minute intervals. Data were recorded on magnetic tape and played back to generate displays of range corrected reflectivity contours at intervals of 6 dbz, and the value of the highest reflectivity contour over the network at hail time was tabulated. The cumulative frequency in figure 25 is in terms of the number of Zmax values observed that were greater than or equal to a given Z value. The plotted points represent the smallest possible Z value observed in a 6-dbz interval. All of the Zmax

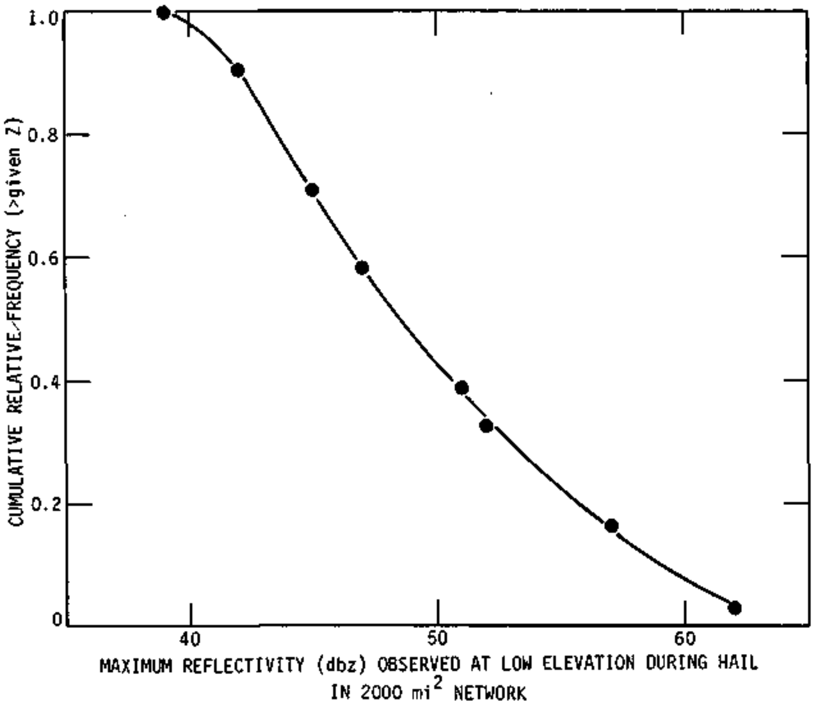


Figure 25. Cumulative relative frequency distribution of maximum reflectivities during hail

observations were ⩾ 39 dbz and none was > 66 dbz. Only about 42% of the hail events were associated with reflectivities ⩾ 50 dbz. This compares favorably with the 3-cm results.

Thus, a 10-cm reflectivity value of 40 dbz appears reasonable as a threshold indicating the presence of potential hail-producing cells. The number of cells with a reflectivity ⩾ 40 dbz over the Illinois networks of various sizes was tabulated. The 40-dbz cells had to be separated from other 40 dbz cells by at least 1 mile to be counted as separate cells. Radar data from the 1972-1973 METROMEX effort and the 1967 central Illinois operations were studied. All radar data used in the cell counts consisted of low elevation angle observations made within ± 15 minutes of hail.

Figure 26 shows cell number distribution curves for five different areas varying from 300 to 2400 mi^2 within or surrounding the hailpad networks. The triangles represent the St. Louis 10-cm radar data for areas of 500 mi^2 and 2400 mi^2. The dots and boxes represent the central Illinois 3-cm data for areas of 300, 1200, and 2000 mi^2. The data for either wavelength treated separately reveal the expected increase in the number of cells present at a given time as a function of increasing network size. The median number of cells present over the 300 and 2400 mi^2 areas (10-cm) are approximately 1 and 3.

Comparison of the data from the two radars is complicated by differences in radar characteristics such as beam width, closeness to network, antenna elevations, range correction procedure, wavelength, and sampling. For example, the median number of cells, 3, observed by the 10-cm radar in the large (2400 mi^2) network is less than the medians observed by the 3-cm radar for both the 1200 and 2000 mi^2 areas. The range in the number of cells observed in the 2000 mi^2 network was from 1 to 13 with an average of about 6 and a median between 5 and 6.

Not all 40-dbz defined cells will be associated with hailfalls. For example, Changnon (1969a) examined 93 raincells which produced hail in the 1600 mi^2 network on 19 days in 1968. The num-

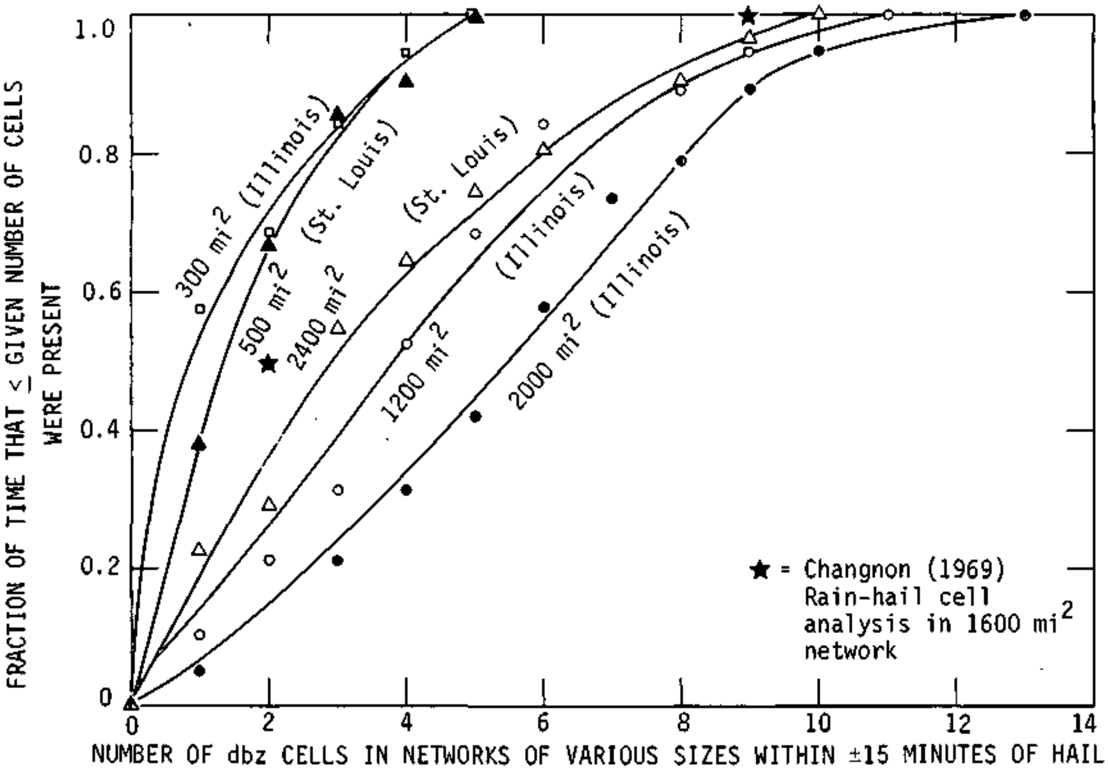


Figure 26. Distribution of 40 dbz cells for different size areas

ber of hail-producing raincells present at a given time was always less than 9 with a median of 2. If a curve is constructed through these two points (shown by stars) and the origin in figure 26 (the abscissa units being considered cells), it would fall to the left of the 2400 mi^2 curve. This indicates that the number of 40-dbz cells present at one time is most likely greater than the number of hail cells. Other raincells which did not produce hail were undoubtedly present during the hail periods. The number of cells that have to be treated will be greater than the number of cells that would have produced hail naturally, unless some very reliable means is found to identify (in advance) the cells which will eventually produce hail.

Cell Development over the Network

Data presented by Changnon (1969a) indicates that over half of 93 raincells that produced hail initially developed within the confines of the 1600 mi^2 network. Since the cells can rapidly develop into hailstorms, this presents a very critical operational problem. Eighteen percent of the hail echoes examined by Towery and Changnon (1970) produced hail within 19 minutes after initial formation, and on at least one occasion within 6 minutes after formation. When developing echo systems are approaching or within a protected network, it will clearly be necessary to have a seeding aircraft (or other equipment) ready to treat such developments within minutes after their appearance on radar. The occurrence of all hail with reflectivities > 35 dbz above the freezing level in spring and > 40 dbz with summer-fall storms suggests these would be suitable criteria for seeding.

C. DESH FIELD MEASUREMENTS

RADAR AND SUPPORT OPERATIONS

Project field operations in the spring of 1973 provided good surface hail data but associated radar data were scanty. The radar had undergone considerable modification (the entire 3-cm radar portion was miniaturized and remounted on the rotating part of the antenna of the 10-cm system) and was not in good operational condition until late March. Signal processor problems then nullified attempts to tape-record data, and the radar had to be dismantled for transfer to Ft. Morgan, Colorado, in the first days of April to be ready for NHRE-related operations beginning on 1 May.

Nevertheless, the operational and forecasting experience gained in this initial period of exercising our weather watch capability was extremely valuable and did produce a very interesting example of a tornado and hail-producing situation. A remarkably similar situation occurred during the fall 1973 operational period and was successfully forecast.

The fall operational period of 2 September to 6 November 1973 was much more successful than the spring 1973 effort. As shown in table 2, useful radar data were collected on four minor hail days. Radar operations also provided data for a study supported by the U.S. Air Force Cambridge Research Laboratory to investigate attenuation, rainfall rates, and liquid water content along ray paths through the atmosphere. That study used dual wavelength radar data in conjunction with surface measurements of raindrop sizes made with 6 spectrometers adjacent to 6 recording raingages fitted with 6-hour gears.

Operational schedules for fall 1973 and spring 1974 were arranged on the basis of spring 1973 experiences. On each day, a team of two researchers was responsible for following the weather situation and forecasting potential operational periods. This scheme allowed the remaining project staff to attend other responsibilities until significant weather began to occur. Once a storm situation began, all available staff were involved. A flexible schedule was developed to cover all possible daytime and nocturnal operational requirements. When a storm period was over, the routine daily schedule was resumed. This scheme was quite successful, and no significant convective weather within radar range was missed. All the hailstorm activity which occurred between 2300 and 0600 CDT was effectively recorded.

Table 2 gives an overall summary of the radar operations during fall 1973 and spring 1974 periods. As noted for 3 September 1973, there were some early problems with the recorded data. Also noteworthy is the fact that there were nearly three times as many hours of data in 1973 as in 1974, yet the number of tapes filled in the 1974 period was double that of the first because of the recording of the doppler data. Overall, we recorded data from 19 days, and 9 of them were hail days and 6 involved tornadic or near tornadic storms.

NETWORK OPERATIONS

Surface hail measurements for DESH came from rain-hail networks operated on four space scales. One area of surface hail measurement was a 780 mi^2 network west of the radar (figure 27). There were 81 recording raingage and hailpad sites spaced 3 miles apart, plus

Table 2. Summary of Radar Data Collections,
Fall 1973 and Spring 1974

Date	*Local time radar on-off*	*Comments*
1973		
3 Sep	evening	no data
4 Sep	1051-1238	
14 Sep	1630-1805	
22 Sep	0000-0500	
23 Sep	1235-1445	
24 Sep	1100-2310	hail
25 Sep	1000-1800	
28 Sep	1400-2110	antenna breakdown
30 Sep	0930-01/0015	hail
1 Oct	1130-2020	antenna trouble – hail and funnel
3 Oct	0850-04/0000	
4 Oct	0000-1125	hail
4 Oct	1400-1515	
	18 data tapes, total period = 86 hr 55 min	
1974		
28 March	0940-1225	
29 March	1430-1815	tornado and hail
1 April	1230-1800	hail and hook echoes
3 April	1235-1930	tornadoes and hail
12 April	2110-2320	small hail and tornadoes
29 April	0950-1120	
16 May	0910-1045	activity to 1200 (tape later erased for reuse)
17 May	0840-1140	hook echo and hail
	37 data tapes, total period = 28 hr 10 min	

5 weather stations (temperature and dew point). The raingages were modified to allow an estimate of the time of hail (Changnon, 1966). A second and finer scale of hail measurement was obtained in a 170 mi^2 'dense network' located inside the larger network (figure 27). This dense network had 151 hailpad sites plus 25 raingage-hailpad sites which makes an overall density of 1 hailpad/mi^2 .

A third scale of hail detection was a micro-network located on the University of Illinois Agronomy Farms (figure 27) and operated in 1974. The spacing between hailpads was only 275 feet. A fourth data source was that compiled by 345 cooperative hail observers in the 3000 mi^2 area enveloping the 780 mi^2 network. An additional data source was the crop loss data from all the crop-hail insurance companies in the area.

In 1973 the large raingage network was operated for the spring and fall radar operations and the dense network was operated from 15 March through 3 November. The large network was opened only during the spring (15 March — 17 May) of 1974. For the summer of 1974, raingage-hailpad-meteorological stations were operated at a few locations. Also in 1974, the micro-network was operated from mid-March until 30 September.

The raingage-hailpad networks were operated in a variety of sizes during the 1967-1974 period, as summarized in table 3. A summary of the surface data collected for the years 1967-1974 is included in this portion of the final report. The summary includes information on the number of hail days, maps of hail occurrences, and various hailstreak statistics.

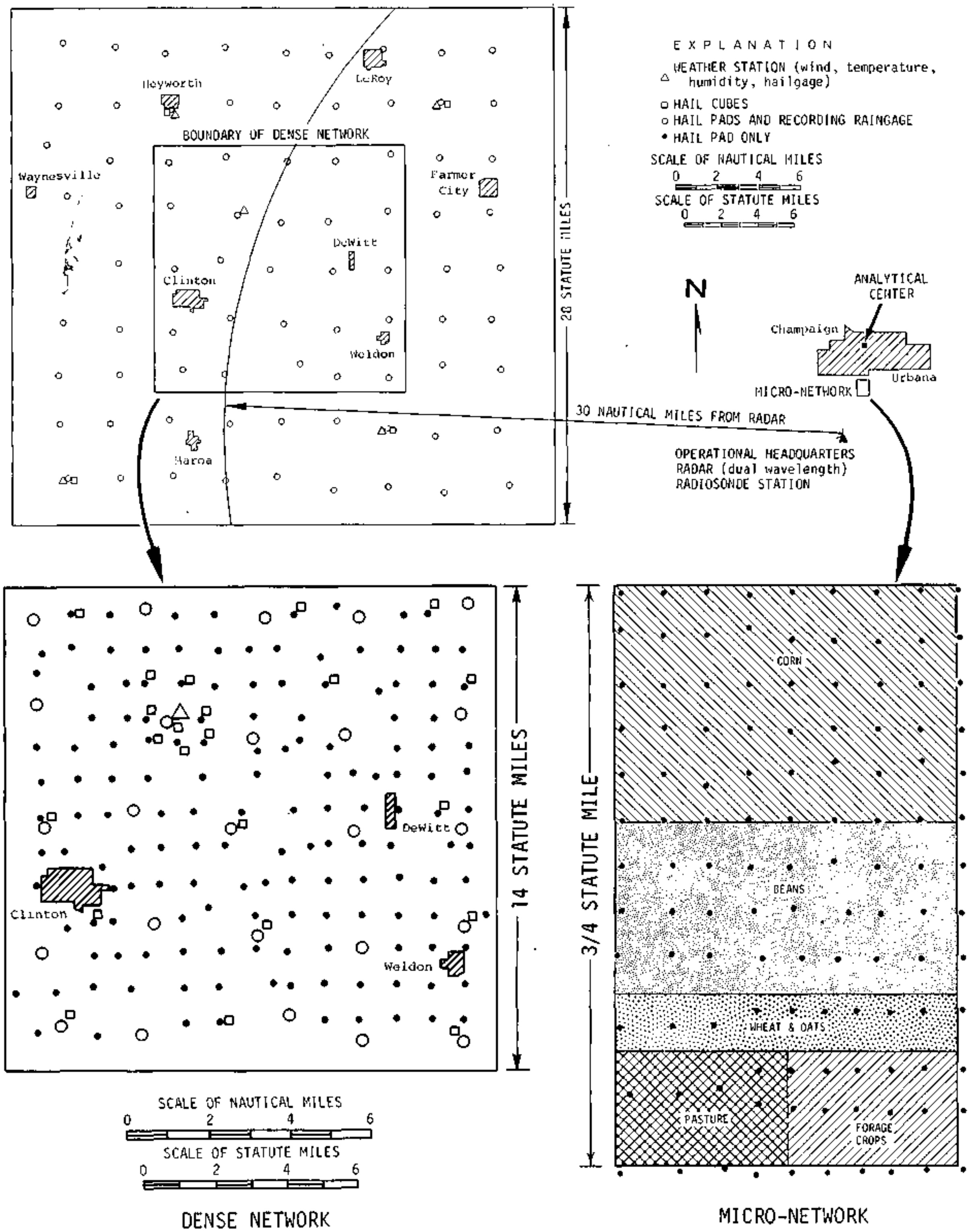


Figure 27. Illinois hail design project networks, 1974

Table 3. Raingage-Hailpad Networks, Cooperative Hail Observers, and Insurance Data Used for Hail Studies in 1967-1974 Period

Year	*Networks**	*Cooperative observers*	*Insurance*
1967	ECIN = 49 gages and pads (400 mi²)	29 counties (18,440 mi²)	29 counties
	Kankakee** = 16 gages (300 mi²)	1325 observers	
1968	CIN = 196 gages; 100 w/pads (1600 mi²) (725 mi²)	29 counties (18,440 mi²)	29 counties
	Dense network = 96 pads (100 mi²)	1325 observers	
1969	CIN = 196 gages; 100 w/pads (1600 mi²) (725 mi²)	6 counties (3878 mi²)	6 counties
	Dense network = 96 pads (100 mi²)	260 observers	
1970	*No measurements collected*		
1971	EIN = 81 gages w/pads (625 mi²)	5 counties (3225 mi²)	5 counties
	Dense network = 151 pads (150 mi²)	345 observers	
1972	EIN = 81 gages w/pads (625 mi²)	5 counties (3225 mi²)	not obtained
	Dense network = 151 pads (150 mi²)	345 observers	
1973	EIN = 81 gages w/pads (625 mi²)	5 counties (3225 mi²)	5 counties
	Dense network = 151 pads (150 mi²)	241 observers	
1974	EIN = 81 gages w/pads (625 mi²)	5 counties (3225 mi²)	5 counties
	Dense network = 151 pads (150 mi²)	241 observers	

*ECIN = East Central Illinois Network, CIN = Central Illinois Network, EIN = Eastern Illinois Network.
**No hailpads – evaporation funnel removed from raingages.

SURFACE HAIL RESULTS

Table 4 gives information on the number of hail days for each month as detected by the hailpads and raingages during the 8-year study period. The table indicates the extreme variability that can be expected in number of hail days per month, regardless of network size. For instance, the extremes for April ranged from 1 to 10 days per month. The 10 days occurred when the network was at its smallest operating size. On the average, 3 to 4 days per month occurred from April through July, and 2 to 3 days per month for August and September.

Table 5 shows the number of hail days as determined by the cooperative observers. These figures again indicate extreme variability (from 1 to 13 days in May). They also show the months April-June to be much higher than August and September. This information is reflected in the observer data for 1971-1974. The size of the observer effort remained virtually unchanged over

Table 4. Number of Hail Days, Based on Hailpads and Raingages

	Mar	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*May-Sep total*
1967	ND*	10	6	4	6	2	2	20
1968	ND	ND	6	1	4	4	3	18
1969	ND	1	3	2	2	0	1	8
1970	*No measurements collected*							
1971	0	2	4	5	3	3	2	17
1972	1	4	1	2	3	3	4	13
1973	7	4	2	6	4	2	2	16
1974	1	3	2	3	ND	ND	ND	ND
Average	1.3	3.4	3.4	3.3	3.7	2.3	2.3	15
Maximum	7	10	6	6	6	4	4	20
Minimum	0	0	1	1	2	0	1	8

*ND = no data

Table 5. Number of Hail Days Based on Observer Reports

	Mar	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*May-Sep total*
1967	0	12	13	8	9	3	2	35
1968	5	5	10	4	7	1	2	24
1969	0	3	6	4	3	2	2	17
1970	1	3	3	1	1	2	1	8
1971	4	2	5	6	3	2	1	17
1972	1	5	1	2	3	3	0	9
1973	3	7	2	6	2	0	2	12
1974	4	6	5	8	4	3	1	21
Average	2.3	5.4	5.6	4.9	4.0	2.0	1.4	17.9
Maximum	5	12	13	8	9	3	2	35
Minimum	0	2	1	1	1	0	0	8
1971-1974								
Total	12	20	13	22	12	8	4	59
Average	3.0	5.0	3.3	5.4	3.0	2.0	1.0	14.7
Maximum	4	7	5	8	4	3	2	21
Minimum	1	2	1	2	2	0	0	9

this 4-year span. The average number of hail days was 5 for April and June, 3 for May and July, 2 for August, and 1 for September.

Some maps of the number of hail occurrences at each hailpad location were included in previous reports (Changnon, 1969a; Changnon and Towe'ry,1972). The most consistent long-term information was obtained from the dense hail measuring network for 1971-1973 because it was operated over about the same time span and with the hailpads in the same location each year. Figure 28 shows the map of total occurrences for 1971-1973. The maximum number of hail occurrences at one location was 13 and the minimum was 3. The 3-year area mean of occurrences was 7.4 and the yearly areal mean was 2.5. This is a very representative mean for a 170 mi^2 area network with a sample locations separated by 1 mile.

The map of hail occurrences for 1973 is shown in figure 29. The range was from a high of 6 occurrences to none.

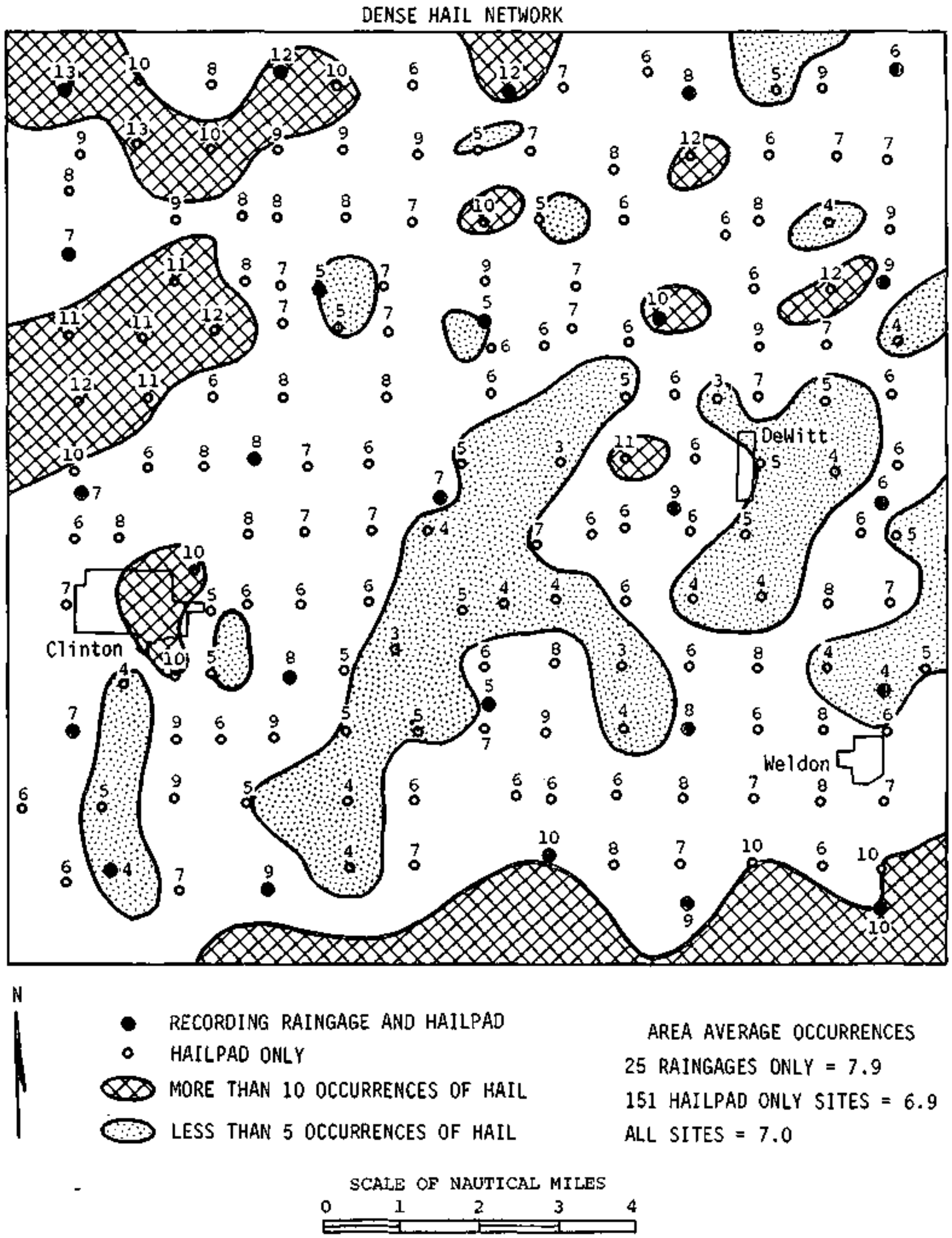


Figure 28. Total hail occurrences for 1971-1973 in the dense hail network

Table 6 gives a monthly breakdown of identifiable hailstreaks. Again, May-July was the most active hail period. The maximum number of hailstreaks was 154 in May 1968 and the minimum was 0 in May 1973.

The 760 hailstreaks and their related data collected over a 7-year period permitted various meaningful analyses. Table 7 contains information on hailstone size frequency for 1967-1968, 1971-1972, 1973-1974, and an average for the years 1967-1974. It is based on measurements of 273,408 hailstones. As can be seen, 92% of the hailstones were ⩽ 1/4 inch. The average number

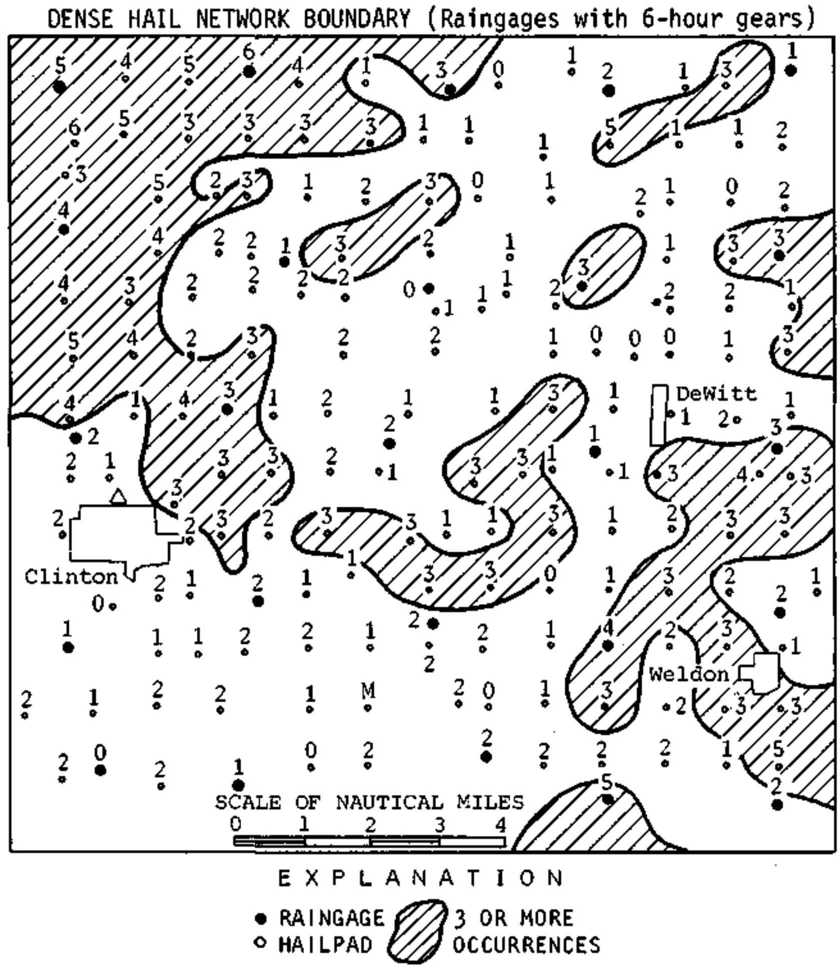


Figure 29. Pattern based on point hail occurrences in 1973

Table 6. Number of Hailstreaks, Based on Hailpad Network

	Network area (mi²)	*Number of sensors*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*May-Sep total*
1967	400	49	ND*	48	36	34	31	6	15	122
1968	725	196	ND	ND	154	33	37	13	27	264
1969	725	196	ND	ND	27	4	20	12	5	68
1970			*No measurements collected*							
1971	625	232	ND	ND	52	26	11	14	17	120
1972	150	176	17	8	1	14	10	20	15	60
1973	150	176	16	12	0	44	10	6	0	60
1974	625	232	0	28	ND	ND	ND	ND	ND	ND
Average			11.0	24.0	45.0	25.8	19.8	11.8	13.2	115.6
Maximum			17	48	154	44	37	20	27	264
Minimum			0	8	0	4	10	6	0	60

*ND = no data

Table 7. Hailstone Size Data for 1967-1974

	Stone diameter (inches)						
	1/8	1/4	1/2	3/4	1	>1	Total
Percent of total							
1967-1968	77	11	9	2	0.8	0.2	100
1971-1972	81	11	7	0.9	0.1	0.04	100
1973-1974	85	11	3	0.32	0.05	0.008	100
Average 1967-1974	81	11	6.4	1.2	0.32	0.08	100
Average number of stones per hailfall							
1967-1968	100	14	12	2	1	0	129
1971-1972	79	11	7	0.9	0.1	0.04	98
1973-1974	105	14	4	0.4	0.1	0.01	123
Average 1967-1974	94.6	13.0	7.7	1.1	0.4	0.02	117
Median number of stones per hailfall							
1967-1968	21	2	1	0	0	0	24
1971-1972	24	3	0	0	0	0	27
1973-1974	22	5	0	0	0	0	27
Median 1967-1974	22	3	0	0	0	0	25
Percent of hailfalls when 1 stone of given size occurred							
1967-1968	94	72	54	24	13	8	
1971-1972	100	100	88	59	38	6	
1973-1974	100	100	89	52	37	15	
Average 1967-1974	99	90.6	77.0	45.0	29.3	9.7	
Maximum number of stones per hailfall (on 1 ft²)							
1967-1968	1240	202	258	108	25	11	1844
1971-1972	1146	186	215	56	17	7	1627
1973-1974	1454	251	131	34	5	2	1877
Average 1967-1974	1280.0	213.0	201.3	66.0	15.7	6.7	1783
Percent of hailfalls when given size was maximum size (on 1 ft²)							
1967-1968	22	24	30	11	6	7	
1971-1972	21	25	38	11	4	1	
1973-1974	0	11	37	15	22	15	
Average 1967-1974	14.3	20.0	35.0	12.3	10.7	7.7	

of stones per square foot was 117 per hailfall and the median number was 25. When hail occurred, small stones almost always fell. Stones greater than 1/2 inch occurred only 45% of the time and stones greater than 1 inch occurred less than 10% of the time. The maximum number of stones for a hailfall was 1877. Sixty-nine percent of the hailfalls had a maximum stone size of 1/2 inch or less.

Table 8 contains statistics on the 760 hailstreaks from 1967-1974. The total number is based on hailstreaks from the opening of the season until the network closed, whereas table 6 includes only those through September.

The areal extent information presented is based on hailstreaks with 3 or more points defining the streak. The data reveal that one-third of the streaks were between 4 and 7.9 mi^2, and 60% were less than 7.9 mi^2. The median size was 6.1 mi^2. Forty percent of the streaks had a mean energy $\leq$ 0.0100 ft-lb/ft^2. The average and median energies were 0.2032 and 0.0400 ft-lb/ft^2 , respectively.

Table 9 contains additional hailstreak information that pertains to duration, direction of motion, speed, length, and width. Forty percent were 6 to 11 minutes in duration, 61% moved from 240 to 280 degrees, 47% moved with a speed of 11 to 30 mi/hr, 63% were 0.6 to 1.5 miles wide, and 42% were 3 to *6.9* miles long.

Table 10 contains information on the relationship between the hail and associated rainfall.

Table 8. Hailstreaks in 1967-1974

	1967	1968	1971	1972	1973	1974	1967-1974	% of total
Number of hailstreaks								
Defined by ≥ 1 point	170	264	120	85	93	28	760	100
Defined by ≥ 3 points	77	100	21	30	34	10	272	36
Number of hailstreaks (defined by ≥ 3 points) for each areal extent (in mi²) category:								
0.1–3.9	24	12	9	13	15	3	76	27.9
4.0–7.9	22	37	7	10	12	0	88	32.3
8.0–11.9	10	19	3	2	2	0	36	13.2
12.0–15.9	7	14	0	2	2	0	25	9.1
≥ 16.0	14	18	2	3	3	7	47	17.5
Total	77	100	21	30	34	10	272	
Average hailstreak size	9.7	21.6	6.8	6.9	6.2	84.1	22.5	
Median hailstreak size	7.2	9.7	5.4	4.4	5.0	108.6	6.1	
Maximum hailstreak size	40.3	788.0	28.3	28.6	21.7	172.6	788.0	
Minimum hailstreak size	0.9	1.8	1.0	1.5	1.3	2.3	0.9	
Number of hailstreaks for each mean energy (in ft-lb/ft²) category:								
.0001–.0005	29	10	0	7	2	0	48	21.4
.0006–.0100	21	17	2	4	4	1	49	21.9
.0101–.1000	20	22	6	14	16	3	81	36.2
≥ .1000	7	10	11	7	9	2	46	20.5
Total	77	59	19	32	31	6	224	
Average energy	.2575	.1754	.3389	.0855	.1820	.1799	.2032	
Median energy	.0049	.0112	.1318	.0212	.0567	.0718	.0400	
Maximum energy	12.6559	6.1875	1.7619	.6751	1.6993	.5574	12.6559	
Minimum energy	.0001	.0001	.0022	0	0	.0045	0	

It is based on 1967, 1968, 1971, and 1972 data when the entire raingage network was operational and rain and hail information could be obtained for an entire raincell associated with the hailstreak. Hail occurred within 10 minutes of the rain initiation in 77% of the cases. The maximum point rainfall within a hailstreak was less than 0.40 inch about 60% of the time. However, the maximum rainfall in the raincell associated with the hailstreak was greater than 0.40 inch about 55% of the time.

Table 11 contains hailstreak statistics stratified by four synoptic classifications. It is a combination of data collected in 1967-1968 and 1971-1972. Air mass conditions provided the greatest number of hailstreaks, but cold front (includes squall lines) systems provided the most hailstreaks per hail-producing system. Cold front hailstreaks had the longest duration and largest area. The mean energies and stone sizes were similar for all three of the synoptic conditions. Hailstreak speeds and direction of movement were quite similar. The maximum number of stones was larger for lows, waves, and troughs. The point hailfall durations were similar for all conditions except cold front hailstreaks. Cold front hailstreaks had the greatest time difference between rain and hail initiations and they also were associated with the greatest amount of rainfall.

Micro-Network Study

A primary need for information on surface sampling errors for hail over areas of less than 1 mi^2 led to a 1973 Survey-proposed project as part of NHRE (Morgan and Towery, 1974). A dense network of 114 hail sensors was installed and operated by the Survey during May-July 1973 in Nebraska under NCAR sponsorship, and data on 3 hailfalls were obtained. This sample was too small to serve the statistical needs, and NHRE support was terminated in 1974.

Table 9. Hailstreak Characteristics for 1967-1974
Percentages for Various Parameters

	Duration of hailstreak, minutes								
	0-1	*2-3*	*4-5*	*6-7*	*8-9*	*10-11*	*12-13*	*14-15*	*>15*
1967-1968	1.6	4.3	8.9	14.7	13.2	12.1	12.1	6.3	26.8
1971-1972	0	3.7	3.7	14.8	14.8	7.4	14.8	3.7	37.0
1973-1974									
1967-1972	1.1	4.3	7.7	14.7	13.6	11.0	12.8	5.7	29.1

	Direction of motion, degrees							
	200-219	*220-239*	*240-259*	*260-279*	*280-299*	*300-319*	*320-339*	*340-359*
1967-1968	1.5	8.1	28.6	39.2	15.0	3.3	3.9	0.4
1971-1972	0	16.2	25.0	43.7	15.0	0	1.0	0
1973-1974	1.7	27.3	20.7	25.6	12.4	9.1	3.2	0
1967-1974	1.2	14.3	25.5	36.0	14.1	4.1	4.6	0.2

	Speed of hailstreaks, mi/hr						
	1-10	*11-20*	*21-30*	*31-40*	*41-50*	*51-60*	*>60*
1967-1968	1.6	15.6	32.9	22.0	18.8	4.8	4.3
1971-1972	0	14.8	25.9	37.0	22.2	0	0
1973-1974							
1967-1972	1.1	15.5	31.4	25.4	19.5	3.7	3.4

	Maximum hailstreak width, miles							
	0.1-0.5	*0.6-1.0*	*1.1-1.5*	*1.6-2.0*	*2.1-2.5*	*2.6-3.0*	*3.1-3.5*	*>3.5*
1967-1968	0.4	37.1	37.9	9.7	2.6	4.0	2.6	5.7
1971-1972	2.4	30.1	21.7	22.9	16.9	1.2	2.4	2.4
1973-1974	37.2	33.1	11.6	3.3	3.3	5.0	0	6.5
1967-1974	10.1	35.2	28.4	10.1	5.3	3.8	1.9	5.2

	Maximum hailstreak length, miles							
	1.0-2.9	*3.0-4.9*	*5.0-6.9*	*7.0-8.9*	*9.0-10.9*	*11.0-12.9*	*13.0-14.9*	*>15.0*
1967-1968	12.6	16.6	26.5	18.8	9.0	8.5	4.0	4.0
1971-1972	38.3	25.9	24.7	3.7	1.2	4.9	1.2	0
1973-1974	59.5	24.0	8.3	0.8	2.5	0	0	4.9
1967-1974	28.8	20.0	21.7	11.8	5.9	5.7	2.5	3.6

Table 10. Hailstreak and Associated Rainfall Data for 1967-1968 and 1971-1972
(478 Hailstreaks)

	Time interval between point beginnings of rain and hail within hailstreaks, minutes							
	0	*1-10*	*11-20*	*21-30*	*31-40*	*41-50*	*51-60*	*>60*
Least difference (%)	36.0	41.0	11.7	5.8	1.9	1.7	0.2	1.7
Greatest difference (%)	25.9	47.4	13.4	6.3	1.9	2.1	1.3	1.7

	1967-1968 and 1971 (383 hailstreaks) maximum point rainfall, inches					
	.01-.10	*.11-.20*	*.21-.40*	*.41-.60*	*.61-.80*	*>.81*
In hailstreak (%)	23.2	17.5	20.9	14.6	7.1	16.7
In associated raincells (%)	9.4	15.7	19.6	13.8	9.9	31.6

	Average point rainfall in hailstreaks, inches						
	.01-1.0	*.11-.20*	*.21-.30*	*.31-.40*	*.41-.50*	*.51-.60*	*>.60*
Percent of total streaks	30.8	14.6	11.5	11.5	8.6	3.4	19.6

Table 11. Hailstreak Characteristics for Various Weather Conditions

	Cold front	*Air mass*	*Lows, waves, and troughs*	*Stationary and warm fronts*
Number of hail-producing systems	9	28	13	26
Number of hailstreaks	165	231	106	157
Average streaks per system	19.4	8.3	11.0	6.9
Average per condition:				
Duration, *min*	14.5	10.2	8.5	11.4
Area, mi^2	11.8	4.9	3.5	3.6
Mean energy, $ft\text{-}lb/ft^2$	.2154	.1656	.0254	.1735
Speed, *mi/hr*	29.1	34.3	30.5	31.2
Direction, *degrees*	261	259	269	258
Maximum stone diameter, *inch*	0.54	0.43	0.30	0.46
Maximum number of stones/ft^2	117	111	311	250
Point hailfall duration, *min*	12.1	2.9	2.8	3.0
Time difference (point) between rain and hail initiations, *min*				
greatest	16.2	8.1	13.4	8.9
least	7.1	2.4	2.2	1.5
Hailstreak mean rainfall, *inches*	0.82	0.42	0.17	0.21

Table 12. Hail Dates and Distribution of Hail on Micro-Network in 1974

Date	*Number of locations with hail*
3 April	112 (6 not installed)
12 April	112 (6 not installed)
21 April	118
6 June	4
19 June	23
22 June	66
2 August	7

However, this project was re-instated in Illinois under state sponsorship in 1974. This micro-network (figure 27) was installed in March 1974 on the Agronomy South Farm of the University of Illinois, and closed on 30 September 1974. This installation consisted of 118 hailpads located 275 feet apart in a 0.32 mi^2 area. This locale also offered a unique opportunity to compare various hailfall parameters with degree and type of losses to a variety of crops. Unfortunately, no crop damaging hail fell in 1974. The proximity of this network to the DESH analytical center and operational headquarters also allowed for rapid and easy servicing, a problem in Nebraska. Furthermore, the point average hail frequency in Illinois for the March-October period equals that in the NHRE network.

A total of seven hailstorms occurred in this network in 1974. The hail dates and the number of hailpad locations with hail appear in table 12.

Figure 30 shows the total number of occurrences of hail at each location. The maximum number of occurrences was 6 and the minimum was 1. The average number of occurrences was 3.4.

The installation of very dense networks (Changnon, 1973b; Morgan and Towery, 1975) demonstrated the extreme small scale variability of hail. This was demonstrated again in the storm data collected in 1974. For instance, figure 31 shows the number of measurable stones per square foot in one storm. The number ranges from less than 10 to over 35 across distances of 600 feet. However, there is a general trend of low to high from the northwest to the southeast part of the network.

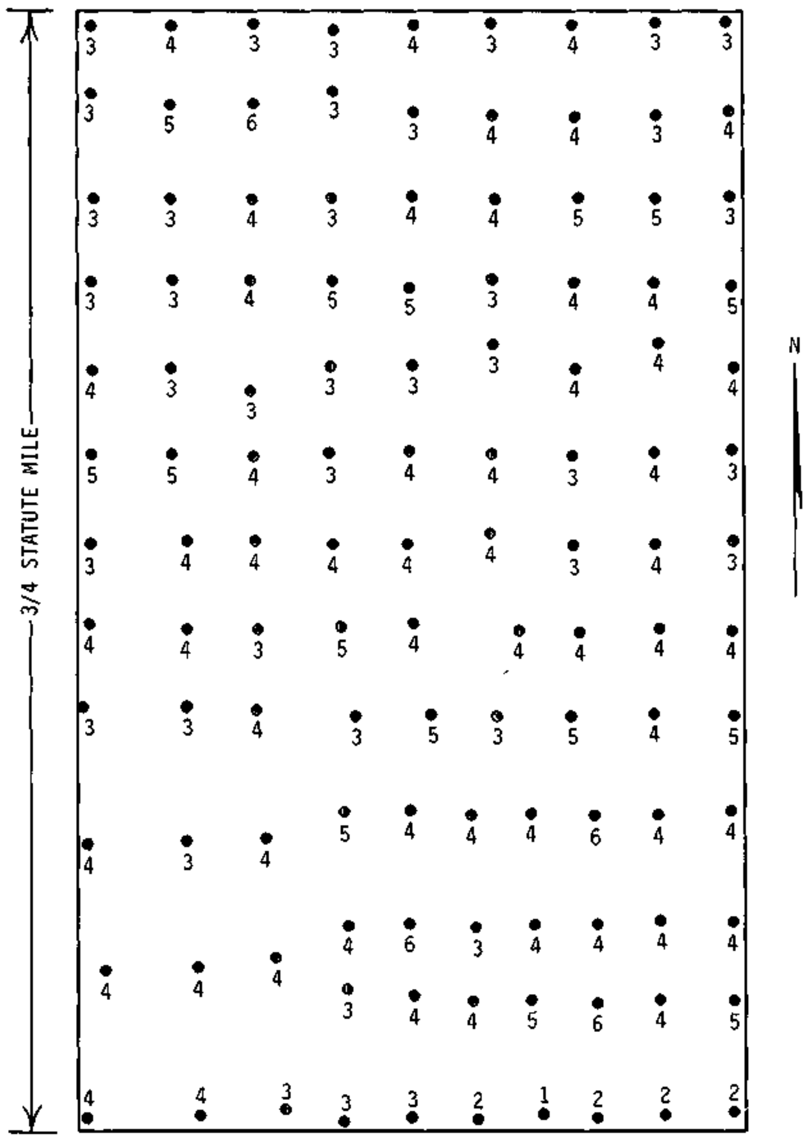


Figure 30. Total number of hail occurrences (April-October) on micro-network, 1974

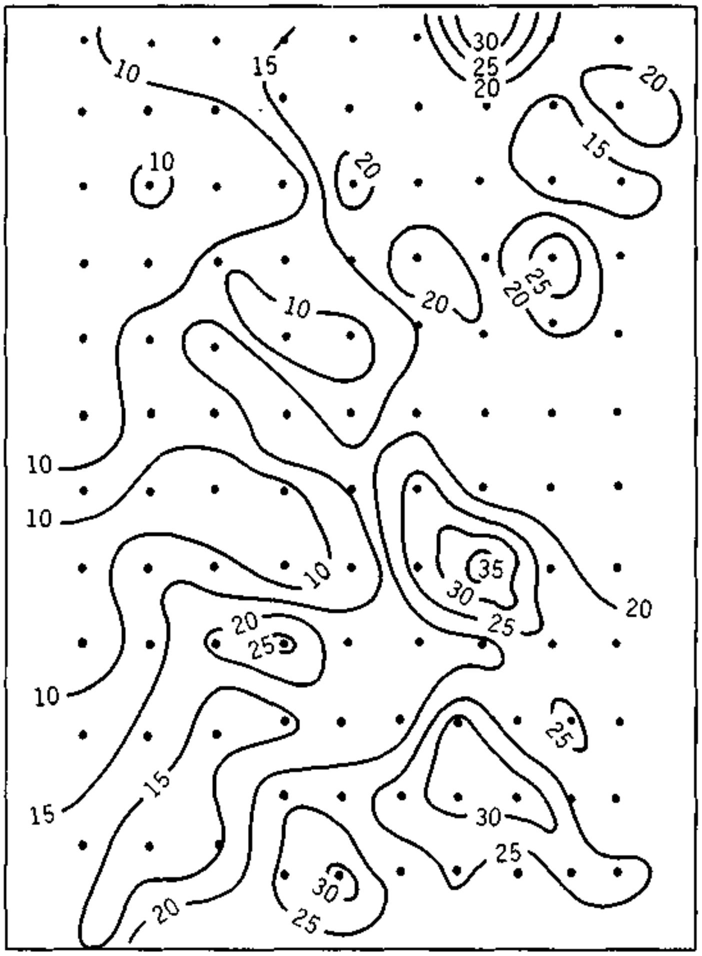


Figure 31. Number of measurable stones on micro-network, storm of 3 April 1974

SYNOPTIC CLIMATOLOGY OF HAIL IN ILLINOIS

Synoptic conditions during all summer precipitation events in St. Louis were typed by Survey analysts as part of METROMEX research (Vogel, 1974). Knowledge of these frequencies is relevant to the use of the radar information in operations. The following definitions were used to classify 177 rain periods:

Squall Systems — Definite trigger mechanism is evident. The convective activity associated with this type of system is well organized and generally intense. The squall system is marked by either a well-formed *line* organization or an *area* which has a well-defined meso-system associated with it (cold dome, dry air aloft, meso-pressure system, etc.).

Fronts — Precipitation which is produced within 75 miles of a front (cold, stationary, or warm) when there is no evidence of it being associated with a squall system that might be moving or initiating in advance of the front.

Low — A large-scale low pressure center located so near to the network that it was not possible to associate the precipitation with any frontal or mesoscale structure.

Pre-frontal — Precipitation between 75 and 150 miles ahead of a front and not be to confused with squall lines or areas in advance of a front.

Post-frontal — Precipitation 75-150 miles behind a front — most often associated with a cold front.

Air Mass — No large-scale synoptic causes. Convection is typically scattered or widely scattered and is generally weak. No area can be discerned which moves along in a well-organized manner.

Thirty-nine rain periods had hailstorms. Hail was most often associated with squall lines (table 13) with 44% of all hail cases with squall lines, and another 21% with squall areas. Cold fronts and warm fronts produced 25% of the hail cases. Together these 4 types accounted for 90% of the hail-producing periods.

Table 13. Frequency of Hail for Various Synoptic Types

Type	*Percent of the 39 hail-producing periods*	*Number of hail cases as a percent of total periods*
Squall line	44	61
Squall area	21	19
Cold front	15	32
Warm front	10	57
Low	5	50
Stationary front	3	9
Air mass	3	2
Post-cold front	0	0
Post-stationary front	0	0
Pre-cold front	0	0
Pre-warm front	0	0

The hail-producing squall line events accounted for 61% of the 28 squall lines associated with rain events (table 13). Table 13 also shows the hail production frequencies of the other synoptic types. Only two other types (warm fronts and lows) have hail probabilities greater than 50% and neither of these is based on a sufficient sample size to be considered reliable. However, the squall area (hail probability of 19%), cold front (32%), and air mass (2%) frequencies rest on sample sizes > 20 and appear to be reliable. A combination of squall lines and areas should be considered since it is not always easy to distinguish between the two when forecasting, particularly for longer periods and before echoes are present. The hail frequency with squall systems is 36% (25 of 70 events) which is the highest frequency of the types with reliable sample sizes.

HAIL AND SEVERE WEATHER CALENDAR

In order to perform forecasting and radar studies, and to examine certain unavailable climatic factors, it was necessary to obtain a basic weather calendar. Such a calendar was developed for the years 1967-1973, and for the March through October period.

Data and Evaluation of Data Sources

Several types of data from several measurement scales were used in making up the calendar and it is important to understand the limitations of each type in using the results in further applications.

The basic area to which the calendar applies (see figure 37) is a broad strip through the central part of Illinois. The area of 26,500 mi^2 contains 42 weather stations, for an average area per station of 630 mi^2.

Insurance data and cooperative hail observer data were available at varying strengths (see table 3). Data from several hail-rain networks and their associated dense networks were available (table 3). Severe weather data came only from *Storm Data,* a NOAA publication (Changnon, 1975c). This gave reports of excessive rains, tornadoes, funnel clouds, hail, and severe wind events. Heavy rain days were extracted from the actual station rainfall data and were defined as days with point rainfall accumulations of 4 inches or more.

The calendar which resulted from these data covered each day of the March through October (growing season) period for 1967-1973. It contains separate entries for each data source, allowing the user to make choices based on his evaluation of a given source. Figure 32 shows a sample of the calendar for the month of May 1968.

The hail, thunder, and rain portions of the calendar have been digitized and stored on magnetic tape for easy access. This can be made available to interested researchers on request. The calendar will not be reproduced here, but some aspects of it must be covered as background to DESH.

Figure 33 shows one of the more difficult problems in classifying days as hail or non-hail for forecasting studies or for climatological purposes. Here, the average monthly number of hail days is shown both with and without the use of insurance data. There is a clear inflation of the hail days, as indicated by the insurance data, during the months when the crops exist and are most vulnerable. This is largely a real effect, since the insurance data are the equivalent of a very fine scale network. This effect would be even more pronounced if the insurance data had been available from the entire 26,500 mi^2 area. As it is, the data from only a 5- to 29-county sub-area (out of 48

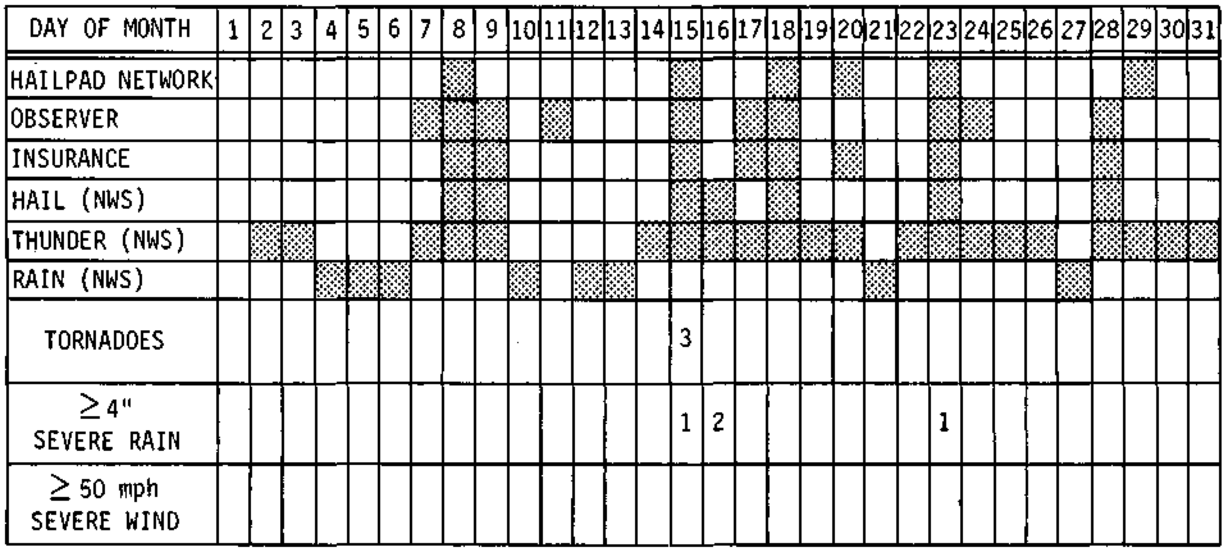


Figure 32. Severe weather calendar for May 1968

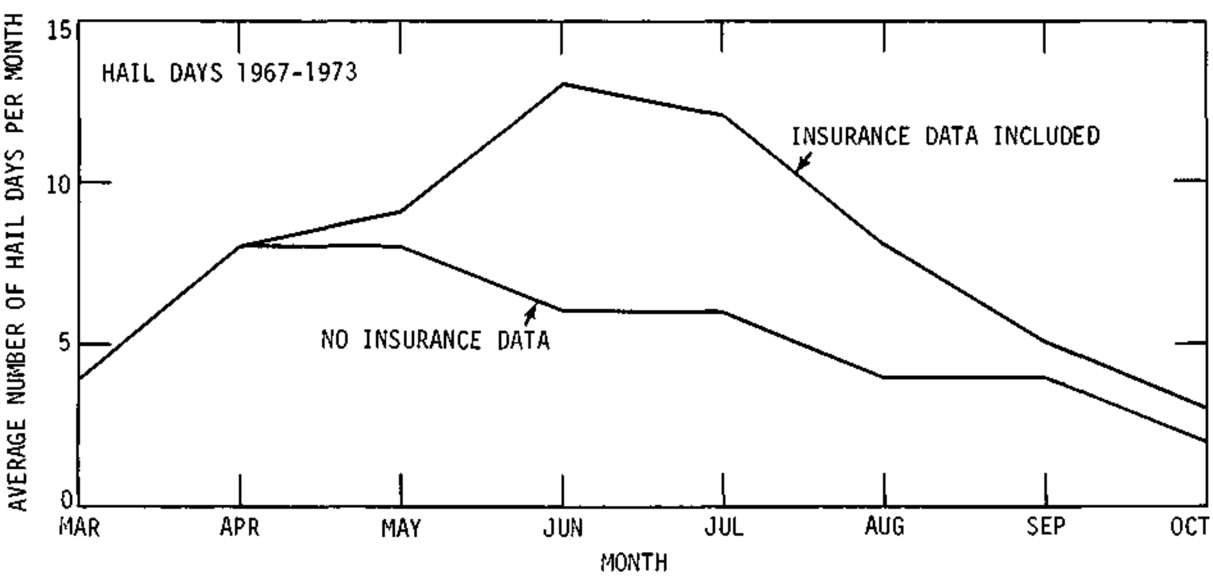


Figure 33. Average number of hail days per month with and without insurance loss data

possible counties) have a notable effect on the totals. However, there is an artificial inflation of unknown extent, due to the erroneous reporting of the date of hail damage by the farmers and/or crop insurance adjusters. A single-day hail event may be reported on two or three different days. Some cases of hail days detected only by insurance data turned out to be days with no rain and no radar echoes present over the study area.

We chose to eliminate any days when only the insurance data indicated hail. Certainly, some such days are true hail days, and this is unfortunate. A further unmanageable data problem is that the non-hail day sample is surely contaminated with some unknown number of undetected hail days. *In carrying out a hail prevention experiment, it will be necessary to ask the insurance field management personnel to ensure that all due attention be given to the reporting of dates of hail damage.*

Coincidence of Hail and Severe Weather

The 56-month period covered by the calendar included 42 days with tornadoes, 1318 thunder and/or rain days, and 433 hail days. Hail occurred on 33% of the thunder-rain days, and on 52% of thunder-only (no rain) days.

Of the 42 tornado days, 30 were hail days and 12 were not. The 30 tornado days with hail are 6.9% of all hail days.

There were 40 severe rain (> 4.0 inch) days in the 56 months. Thirty of these were hail days, amounting to 75% of severe rain days. Thirty hail and heavy rain days would represent 6.9% of all hail days. Six of the severe rain days were also tornado days. Thus, 54 days with hail had tornadoes or severe rains as well. This raises the percentage of hail days associated with severe weather to at least 18%.

As expected, the tabulations of severe wind events (straight winds only) did not yield reliable estimates. This is a severe weather phenomenon which is nearly as elusive as hail occurrence, because of the unsatisfactory reporting criteria and the basic scale of the events.

OBJECTIVE WEATHER ANALYSIS

Objective techniques to treat a wide range of synoptic, sub-synoptic, and mesoscale problems have been studied as an integral part of DESH (Changnon et al., 1975). These efforts look toward the use of synoptic weather parameters, both in seeding-evaluation research [as recommended for the National Hail Research Experiment by Schickedanz and Changnon (1971)] and in the operations of a field hail-prevention (or precipitation management) experiment.

A successful hailstorm forecast depends upon an ability *a)* to identify hail-prone conditions, and *b)* to provide suitably accurate thunderstorm forecasts. Definite criteria must be established to identify hail-prone conditions. Although tornado-producing synoptic conditions have been described (Miller, 1967; NSSFC, 1956), they do not suffice since severe hailstorms often occur with non-tornadic systems. DESH included a concerted search for parameters on the synoptic and sub-synoptic scales to help define hail-prone conditions in the Midwest. This included the study of various stability indices and hail forecast parameters derived from upper air and surface data coupled with records of severe weather events in the calendar.

The thunderstorm forecast needed should address the severity, time of occurrence, and location of thunderstorms. Wise and economically sound operations of a hail suppression experiment demand proficiency at predicting the occurrence time far enough in advance to allow scheduling of aircraft and field operations. The location of thunderstorms must be.predicted accurately so aircraft vectoring and fuel waste will be minimized. Radar-hail echoes can be tracked and their locations forecast over short time periods (usually 2 hours or less), but it is clear that the radar detection must be supported by forecast techniques, based on meteorological observations, which can provide information about onset times and intensity trends more than 2 hours before the events.

Dynamic Destabilization as a Convective Release Mechanism

The analysis proceeded with the view that differential advection of thermodynamic properties, diabatic heating, and dynamic lifting may act in any combination to destabilize the lower troposphere prior to the onset of convection. When convective instability is released through insolational heating and subsequent destabilization within the sub-cloud layer, maximum activity occurs during hours of maximum temperature. In the absence of localized destabilization or triggering mechanisms, there should occur a near random distribution of showers within the favorable air mass. From morning soundings, estimates of afternoon shower intensity and seedability can be made with cloud models subject to a number of assumptions.

However, it is also well known that convection seldom occurs completely randomly. Lines, complexes, and groups of convective showers with high coverage percentages may occur adjacent to areas completely shower free, all within essentially the same air mass. This tendency for mesoscale convective organization, particularly during instances of severe weather outbreaks, is especially evident in the upper Midwest even during midsummer when synoptic scale systems are quite weak.

Convergence and dynamic lift within the low-level moist layers deepen the moist layers and destabilize the air mass making it locally more favorable for convection. Conversely, divergent zones would tend to become less favorable for convection. Dynamic lift is operative at any time, whereas diabatic destabilization is effective during daytime heating.

A theoretical statement describing the local change in stability can be derived from the First Law of Thermodynamics. The local temperature tendency is given by:

$$\frac{\partial T}{\partial t} = \frac{1}{c_p}\frac{dH}{dt} - \vec{V} \cdot \nabla T - w(\gamma_d - \gamma) \qquad (3)$$

where $\gamma_d = g/c_p$ and $\gamma = -\partial T/\partial z$.

Differentiating with respect to z yields the stability tendency equation:

$$\frac{\partial \gamma}{\partial t} = \frac{1}{c_p}\frac{\partial}{\partial z}\frac{dH}{dt} - \vec{V} \cdot \nabla_H \gamma + \frac{\partial \vec{V}}{\partial z} \cdot \nabla_H T + w\frac{\partial}{\partial z}(\gamma_d - \gamma) + (\gamma_d - \gamma)\frac{\partial w}{\partial z} \qquad (4)$$

The first term on the right represents the effect of differential diabatic heating in the vertical. This term contributes to destabilization through *a)* surface heating which increases the net energy in the lowest levels and initiates convective overturning, *b)* evaporational cooling from precipitating mid-level clouds that are advected over convectively unstable air (Miller, 1967), and *c)* latent heat released when moist air is brought to its condensation level.

The second term contributes to $\partial\gamma/\partial t$ through the change of lapse rate by horizontal advection and is roughly proportional to the vertical differential of the thermal wind. If $\vec{V}$ is geostrophic, the third term tends to vanish. Haltiner and Martin (1957) suggest that in any case the term is small and may be neglected.

The fourth term gives the vertical advection of lapse rate. Vertical stretching gives rise to the last term. It gives no contribution to $\partial\gamma/\partial t$ where $\gamma = \gamma d$ (well mixed sub-cloud layer) or for layers where $V \cdot \vec{V} = 0$. We propose a vertical distribution of divergence and vertical velocity for Illinois much like that in figure 34. Destabilization effects of vertical stretching are confined below 700 mb (10,000 feet) and above the mixing layer. With this model the last term contributes most toward destabilization when stable layers are found within convergent layers.

The success of the DESH thunderstorm prediction model rests upon *a)* our ability to evaluate with acceptable accuracy the terms on the right hand side of equation 4 and *b)* the extent to which fields of stability at one time are predictive of the location and approximate time of precipitating convective outbreaks at a later time. Diabatic heating rates can be obtained from cloudiness predictions and daily insolation tables. The second term can be estimated qualitatively from a single sounding or approximated quantitatively by the use of the three upper air observing sites arrayed as vertices of a triangle. The last two terms rely on methods for determining sub-synoptic scale and mesoscale vertical velocities.

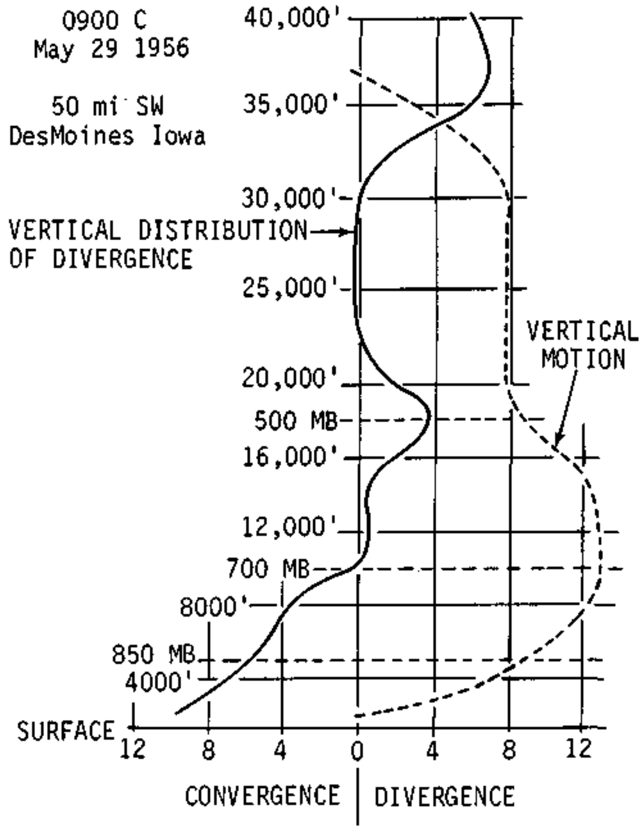


Figure 34. An example of the vertical distribution of divergence (times 10^{-5} sec^{-1}) and vertical velocity (cm sec^{-1}) (Divergence and vertical velocity are positive to the right of the zero ordinate) *[From House, 1963]*

Calculation of Mesoscale Vertical Velocities

Upper midwestern thunderstorm activity often results from complex interactions between motion scales that concentrate latent energy and destabilize the troposphere prior to the onset of convection. Thunderstorm scales have never been adequately described; however, it is possible to isolate synoptic scale influences and, to a limited extent, mesoscale effects provided the observations are of sufficient accuracy, resolution, and frequency. Further, convergence and dynamic lift accompany upper level short waves which, in summer, may have wavelengths so short and energies so small that the disturbances cannot be identified from upper level charts.

Lift must be frequently monitored to update changes in stability that can occur over a relatively short period of time. Low-level inversions have been destroyed over a period of time from 1 to 3 hours in advance of squall lines (Long, 1963). Hudson (1971) found good correlation between analyzed horizontal moisture convergence and convective cloud formation up to 3 hours after the initial observation time for a case study over the Midwest.

Other investigations found convergence-precipitation lag times of only 0.5 hours for northeastern U.S. frontal bands (Copeland and Hexter, 1957) and south Florida convective rainfall (Fernandez-Partages, 1973). However, identifiable zones of convergence preceded convection by up to 5 hours for several northeast Colorado thunder days (Anderson and Uccellini, 1974).

Estimates of vertical motion can be obtained from surface fields of horizontal wind, pressure, and pressure tendency. Triggering mechanisms such as fronts, trough lines, disturbances aloft, etc. can be monitored to follow areas most likely to experience lift. The supposition here is that vertically integrated effects of sub-synoptic and mesoscale phenomena are detectable in the surface observations, both in space and time. *This is not to say that these systems can be accurately described by the surface observations, but just that their presence can be detected in them.*

The use of objective computer techniques to plot, analyze, and display meteorological data amplifies greatly the amount and quality of information the scientist or the forecaster-analyst can examine and utilize in an experiment. It does a quicker and certainly cheaper job of presenting the simple fields he is trained to analyze by hand (fields such as temperature, moisture, cloud cover, pressure, wind streamlines, etc.). More importantly, it makes possible routine examination of derived fields (such as derivatives and fluxes) which are otherwise not available.

Noise due to poor instrument exposure, poor instrument calibration, errors in observation and transmission, channeling by local topography, and effects of subscale phenomena is expected to contaminate surface observations. It may obscure important mesoscale disturbances, especially in summer when wind and pressure regimes are extremely weak. Further, objective extrapolation tends to place axes of convergence and divergence midway between stations causing errors in interpreting these fields. These problems can be minimized, but not eliminated, by combined multi-field analyses.

An example of multi-field objective meso-analysis for 12 August 1973 is presented in figure 35. The five fields presented are wind streamlines, surface pressure, temperature, divergence, and wet bulb potential temperature. Locations of pressure centers and suspected first-order discontinuities have been adjusted chronologically with the aid of the original station plots. Temperature and wet bulb potential temperature fields proved ideal for identifying the frontal zone and cool surges at the leading edges of the squall meso-systems. Streamlines and pressure patterns were most useful in locating trough lines and pressure centers. Stippled areas identify 'major convective areas' where echo tops exceeded 40,000 feet as deduced from hourly radar maps.

Fifteen assorted surface fields including tendencies, frontogenetial effects, and advective quantities were included in the effort to identify patterns related to convective outbreaks. Endlich and Mancuso (1967) undertook a similar study to identify environmental conditions associated with severe thunderstorms and tornadoes. Although tornadoes, hailstorms, and windstorms occurred on 12 August 1973, the weak midsummer, sub-synoptic and mesoscale patterns were not as well organized as severe weather producing springtime patterns and the anticipated correlations could not be confidently constructed from a single case study.

Vertical velocities were estimated hourly from:

$$w_1 = \overline{\nabla} \cdot \vec{V}\, \Delta z \qquad (5)$$

$$w_2 = 0.5 \gamma \nabla^2 p\, \Delta z\, \Delta t \qquad (6)$$

$$w_3 = 0.5 \gamma \nabla^2 (\partial p / \partial t)\, \Delta z\, (\Delta t)^2 \qquad (7)$$

where γ is the specific volume.

Equation 5 derives from the mass continuity equation and, if density variations are neglected, gives the vertical velocity due to an average divergence in a column of depth Δz. Inspection of the divergence theorem (Hess, 1959) reveals that low centers and pressure troughs should be preferred areas for upward vertical motion. Equation 6 expresses the predicted average vertical velocity over a 1-hour period (At) at the top of a column of depth Δz as deduced from the laplacian of the surface pressure field.

Equation 7 is also predictive and gives vertical velocity from estimates of the divergence acceleration. If in regions of convergence the pressure is rising locally, then mass is not being re-

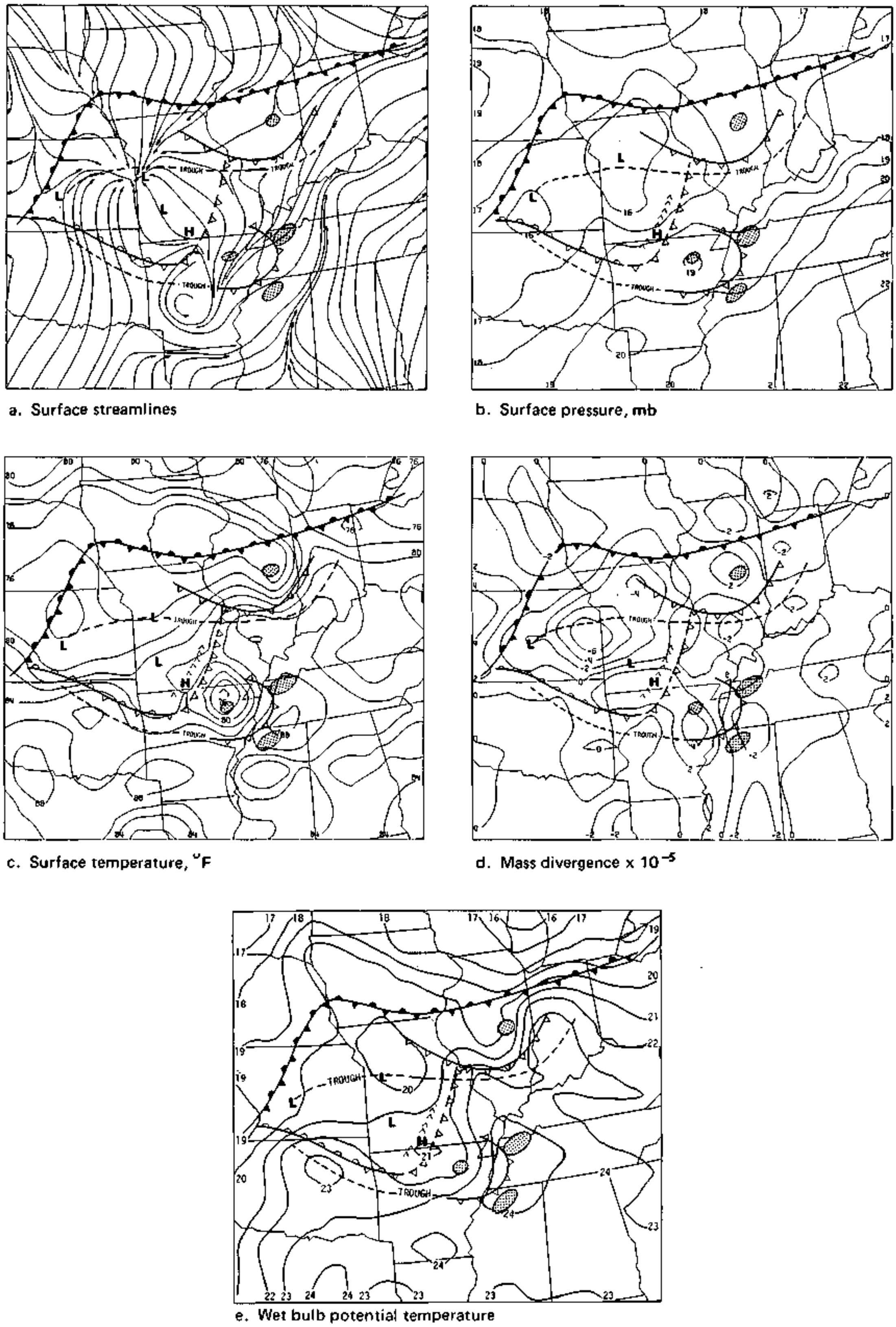


Figure 35. Multi-field objective mesoanalysis for 12 August I973, 1100 CDT

moved from an air column as rapidly as it is being added from below. This condition suggests that a surface convergence system has lost or will soon lose its support aloft and there will result a rapid decrease in precipitation probability in the affected air mass. Conversely, pressure falls over convergent regions imply an increase in support aloft and an increase in the precipitation probability within the affected air mass.

The surface fields were analyzed independently with the exponential weighting function described by Barnes (1973) but without the time-to-space conversion option. Weighting parameters were chosen so that, in two passes through the data, 90% of the variance of the 2Ax (Nyquist) wave was returned to the analyzed fields. Of course the response functions (from which the parameters were determined) were derived assuming a continuum of information. Further, if the data are not evenly distributed, phase changes and increased noise level will contaminate the analyzed fields.

In practice it was found that the interpolated pressure and pressure tendency fields were not sufficiently free from noise to allow meaningful curvature computations. Further, gravity waves were consistently present throughout the 18-hour period of study and had amplitudes large-enough to invalidate the assumptions inherent in deriving equation 7.

The present vertical velocity model proposes that the lower troposphere is destabilized over a period of time prior to the onset of convection. We combined convergence, pressure, and pressure tendency over 5-hour sliding periods to compute a quantity called cumulative lift. The 5-hour period was chosen as representative of the residence time of a typical mesosystem between stations with average separation of the present airways network. Studies that have found mesoscale destabilization occurring up to 3 hours before convection have already been mentioned. Bonner et al. (1971) showed high linear correlation between intense convection and the forecast 12-hour net surface convergence for a 51-day sample.

Cumulative lift (CL) fields should have several applications. If thermodynamic structures are isotropic, thunderstorms should most likely form within CL zones if they have not developed already. If thunderstorms are present outside CL zones, but will enter CL zones within the next several hours, increases in areal coverage and intensity should be expected. Similarly, thunder activity moving out of CL zones is expected to decrease in areal coverage and intensity.

The convergence is computed from the surface horizontal wind field and, with the use of equation 5, is integrated through a 1-km deep layer, assuming constant convergence, to find the vertical velocity at the top of the layer. Obviously, this estimate would not return the magnitude of the vertical velocity at the top of the convergence layer given in figure 34. Also, the calculated convergence should be less than the actual mesoscale convergence because the convergence is inversely proportional to the station separation which is too large to adequately resolve mesoscale convergence patterns. Then the weighting constant used in the objective interpolation scheme acts to filter smaller scale convergence from the gridded fields. Thus, there is no way to determine the 'true' vertical velocities. Consequently, the model vertical velocity will be determined from a regression between the estimated vertical velocity, the time and location of shower occurrences, and the remaining terms of equation 4.

Recognizing that significant convergence and lift often occur along trough lines, pressure is melded into the analysis through a pressure trough analysis. Trough lines and low centers are objectively identified and vertical velocities along these axes are computed from equation 6 by replacing $\nabla^2 p$ with $\partial^2 p/\partial n^2$ where n is directed normal to the trough axis. Then, to permit smooth meshing with convergence fields, grid points immediately adjacent to the trough axes are accorded vertical velocities equal to one-half the adjacent trough axis vertical velocity.

The cumulative lift is formed by multiplying each hourly vertical velocity estimate by 1 hour and summing over 5 hours. This result is modified by replacing the vertical velocity (convergence) by the vertical velocity (pressure) whenever the latter is greater than zero and greater than the former.

Then pressure tendency fields are used to tune the cumulative lift. These fields are noisy on an hourly basis but, when averaged over the sliding 5-hour period, give estimates of sub-synoptic scale pressure tendency with reasonable continuity. This analysis is built into the cumulative lift by empirically increasing or decreasing the CL according to the sign of the pressure tendency and by an amount proportional to its magnitude. Unwanted diurnal pressure tendencies are eliminated by subtracting the average pressure tendency from the pressure tendency fields before the CL corrections are made.

A quantitative expression for the cumulative lift is:

$$CL_{i,j}(\text{meters}) = \sum_{k=t-5}^{t} [a(\nabla \cdot \vec{V})^k{}_{i,j}\, \Delta z + 0.5(1-a)\, a(\partial^2 p/\partial n^2)^k{}_{i,j}\, \Delta z\, \Delta t]\, \Delta t$$
$$-100 \sum_{k=t-5}^{t} [(\partial p/\partial t)^k{}_{i,j} - \overline{(\partial p/\partial t)^k}] \qquad (8)$$

where: $a = \begin{cases} 0 & w_2 > w_1 > 0 \\ 1 & w_2 < w_1 \\ & w_2 \leq 0 \end{cases}$

Results from the cumulative lift analysis for 1200 and 1700 CDT 12 August 1973 are shown in figure 36. In the absence of soundings, none of the terms of equation 4 can be calculated. However, since upward vertical motion is crucial to destabilization through the last two terms of the stability equation, a positive correlation between areas and magnitudes of CL and convection should be found.

A further modification has been made through the introduction of a temporary artifice, the thunderstorm forecast algorithm (TFA), that limits CL only to areas where the dew point temperature exceeds 50° F and where the v component of the vector surface wind is greater than zero. The latter artifice eliminates areas that have experienced recent cold frontal passage but where CL values remain quite large due to the inclusion of lift aged 5 hours from the analysis time.

A cumulative lift of 200 m corresponds to an average upward vertical velocity of 1.1 cm/sec active over 5 hours at the top of a 1-km deep layer. A value of 400-m corresponds to 2.2 cm/sec over 5 hours or 11.0 cm/sec over 1 hour. This corresponds to a convergence of 1.1×10^{-4} sec^{-1} which is a typical order of magnitude for mesoscale convergence across gust fronts and strong cold fronts *given* the present separation between stations within the aviation surface network. Interestingly, CL produced by a slow moving, weak mid-summer weather system can reach CL magnitudes produced by a fast moving, strong springtime weather system.

Radar echo tops and locations of lines of convective activity taken from radar summary charts valid 2 to 3 hours after the analysis time are also included in figure 36 to show the short range predictive value of the cumulative lift. Comparison of the 1400-1500 CDT echo tops with the 1200 CDT CL pattern shows little correlation. There was some question whether this analysis, which included lift from 0700 CDT onward, would be revealing since the period began prior to boundary layer mixing. Further, the diabatic heating term of equation 4 reaches peak values during afternoon hours. Much of the convection occurring between 1400-1500 CDT could be attributed to low level heating within convectively unstable humid air masses.

The 1700 CDT CL forecast for 1900-2000 CDT thundery activity (figure 36b) shows an increased tendency for convection to be located within CL zones. The contribution to destabilization by the diabatic heating term has decreased leaving dynamic lift as the more important destabilization mechanism. The CL maximum over western Arkansas is a false alarm caused by channeling effects of the Ozark Mountains.

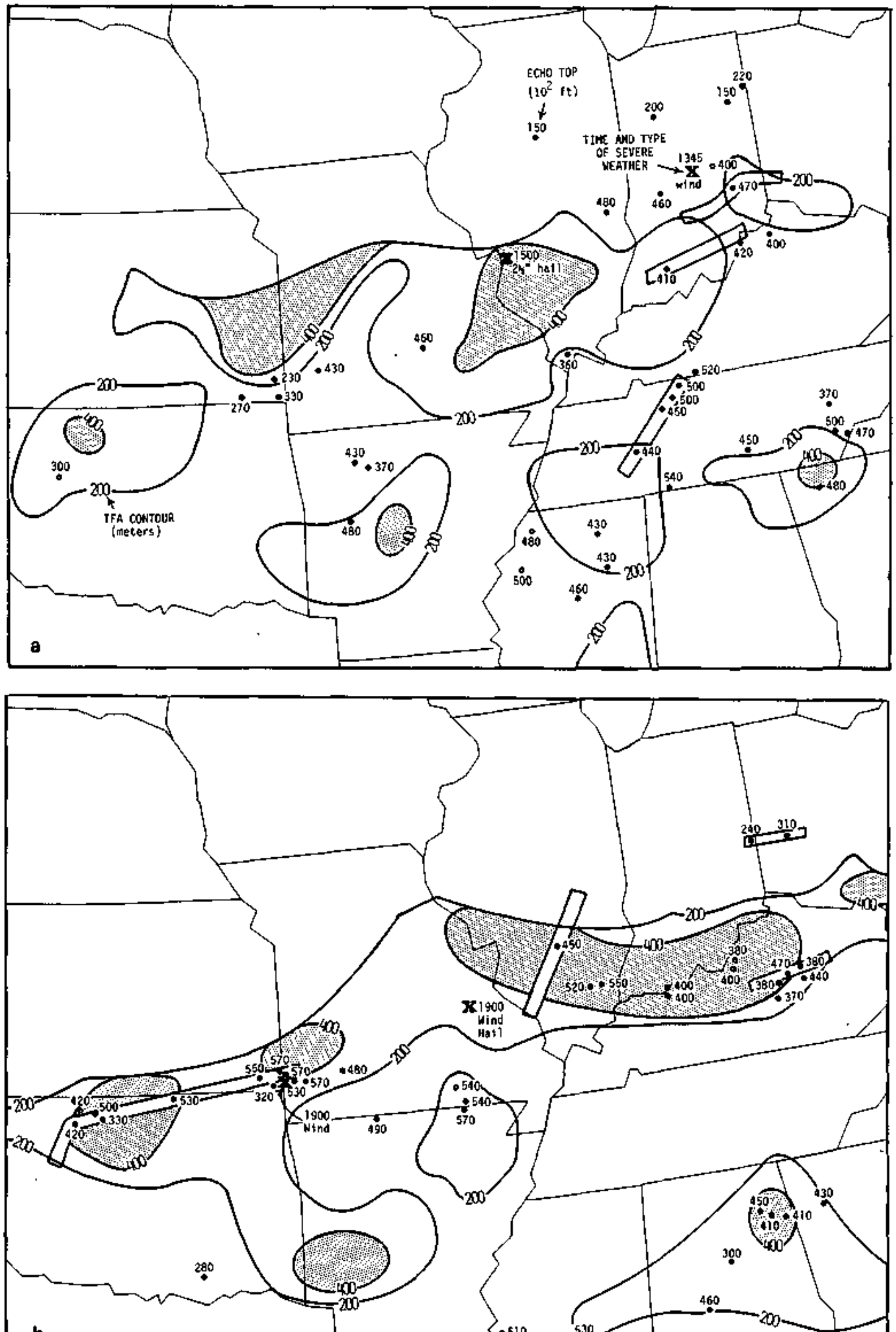


Figure 36. Thunderstorm forecast algorithm (TFA) for 1200 CDT, 12 August 1973 with the reported radar echo tops at 1400 and 1500 CDT *(a)* and 5 hours later *(bj* (X locates severe weather events)

Application of Cumulative Lift to Illinois Thunderstorm Data

A 58-day data set that consisted of hourly surface observations of pressure, temperature, dew point, vector wind, altimeter, and cloud cover was prepared from 12 stations in Illinois and surrounding states. The data set covered the periods of 6 to 30 June and 28 July to 30 August 1972. These periods consisted of 31 thunder days (7 hail days) and 27 no-thunder days. These meteorological categories were obtained from the 7-year (1967-1973) calendar containing all dates (March-October) with rain, thunderstorms, hail, damaging windstorms, and tornadoes for central Illinois. The Illinois calendar area (shaded), the 12 surface stations, and the regular 63-km 7×7 oint mesh boundary are shown in figure 37.

The 5-hour cumulative lift was computed from equation 8 and the results stratified by thunder/no-thunder days. On the average, cumulative lift on thunder days exceeded CL on no-thunder days in both areal coverage and magnitude. This was particularly true for the August period. However, the no-thunder CL for several days in the June period was large enough to raise some questions as to the usefulness of CL in discerning thunder from no-thunder days.

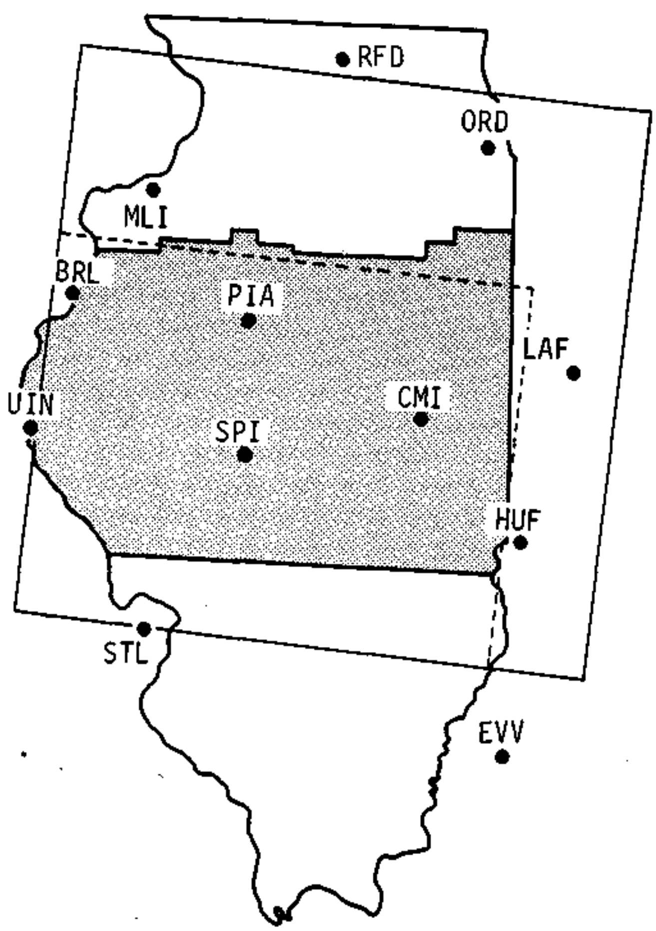


Figure 37. Map of Illinois showing the location of the thunder day calendar area (shaded), sites of 12 stations included in the objective analysis and boundary of the analysis grid (Area bordered by the dashed lines was included in the comparative studies with the thunder day calendar, 58-day sample)

Threshold = 200 m

CL (TFA) — number of grid points

	>4	<4	Total
TD	31(29)	0(2)	31
NT	20(7)	7(20)	27
TOTAL	51(36)	7(22)	58

	>7	<7	
TD	30(28)	1(3)	31
NT	15(1)	12(26)	27
TOTAL	45(29)	13(29)	58

	>10	<10	
TD	27(23)	4(8)	31
NT	9(1)	18(26)	27
TOTAL	36(24)	22(34)	58

	>15	<15	
TD	18(11)	13(20)	31
NT	4(0)	23(27)	27
TOTAL	22(11)	36(47)	58

Threshold = 300 m

CL (TFA) — number of grid points

	>4	<4	Total
TD	27(25)	4(6)	31
NT	10(3)	17(24)	27
TOTAL	37(28)	21(30)	58

	>7	<7	Total
TD	23(18)	8(13)	31
NT	5(0)	22(27)	27
TOTAL	28(18)	30(40)	58

Threshold = 400 m

CL (TFA) — number of grid points

	>4	<4	Total
TD	22(18)	9(13)	31
NT	4(0)	23(27)	27
TOTAL	26(18)	32(40)	58

Figure 38. Contingency tables for the cumulative lift (CD and TFA [in parentheses] thresholds of 200 m, 300 m, and 400 m, observed for at least 1 hour at specified number of grid points

The no-thunder CL distribution may be misleading as a result of a number of factors. Convergence may be high on shower days when a stable environment prevents thunderstorm development. The inclusion of convergence aged up to 5 hours in the CL calculations causes the CL to remain high for several hours after cold frontal passages have pushed thundery activity out of the calendar area. Dry cold frontal passages, especially secondary fronts in anticyclonic flow, generate large convergences. Turbulence in strong anticyclonic flow causes increased variability in speeds and directions that results in higher noise levels in convergence calculations.

In the absence of a stability analysis, we return to the TFA artifice restricting cumulative lift calculations to those areas with southerly winds ($v > 0$) and where $T_d > 50°$ F.

The abilities of the CL and the TFA to distinguish the appropriate weather categories were established with the aid of contingency tables. These tables (figure 38) show that areal coverages of these quantities are as sensitive as indicators of weather category as are CL and TFA magnitudes. As the thresholds for both the minimum magnitudes and the minimum number of grid points where the minimum magnitudes of CL (TFA) are exceeded are increased, the number of failures to correctly identify thunder days also increases. Heidke skill scores of 0.55 were computed for the CL at thresholds 200 (10), 300 (7), and 400 (4). The maximum TFA Heidke score of 0.86 was computed for 200 (7). For this threshold, thunder/no-thunder days were correctly identified on 93% or 54 of 58 days. There was 1 false alarm and 3 failures.

Although the TFA offers considerable improvement over the CL, false alarms and failures still occur. Failures (thunder days for which the TFA remains below its designated threshold) may be due to a number of factors. Convective systems with small subgrid spatial scales (including air mass thunderstorms) may be present over the network. Convective systems may develop near grid boundaries and the TFA cannot exceed the specified threshold for areal coverage. Atmospheric conditions may occur for which the surface convergence is not a valid indicator of vertical motions aloft. Warm fronts, overrunning, post cold frontal flow, and general northwesterly flow frequently violate the assumptions made in deriving the TFA. Failures may occur when convective instability is released with little or no mesoscale'lift.

False alarms (no-thunder days for which the TFA exceeds its designated threshold) may occur when local wind channeling effects contribute to large TFA. Isolated thundery activity may not occur at stations that report thunder. The TFA may exceed the threshold near grid boundaries in instances when thundery activity occurs beyond the calendar area. Showers may occur under stable conditions that prevent cloud growth into thunderstorms. The TFA may build up late in response to an approaching system that produces thunderstorms early the following morning.

The results from the 58-day sample are summarized by month and weather category in table 14. The number of correct weather type identifications are followed by the number of incorrect identifications. For this limited sample, the TFA did equally well for June and August. A further discussion of the 58-day sample is given by Achtemeier and Morgan (1975).

Table 14. Summary of Correct and Incorrect
Weather Category Identifications by TFA

With the lower threshold of 200 m at a minimum of 7 grid points (~ 10^4 km^2)

1972	*Number of days*	*No-thunder*	*Thunder*	*Hail*	*Total*
June	25	13-0	9-1	2-0	24-1
July	4	4-0	0-0	0-0	4-0
August	29	9-1	12-2	5-0	26-3
Total	58	26-1	21-3	7-0	54-4

A second data set composed of 106 no-thunder days, 107 thunder days, and 100 hail days was compiled for selected spring and summer periods from 1968-1971. This data set differs from the 58-day 1972 sample in 6 respects. It is biased toward periods of unsettled weather. Days with no-thunder occurred as 1- to 2-day respites between stormy periods. Long quiescent anticyclonic periods (4-7 day durations) were not included in this data set. Observations were recorded at 3-hourly intervals as opposed to the 1-hourly interval for the 58-day set. The residence time for mesoscale systems was increased to 6 hours. Only 3 convergence analyses were included in the CL calculations.

The grid for which the TFA for the 58-day sample are verified with respect to the calendar is outlined by the dashed lines in figure 37. It was later recognized that the lower row of grid points was too far removed from the southernmost boundary of the calendar and contributed to false alarms through extrapolations within the data void between STL and HUF. This row was omitted to bring the verification grid into closer alignment with the calendar area. The results from the recalculations of the 58-day TFA thresholds for the new verification grid led to the replacement of the TFA 200 (7) by the TFA 200 (5) threshold. The new threshold and the new verification grid were used in the analysis of the 313-day data set.

Finally, the dew point artifice of 50° F was dropped because of the wide dew point variation from March through August. Only the wind direction artifice was retained.

The 313-day sample was processed as an independent data set and the computed TFA was verified with the TFA = 200 (5) threshold. The results for the hail days, stratified by month and season, are presented in table 15. Two hail-producing systems that violated the assumptions made in deriving the TFA were easily identified with the aid of the temperature and dew point observations. These are the post cold front system (PCF) which occurred 12 times during the spring months and the northeasterly flow system (NEF) which accounted for 11 reported hail days. The post cold front system comprised multiple day hail-producing events. The sequence., of events suggested from subjective comparisons of temperature, dew point, radar echo tops, and TFA patterns is as follows. The first hail-producing day was characterized by the passage of a strong cold front or low pressure center through central Illinois. This system was accompanied by high TFA values and correctly identified as a storm (hail or thunder) day. High dew points and mild temperatures suggested that air masses of Gulf of Mexico origin were present in central Illinois in advance of the system.

Frontal passage through central Illinois was accompanied by intense convection. Radar echo tops in excess of 40,000 feet were frequent and several days with tops to 50,000 feet were reported.

Frontal passage was accompanied by sharp drops in temperature and moisture. Strong westerly or northwesterly flow covered central Illinois on the second hail event day. Rapid evaporation of moisture deposited by the previous day's storms and absorption of sensible heat from plowed ground could have contributed to rapid destabilization within the cold air masses. Increases in dew points frequently occurred. Further, dynamic destabilization was inferred from high CL values that occurred on most of the PCF days. However, radar echo tops on these PCF days were much lower than radar echo tops observed on the first PCF day. In only two instances did tops exceed 35,000 feet. Most PCF days had tops not exceeding 25,000 feet, and in a few instances tops were less than 15,000 feet. Thus, these PCF days were characterized more by hail 'showers' rather than by hailstorms.

The northeasterly flow (NEF) days were also characterized by cold frontal passages, but the subsequent weather history departed considerably from the PCF events described above. NEF days were overrunning days. Typically, a cold front would push southward or southwestward across central Illinois. Winds behind the front were from the north or northeast. Several hours after frontal passage, and in some cases on the following day, intense convection with echo tops to 50,000 feet was frequently observed behind the front. Upon examination of the Daily Weather Maps we found that on some but not all of the NEF days, weak low-pressure centers that developed and moved along the front south of central Illinois enhanced overrunning conditions.

Table 15 lists the TFA monthly hail day identifications first giving the correct and then the incorrect identifications. It was found that 38 of 58 *(66%)* of spring season hail days and 33 of 42 (79%) of summer season hail days were correctly identified. When the PCF and NEF days are removed from the sample, both seasons have approximately the same identification ratios, e.g., 30 of 39 (77%) for spring and 31 of 38 (82%) for summer. Interestingly, for an equivalent period of the 58-day study, June and August, 23 of 24 (96%) of the hail days were identified.

Climatologically in central Illinois, July is a warm and humid month dominated by Gulf air masses. High potential instability can be released locally producing more air mass type thunderstorms and meso-systems of small horizontal scale than in June and August. Less dynamic lift is required to release the instability, so the number of failures to identify July hail days increases. The surface TFA analyses coupled with an upper air stability analysis through equation 4 should lead to improved identification of July storm days.

Table 15. Stratification by Month of 100 Correct and Incorrect Hail Day Identifications by TFA

With a lower magnitude threshold of 200 m at a minimum of 5 grid points

Month	Total days	Correct	Incorrect	PCF	NEF	Without PCF, NEF days Correct	Without PCF, NEF days Incorrect
March	6	4	2	1	1	4	0
April	12	8	4	1	1	8	2
May	40	26	14	10	5	18	7
June	21	18	3		2	18	1
July	16	10	6		2	8	6
August	5	5	0			5	0
March, April, May	58	38	20	12	7	30	9
June, July, August	42	33	9		4	31	7
Total	100	71	29	12	11	61	16

Table 16. Summary of TFA (5) Successes and Failures for Hail Days Excluding Events Not Satisfying Prescribed Constraints

Success	Failure	Percent success	Total days	Additional constraint
71	29	71	100	None
60	19	76	79	Dew point
58	18	76	76	Dew point and tops ≥ 30,000 ft
65	25	72	90	Tops ≥ 30,000 ft

Warm front systems are not well handled by the TFA analysis because precipitation areas are often several hundred miles removed from frontal convergence zones. When active warm fronts were located within the analysis network high TFA values were calculated. However, there will be occasions when convective activity is present over the network and the frontal zone convergence is located beyond the network and may enter several hours later, possibly on the following day. In these warm frontal circumstances *a)* the TFA threshold may not be exceeded with thundery activity present, or *b)* the TFA threshold is exceeded *but* thundery activity left the central Illinois network on the previous day. Both instances will result in incorrect weather category identification.

Stratifications of hail days with respect to the dew point temperature threshold of 50° F, echo top height threshold of 30,000 feet, or both, were also made. Correctly or incorrectly identified hail days were dropped from the sample if the selected threshold(s) was not exceeded. These results, summarized in table 16, show little improvement over the TFA identifications with none of these artifices. Thus, the TFA for hail days shows no dependence upon a fixed dew point temperature threshold or upon maximum tops of radar echoes.

The hail days were further stratified according to frontal type in an effort to determine the TFA effectiveness in correctly identifying hail events under various meteorological conditions. The frontal types as determined from the Daily Weather Maps for 84 hail days were defined as follows. The cold front type included those days when cold fronts were found within the network or when cold fronts passed through the network. Pre-cold frontal squall lines were included within this group. The TFA correctly identified 26 of 30 (87%) of the cold front type hail days. The warm

Table 17. Stratification by Month of 107 Correct and Incorrect TFA Thunder Day Identifications

With a lower magnitude threshold of 200 m at a minimum of 5 grid points

Month	Total days	Correct	Incorrect	Tops > 30,000 ft Correct	Tops > 30,000 ft Incorrect
March	1	0	1	0	1
April	12	7	5	1	1
May	26	16	10	8	3
June	33	25	8	21	4
July	28	13	15	11	9
August	7	5	2	5	1
March, April, May	39	23	16	9	5
June, July, August	68	43	25	37	14
Total	107	66	41	46	19

front type consisted of those days when warm fronts were located to the south of the southern one-half of the network and passed through the network during the day. There were only 10 warm front type days and 9 of these (90%) were correctly identified as hail days. The ratio 3:1 of cold front type to warm front type compares favorably to the ratio of 3:1.1 given by Morgan et al. (1975).

PCF and NEF days accounted for 20 hail days. The TFA correctly identified 8 of 20 (40%) of the hail days in this category. The remaining set of hail days could not be positively associated with any of the 3 weather types. This set included air mass storms, squall lines, and meso-systems not associated with cold and warm fronts, storms accompanying stationary fronts, dissipating warm and cold fronts, and overrunning storms generated by frontal waves traversing south of the network (not identified as NEF days). Eighteen of the 24 hail days (75%) included within this set were correctly identified by the TFA.

Results of the TFA analysis for the 107 thunder/no-hail days, presented in table 17, show much the same distribution as the hail day stratification. The TFA best identified thunder days in June and August with a total for both months of 30 correct and 10 incorrect (75%). Air mass thunderstorm-prone July gave the poorest results with less than 50% of the thunder days properly identified. The TFA accuracy for the spring season was also low with only 59% correct thunder day identifications. PCF, NEF, and warm front conditions probably accounted for the lowered TFA accuracy. PCF and NEF stratifications were not made for the thunder days.

Seasonally, thunder days were shifted toward the warmer months with 39 thunder days for spring and 68 thunder days for summer. By contrast the hail days were shifted toward spring with 58 for spring and 42 for summer.

In total, only 62% of all thunder days were correctly identified compared with 71% correct identifications for the hail days. These results imply that, on the whole, hail-producing systems were more dynamic with greater convergence, hence, greater dynamic destabilization, than were the thunder days. Hail days were equally well detected regardless of echo top height, whereas correct identifications of thunder days were particularly sensitive to echo top height. On only 16 hail days did echo tops fail to exceed 30,000 feet and 8 of these were PCF days. By contrast, 42 of 107 thunder days were characterized by tops less than 30,000 feet and the distribution of these days was independent of season. When the 42 thunder days were dropped from the sample, the TFA identifications improved to 71%.

There was no improvement in TFA identifications when the thunder days not satisfying the 50° F dew point temperature constraint were dropped from the sample.

Shower, rain, and no-precipitation days were classified as no-thunder days. The TFA correctly identified 43 of 66 (65%) precipitation days as no-thunder days and correctly identified 30 of 43 (70%) non-precipitation days as no-thunder days. The no-thunder days were sensitive to the dew point constraint which decreased the number of failures from 34 to 14. This result was expected since no-thunder days were, on the whole, drier and cooler than were thunder days.

Application of the Cumulative Lift to Short-Range Storm Forecasts

The foregoing results give a strong argument that thunder days, and particularly hail days, can be reliably distinguished from no-thunder days on the basis of the threshold magnitude and areal coverage of the modified cumulative lift (TFA). What remains is to determine whether the time of attainment of the optimum TFA criteria (decision event) is predictive of the time of thunderstorm development and/or intensification and whether the areal location of high TFA is predictive of the location of the more intense storms and/or greater areal coverage of storms.

To properly estimate the predictive capabilities of TFA, it is necessary to create a scenario of aircraft operations in a hail suppression experiment. We presume a minimum of 2 hours is required to get aircraft airborne once a decision event is declared, and that the maximum continuous operation time, using multiple aircraft, is from 4 to 5 hours. Thus, the optimum thunderstorm intercept period is 2 to 7 hours after the decision time.

Once the forecast is verified, seeding operations will be conducted continuously until:

1) The echo tops fall below 30,000 feet and the TFA falls below the critical threshold
2) Echoes have moved out of the experimental area and the TFA, if above the critical threshold, shows no definite trend toward increases in area or magnitude
3) The TFA remains above the threshold but echo tops stay below 30,000 feet for 5 consecutive in-flight hours

When operations are terminated, the aircraft have 2 hours to return to base. After that interval, a new decision event is declared if the TFA optimum threshold is again reached, or, if already above the threshold, a TFA increase is observed. Thus, the aircraft operations, at one time, restrict decision times for future operations.

An example of how an operation day might be conducted is given for the 6 August 1972 hail day, with the distributions of echo top heights and the number of grid points containing TFA values exceeding specified thresholds as shown in figure 39.

The 58-day sample TFA $\geq$ 200 (7) threshold is first exceeded at 0000 CDT. Two hours later aircraft are airborne and successfully intercept storms with tops in excess of 40,000 feet. Echo tops drop below 30,000 feet by 1200 CDT and move out of central Illinois by 1300 CDT. Aircraft return to base by 1400 CDT. However, strong increases in TFA are observed and, according to the procedures just outlined, 1400 CDT is the earliest time for a new decision event. By 1600 CDT, aircraft are airborne and intercept an area of new thunderstorms that produce maximum tops in excess of 50,000 feet by 1900 CDT.

Decision events were determined according to the criteria listed above. Then, for those decision events for which echo tops exceeded 30,000 feet, a table was constructed which contained the history of echo top heights by hour beginning 3 hours prior to and ending 7 hours after the

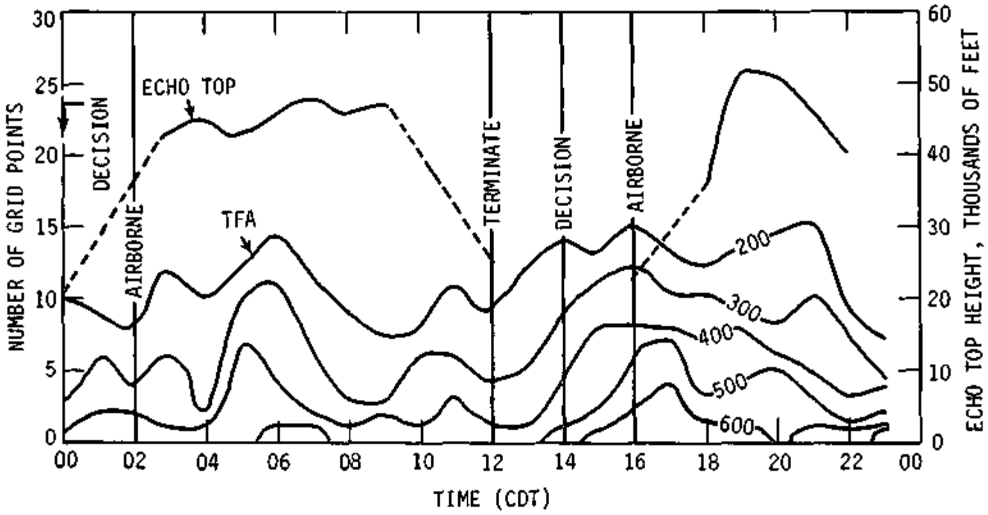


Figure 39. Distribution by hour of reported radar echo top heights and the number of grid points with TFA exceeding specified thresholds for the 6 August 1972 hail day

time of the decision event. Entries with echo tops below 30,000 feet were set equal to zero. Then the echo top heights for each of the 11 hourly columns were summed. Relative differences between these hourly sums were dependent upon two factors. Echoes at one hour might be consistently taller than echoes at another hour. Echoes exceeding 30,000 feet might have occurred more frequently at one hour than at another hour.

Plots of the resulting values are presented in figure 40. A constant was subtracted from each value. The graphs for the hail days and thunder days show that, on the whole, radar echo tops are higher more frequently several hours after the decision time. For the hail days, maximum values are reached about 2 hours after decision time. Top height frequency remains essentially constant thereafter. On thunder days, values maximize 3 to 4 hours after decision time then decrease substantially.

On many thunder days, the period of time during which echo tops exceeded 30,000 feet was only 3 to 4 hours. Hail days were more often characterized by 5 to 10 hour periods with tops in excess of 30,000 feet.

The curves in figure 40 suggest that the TFA is generally predictive of increases in echo top height, hence intensity, of hail and thundery activity. A forecast technique was developed from the TFA on the basis of the following criteria.

For a decision event to qualify as a forecast, echo tops must exceed 30,000 feet for at least 1 hour at least 2 hours after the decision time (if echo tops exceed 30,000 feet prior to the decision time, increases in echo top height must occur). A false alarm is declared when no echoes exceed 30,000 feet within the 7-hour post decision period or when tops exceeding 30,000 feet that were present prior to decision decrease in height following the decision. A failure is declared when tops exceed 30,000 feet but no TFA threshold is reached.

Decision events for the 58-day sample were combined with the decision event for the 313-day sample. There were 116 events for which decisions were or should have been made for the hail day sample. The thunder days produced 131 decision events and the no-thunder days produced 30 decision events. These are tabulated in table 18 to include verifications, false alarms (no echo), false larms (tops < 30,000 feet), false alarms (decreasing top heights), and failures.

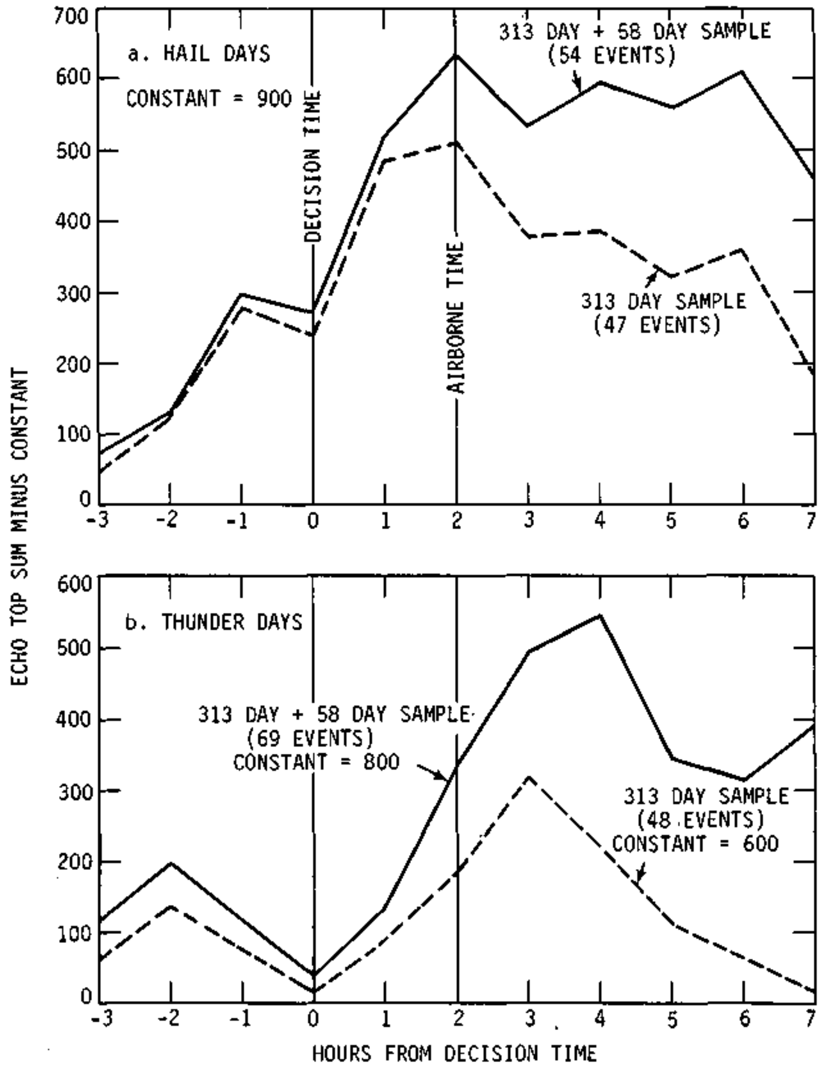


Figure 40. Sums by hour of maximum reported echo top heights above 30,000 feet relative to the decision time when the TFA threshold 200 (5) is exceeded

Table 18. Summary of Decision Events for the 58-Day and 313-Day Samples

		False alarms				
Category	*Verifi-cations*	*No echoes*	*Tops < 30,000 ft*	*Dec. top hgts.*	*Failures*	*Total*
Hail	48	4	12	13	39	116
Thunder	34	9	24	19	45	131
No-thunder	1	11	16	1	4	33
Total	83	24	52	33	88	280

The results show that of 192 decision events actually made, only 83 would have resulted in successful interception. The hail days gave the best results with 48 of 77 (62%) successful interceptions. However, 39 hail-producing systems would have escaped notice.

The method of determining the decision events may have biased the results toward false alarms and failures. We used event A (TFA exceeding the prescribed threshold) to forecast event B (development of echoes with tops > 30,000 feet or increases in tops of pre-existing echoes). If event B followed event A within the specified time span (2-7 hours after decision time) the decision was recorded as a verification. If event B preceded event A, a false alarm (decreasing top heights) was declared. However, if event B followed (or preceded) event A by more than the specified time span, a false alarm (no echoes or tops < 30,000 feet) was declared for event A and a failure was declared for event B.

False alarms (no echoes) comprised those situations for which decision events were declared too far in advance of precipitation systems. False alarms (tops < 30,000 feet) included the above, and situations when increases in echo top heights were correctly predicted but tops remained below 30,000 feet. Several PCF hail days fell into this category.

The TFA decision events were stratified by 3-hour periods to find diurnal variations of all the verifications and false alarms for the 313-day sample. The distributions of decision events for TFA ⩾ 200 (5) presented in figure 41 show a tendency for verifications to peak in mid-afternoon hours.

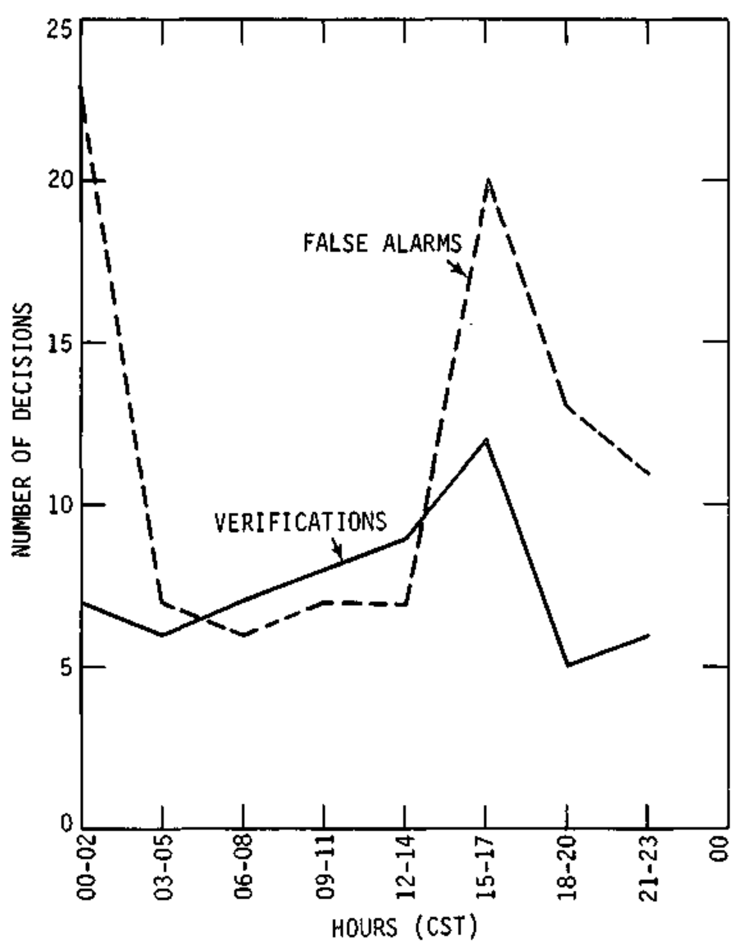


Figure 41. 3-hourly diurnal distribution of verifications and false alarms for all decision events in the 313-day sample

False alarms show pronounced peaks during the mid-afternoon and again in the early morning hours. Some of the early morning false alarms may be caused by convergence within stable post-thunder activity air masses. Separate stratifications were carried out for the hail days. No definite trends were found in the distributions of either the verifications or the false alarms.

We now turn to the problem of areal predictability. Economic operation of a regional hail suppression experiment requires some advance knowledge of where thundery activity will develop, or if present already, where the more intense cells will be located. The predictive time scale of only 2 to 4 hours adds further import to the necessity to get aircraft into the development areas before storms can become organized into hail-producing systems.

We extend the operational scenario, describing decision times, to this additional problem of defining the 'decision area' based upon those areas where the TFA critical threshold is exceeded. Once airborne (defined as 2 hours after decision time), aircraft would be vectored *a)* to locations of greatest TFA if there were no precipitation systems or *b)* to a location nearest to precipitating clouds but still within the TFA threshold area. TFA threshold positions would be monitored hourly and aircraft positions adjusted according to the above criteria.

Table 19 shows the 17 verifications and 14 false alarms for the 58-day sample when stratified according to distance from the TFA threshold. There were instances when TFA 200 covered extensive areas of the mesh and rendered a development area forecast meaningless. Therefore, TFA 300 was used whenever possible to delineate the critical areas. In 11 of the 17 verifications strongest convection was confined within the critical areas. In 4 cases major activity occurred within 100 km of the critical area. Convective outbreaks too far (> 100 km) from the critical area to permit timely aircraft interception occurred once. Convection in one instance (other) occurred 200 km ahead of the surface position of a warm front. It should be possible to identify warm frontal situations and to vector the aircraft accordingly.

The time-consuming area-echo analysis of the 233 decision events from the 313-day sample was not undertaken. However, spot checks suggested a significant correlation between the TFA area and locations of radar echoes.

The false alarm TFA areas were not well correlated with echo positions. There were only 2 of 14 instances where echoes developed within the TFA areas. There was one near-miss, but 6 instances where the TFA was more than 100 km separated from nearest radar echoes. Absence of echoes and apparent warm front conditions accounted for most of the 5 'other' cases.

The occurrence of 6 of the 14 false alarms to the rear of or behind convective activity is suggesstive of convergent, stable post-squall flows. Further investigation should reveal criteria by which these case types can be identified and eliminated as possible decision events.

Table 19. Locations of Major Convective Activity
Relative to 200 (7) Critical Areas, from 58-Day Sample

Echoes within TFA	TFA <100 km ahead of echoes	TFA <100 km behind echoes	TFA >100 km ahead of echoes	TFA >100 km behind echoes	Other	Total
Verifications						
11	2	2	1	0	1	17
False alarms						
2	0	1	1	5	5	14

Meshing the TFA with Surface and Upper Air Thermodynamics

In the discussions which were stated formally in equation 4, we found that the vertical velocity was just one of several physical parameters which directly determine air mass stability which in turn determines the locations and onset times of convective outbreaks. Other important destabilization parameters are the stability at the sounding time, the diabatic heating, rate, the vertical distribution of thermal advection, and the surface distribution of temperature and moisture.

An attempt to incorporate the surface moisture into the TFA by introducing the dew point temperature ⩾ 50° F constraint did not lead to tangible increases in the method's accuracy (see table 16), but did lead to the dropping of a substantial number of hail days from the data set. Pilot studies with the 58-day sample showed that, with the exception of a few strong frontal systems with large moisture contrasts, the cumulative lift developed from the moisture convergence offered no detectable improvement over the cumulative lift developed from convergence only. However, it is well known that major convective activity usually occurs in association with moist air masses. Therefore, we abandoned the moisture convergence in favor of a moisture weighted convergence. Values of weekly mean moisture were constructed with the 0000 and 1200 CST dew point temperatures obtained from the records of 6 stations located within the calendar area. These values were plotted for each week from the end of March to 20 August for the 4-year period, and a smooth curve was drawn subjectively to approximate a best fit. The mean dew point temperature increased quasi-linearly from the last week of March through May. Dew points increased from 32° F at the first of April to 43° F by the end of the month. The May range was from 44 to 56° F. The dew point curve began to level off in June, which had a dew point range from 56 to 63° F. Dew points increased from 63 to 66° F in July and remained essentially constant at 66 through 20 August.

The dew point temperature departures from this 'climatological' curve were computed for the hail days and no-thunder days and compared with the magnitudes and areal coverages of the TFA. Most, but not all, hail days had positive dew point temperature departures and most, but not all, of the no-thunder days had negative dew point temperature departures. However, most of the no-thunder days that gave large negative departures were post cold front days and the TFA constraint $v > 0$ had already caused the TFA for these days to be set to zero.

No tangible correlations between the magnitudes and areal coverages of the TFA and the dew point temperature departures were found. However, hail did not occur on days when the departures were less than -5° F. [One PCF hail day occurred with a dew point temperature departure of-9° F.]

We chose the -5° F dew point temperature departures as the moisture constraint for the TFA and subjectively tabulated the maximum dew point departures that occurred when the TFA exceeded the prescribed 200 (5) threshold. This method allowed close monitoring of the dew point in the convergent areas. Table 20 shows contingency tables for the hail day and no-thunder day identifications, with and without the moisture weighted TFA.

Table 20. Contingency Tables for Hail Day and No-Thunder Day TFA Identifications

	Without moisture			*With moisture*		
	TFA > 200 (5)	*TFA < 200 (5)*	*Total*	*TFA > 200 (5)*	*TFA < 200 (5)*	*Total*
Hail	71	29	100	70	30	100
No-thunder	34	72	106	21	85	106
Total	105	101	206	91	115	206
Heidke score	.39			.50		
Percent correct	71			80		

There was considerable improvement in the no-thunder TFA identifications when the moisture constraint was included. Also, the moisture constraint decreased by 8 the number of no-thunder false alarm decision events shown in table 18.

Continuing Research

The results from the surface analyses show that the TFA has considerable skill in identifying hail and thunder days from no-thunder days. When used as a forecast parameter, the TFA shows less skill. However, it was never intended that the TFA alone should constitute a short-range thunder/hail forecast technique. The complete method combines the surface analyses with the upper air observations to produce a 4-dimensional mesoscale update model. Two models are being developed. One produces 4-dimensional temperature and moisture fields in accord with the assumptions already made, namely, that the convergence of the surface wind field is reflective of the convergence in the lowest 1 km of the atmosphere and that the vertical distribution of convergence and vertical velocity are similar to the profiles given in figure 34. These assumptions are frequently violated in warm frontal and overrunning conditions. The second model will be designed to handle these latter conditions.

The first model melds the surface analyses with at least one nearby sounding to produce a 4-dimensional structure of the lower atmosphere ($p \geqslant 500$ mb). Temperature gradients can be deduced from the thermal wind approximation and temperatures extrapolated horizontally over the grid at significant and standard pressure levels. Then temperature advection can be calculated from the horizontal temperature fields and the observed wind. These 'extrapolated soundings' are modified according to dictates of the surface fields, e.g., moisture, diabatic heating, convergence, wind direction. The new soundings will be compared with precipitation areas and correlations will be determined by statistical comparisons of a large number of kinematic and thermodynamic variables calculated from the soundings and surface fields.

The warm frontal destabilization model will be similar in principle to the general model, but will make special provision for overrunning. Warm frontal slope will be determined from the frontal height on a sounding taken ahead of the front and the surface frontal position. Then warm sector surface air which overtakes the front will be displaced upward according to its speed relative to the front. The frontal surface will be treated as a material surface. Then destabilization will be computed.

E. CLOUD PROPERTIES

Two other Water Survey projects utilizing aircraft to measure important cloud properties were to provide cloud data relevant to the DESH effort. Information on updrafts and cloud properties were essential to DESH for proper design. Some information was provided from cloud base flights performed as part of METROMEX and from mid-cloud penetrations of growing cumulus clouds as part of the Survey's Precipitation Enhancement Project (PEP), although funds were cut back before all desired information could be obtained.

CLOUD BASE UPDRAFTS

The primary objective of the METROMEX cloud base flights in 1972 and 1973 was to release unique tracer materials (lithium chloride and indium) into updrafts of convective clouds (Gatz, 1974) to study scavenging processes. This objective required that measurements of the updraft speed be obtained prior to release of the material. The measurements which were logged by the on-board meteorologists were obtained from an instantaneous vertical speed indicator (IVSI). Measurements from the IVSI system require that the power settings and aircraft attitude be maintained for level flight. Information was not entered into the notes or logs unless proper aircraft attitude was being maintained for a particular measurement; therefore, the updraft data collected should be of good quality.

The cloud base data analyzed herein were derived from 15 cloud flights on 13 days during 1972 and 1973. Sixty-nine cloud base updraft velocity measurements were obtained from cumulonimbus clouds.

The analysis of the data focused upon the location of the updraft relative to the direction of movement of the FPS-18 radar echoes and, or course, the speed of the updraft. The results of the analysis are presented in table 21. Seventy percent of the 51 known-position updrafts occurred

Table 21. Cloud Base Updraft Data of Illinois Thunderstorms Stratified by Their Position Relative to the Radar Echo Movement

	Left front	*Right front*	*Left rear*	*Right rear*	*Unknown*	*All*
Number of updrafts	14	24	6	7	18	69
Average speed, *m/sec*	2.5	2.3	2.3	2.0	3.4	2.5
Median speed, *m/sec*	2.5	1.7	2.5	1.3	3.6	2.5
Maximum speed, *m/sec*	6.1	5.5	3.1	3.1	7.1	7.1
Number of updrafts ≤ 1.5 m/sec (≤ 300 ft/min)	6	12	0	4	3	25
Number of updrafts 1.5–2.5 m/sec (301–499 ft/min)	0	4	2	0	3	9
Number of updrafts 2.5–3.8 m/sec (500–749 ft/min)	5	3	4	3	2	17
Number of updrafts 3.8–5.1 m/sec (750–999 ft/min)	0	1	0	0	5	6
Number of updrafts ≥ 5.1 m/sec (≥ 1000 ft/min)	3	4	0	0	5	12

on the front of the echoes, and the predominance of those were located on the right front. Their average speed was 2.4 m/sec (470 ft/min) and their median speed was 2.0 m/sec (390 ft/min). The speeds were higher [average was 3.4 m/sec (660 ft/min) and median was 3.6 m/sec (700 ft/min)] for the 'unknown' category. The unknown category refers to updrafts that were measured but could not be located relative to the radar echo because the radar echoes were obscured by ground clutter. When all of the updrafts were considered, the average and median speeds were 2.5 m/sec (500 ft/min).

Table 21 also includes a distribution of various updraft speeds relative to radar echo position. Fifty-eight percent (22 of the 38) 'front-located' updrafts were less than 2.5 m/sec (500 ft/min), and only about 20% were greater than 5.1 m/sec. The updrafts with 'unknown' positions were stronger, on the average, than those known. This is reflected in their distribution of updraft speeds. More than 50% of the unknown updrafts were ≥ 3.8 m/sec (750 ft/min). This result may occur because the storms involved were more complex and stronger; hence, the echo position could not be determined satisfactorily. When all the updrafts are considered, approximately 50% of the 69 updrafts were ≤ 2.5 m/sec (500 ft/min), and about 75% were ≤ 3.8 m/sec (750 ft/min).

The flight crew, who were experienced in updraft and cloud flying (Henderson and Duckering, 1973), noted that:

1) Most inflow areas are of small diameter and short duration
2) Weak thunderstorms or dissipating cloud systems provide no identifiable base inflow areas
3) The base inflow areas are identifiable in large cumulus clouds with durations ≥ 30 minutes

The cloud base updrafts were often difficult to find from the aircraft because of multi-cloud visibility problems, and the conditions often required radar direction to help locate potential updraft areas.

MID-CLOUD PENETRATIONS

Considerable data on mid-cloud characteristics were obtained as part of the Precipitation Enhancement Program (PEP) sponsored by the Bureau of Reclamation (Contract DI-14-06-D-7197). The Pennsylvania State University Aerocommander aircraft was contracted to provide the airborne measurements. The measurement program was carried out in June and July 1973 in the St. Louis area to utilize meteorological data (radar, recording rangages, rawinsondes, etc.) collected as part of project METROMEX. The main purpose of the DESH-related study of the PEP data was *a)* to investigate mid-cloud updraft parameters, and *b)* to examine certain moisture variables within the cloud and the updrafts.

The objective of the cloud sampling portion of the PEP project was to determine the magnitude of a number of cloud parameters considered to be important for the evaluation of the physical potential for the modification of warm season precipitation in Illinois. This objective necessitated cloud penetrations into a variety of cloud types but basically those of the cumulus family. Most penetrations were into a variety of cloud types:

1) Cumuliform tower families which merged into cumulonimbus calvus
2) Cumulus congestus associated with cumulonimbus, both in clear areas or imbedded in altostratus-altocumulus layers
3) Young cumulonimbus calvus
4) In a few instances, young thunderstorm cells

All of the clouds were usually classified as 'vigorous' growing entities before aircraft entry. Cloud bases were typically 4000 feet MSL, tops were 17,000 to 24,000 feet MSL, and penetrations were near the freezing level (~ 14,500 feet MSL, or 600 mb).

An estimate of updraft and downdraft regions was obtained from the recorded output of a rate-of-climb meter. The particular instrument used (the IVSI, Teledyne Corp.) incorporated a spring device to detect the initial vertical acceleration in addition to the normal differential pressure transducer. These measurements, in conjunction with those of aircraft pitch and angle of attack, permit a qualitative, and often semi-quantitative, estimate of vertical draft strength.

Three independent measurements were used in determining the partition of the total condensate into cloud and precipitation water content: *a)* the total water content meter developed at the Naval Research Laboratory (Ruskin, 1967) which measures water in all phases; *b)* the commercially available Johnson-Williams hot-wire liquid water content meter which responds primarily to the cloud droplets, measuring little of the contribution to the condensate from solid particles and liquid particles larger than about 60 to 80 μm diameter (Barrett, 1958); and *c)* the Cambridge Systems dew point hygrometer which measures the water-vapor content. The Johnson-Williams meter was mounted on the bottom of the housing for the total water meter and the entire assemblage was attached to the underside of the airplane wing well out of the region of disturbed flow. A water-free air sample was introduced into the dew point hygrometer, which was located toward the rear of the airfoil.

All the measurements were digitally recorded every half second on computer-compatible magnetic tape. The total water meter has very short (0.5 second or less) response time and has space resolution of 2 or 3 m. In order to minimize the possibility of bias arising from the sensing of single large drops, the current was electronically linearized and averaged over an interval of 0.5 second.

The data used for the DESH study were collected on 16 flight days in 1973, usually within 100 miles of St. Louis. It involved 20 flights and 163 cloud penetrations. Figure 42 shows an example of some of the data obtained. These data have been smoothed, either by a 5-point running mean (providing averages over about 200 m), or by consecutive averaging over three data points (120 m). In interpreting these graphs it is important to realize that the response characteristics of the various instruments differ significantly. The rosemount platinum resistor thermometer and the two water meters have rapid (0.5 second or less) response. The response time of the dew point hygrometer, from which vapor density is determined, is close to 2 seconds. The airplane itself is the sensor for measurements of vertical velocity. Although the initial change due to entry into a vertical draft is sensed rather quickly by the IVSI, the inertia of the aircraft results in a response time of the order of 5 to 10 seconds. Thus, a draft may be indicated in the airplane rate-of-climb for some seconds after the plane has left it.

The procedure for each cloud penetration was to obtain various parameters for that cloud. This involved looking at all of the single display graphs of each parameter for a particular cloud and tabulating the values that applied to that cloud. The following is a list of all the parameters obtained:

1) Cloud enter and exit time (CDT)
2) Peak rate of climb (m/sec)
3) Peak Johnson-Williams liquid water content (g/m^3) in the updraft and in the cloud (if a high value occurs outside the updraft. If no higher value occurs the cloud and updraft values are the same)
4) Peak Ruskin total water content (g/m^3) in the updraft and in the cloud
5) Updraft entry and exit time and, thus, time width of updraft
6) Altitude (feet above MSL)
7) Cloud entry-exit static pressure (mb)

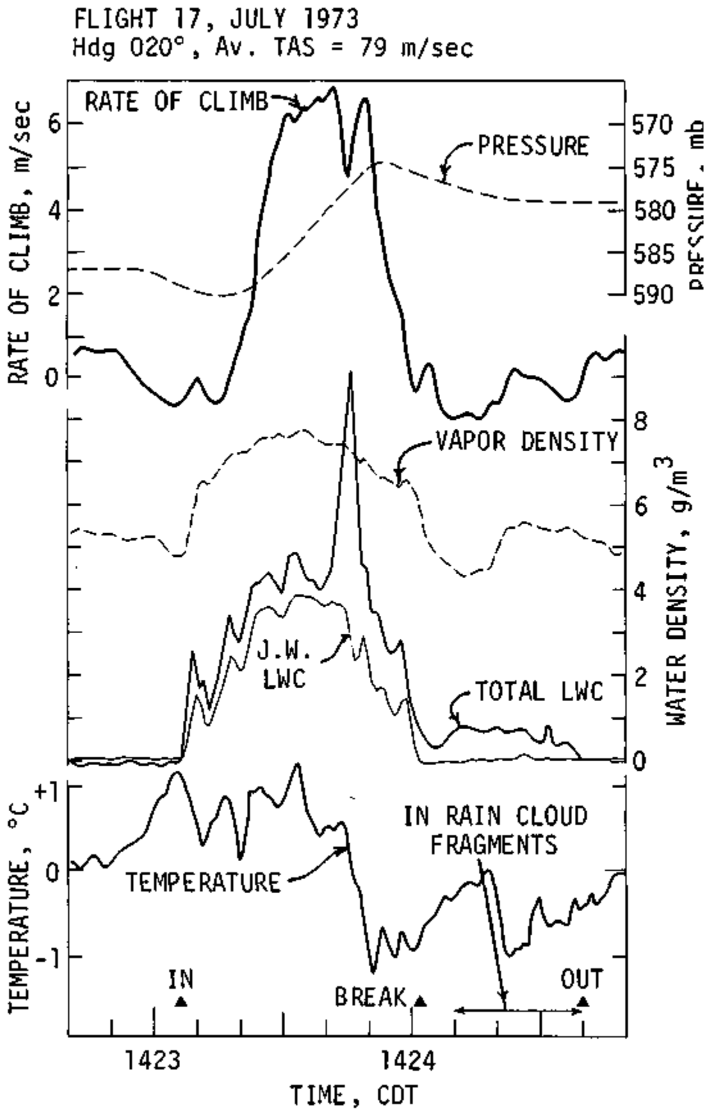


Figure 42. Variations of several cloud parameters during a penetration through a vigorous, broad cumulus congestus (Data smoothed by 5 point running mean, about 200 m)

8) Average fast Rosemount cloud temperature (C)
9) Aircraft position at cloud entry-exit
10) Cloud type as defined by on-board meteorologist
11) Aircraft heading (degrees azimuth)

After the data were tabulated, it was possible to determine cloud size and updraft size from the true air speed and time data by simply multiplying the values. Also, from the time data and aircraft heading, it was possible to locate the position of the updraft relative to the outer portion of the cloud. This was done by assuming all clouds were round, and all penetrations were through the center of the cloud and updraft. Then, knowing the width of the cloud in time, time of updraft entry and exit, and time width of the updraft made it possible to calculate the percent time from cloud entry to the updraft, the percent time width of updraft, and the percent time after the updraft. Use of these figures coupled with the aircraft heading allowed proper location of the updraft within the 'symmetrically round' cloud.

Tables 22 and 23 contain most of the results obtained. They present the following information: cloud type; number of clouds in sample; mean rate of climb (ROC) time in minutes; percent of total cloud penetration time prior to entering the updraft; percent time in updraft; percent of total cloud penetration time after leaving the updraft; cloud width in nautical miles; updraft width; peak rate of climb; peak Johnson-Williams (JW) water content in the updraft; peak JW water content outside the updraft (when peak in the cloud was not located in the updraft); peak Ruskin liquid water in the updraft; peak Ruskin liquid water outside the updraft (peak in the cloud not located in updraft); peak vapor density in the updraft; peak vapor density outside the updraft (peak in the cloud not located in the updraft). The peak Ruskin and JW values may not coincide in actual location within a cloud. Therefore, those values should not be used as though they occurred together.

The cloud types, identified by numbers in the tables, are as follows:

1 Cumulus congestus —towering cumulus
2 Cumulus congestus adjacent to thundershowers
3 Front feeders
4 Trunk feeders
5 Congestus showers —cumulonimbus calvus
6 Cumulus cells in layers
7 Squall line back feeders
8 Cumulus congestus going to cumulonimbus calvus

Perusal of the mean values, stratified by cloud type in table 22 reveals little difference in the first five cloud types (the only types with more than 10 clouds in each sample). Median values are not too different from mean values (table 23).

An overview look at all the clouds reveals a growing 'typical' cloud to be 3 n mi in diameter with a centrally located 1 n mi diameter updraft which has a speed of 6 m/sec (1200 ft/min). The updraft occupies about half of the cloud. Peak JW, Ruskin, and vapor density values of 1.8, 12, and 5.6 g/m^3, respectively, can be expected.

Table 24 is an analysis of the location of the updraft within the cloud and is based on the assumption that each updraft and each cloud were round and each updraft and cloud were penetrated through the center. Furthermore, clouds in which the aircraft headings at entry and exit points were in opposite quadrants were used. For instance, data from an aircraft heading of 045° on entry into the cloud and 090° on exit from the cloud were not used in this table. This helped ensure that the full extent of the cloud and updraft was sampled. Table 24 presents for each cloud type the location of the updraft in percent of cloud from the edge of the cloud for a particular quadrant (relative to true north). For instance, for cloud type 1 the updraft edge is located 26.1% of the way from the cloud edge in the 0-90° quadrant. These percentages were determined by looking at updraft entry and exit locations in each of the four quadrants and calculating by the same procedure as the percentages calculated and described earlier.

There is a general tendency for the updrafts to be located slightly toward the west side of the clouds (large numbers for the 0-90° and 91-180° quadrants). This is especially true for cloud types 2-5 which are associated with precipitation echoes. However, if one looks at the type 1 clouds the updraft is almost symmetrically located with the cloud. The weighted average of the clouds is based on all of the 142 clouds and is not simply an average of the 8 cloud types. For instance, the type 1 cloud category is more strongly weighted (67 times greater) than type 6. On the basis of the average of all the clouds, the updraft is slightly displaced to the west side of the clouds.

Table 22. Median Cloud and Updraft Parameters Stratified by Cloud Type, Based on Penetrations near 0 C Level

Type	*Clouds*	*ROC time (min)*	*% Time before UD*	*% Time in UD*	*% Time after UD*	*Cloud width (n mi)*	*UD width (n mi)*	*Peak ROC (m/sec)*	*Peak JW in UD (g/m³)*	*Peak JW out UD (g/m³)*	*Peak RUS in UD (g/m³)*	*Peak RUS out UD (g/m³)*	*Peak Vap D in UD (g/m³)*	*Peak Vap D out UD (g/m³)*
1	72	0.33	19	44	21	2.2	0.9	4.2	1.5	1.7	9.7	10.9	5.5	5.5
2	20	0.46	20	37	23	3.4	1.2	7.0	1.6	0.8			5.6	4.9
3	22	0.38	8	44	23	2.3	1.0	5.8	1.2	1.4	12.4	10.1	5.9	6.2
4	15	0.33	40	42	8	3.1	0.9	6.0	2.4	2.8	9.8	12.1	5.7	6.2
5	20	0.42	12	34	11	3.4	1.1	8.0	1.7	2.0	11.1	10.1	5.8	5.7
6	4	0.50	38	16	46	2.6	1.4	4.4	2.0	2.1	10.2	11.9	4.8	5.0
7	3	0.25	18	51	49	2.2	0.7	3.7	0.9		7.7		5.6	
8	7	0.58	19	60	21	2.8	1.5	5.5	1.5	0.9	9.5	12.1	5.7	
Total	163													
Median		0.46	26	44	31	3.6	1.2	6.1	1.7	1.9	11.0	13.0	5.6	5.6

Table 23. Mean Values of Various Cloud and Updraft Parameters Stratified by Cloud Type, Based on Penetrations near 0° C Level

Type	*Clouds*	*ROC time (min)*	*% Time before UD*	*% Time in UD*	*% Time after UD*	*Cloud width (n mi)*	*UD width (n mi)*	*Peak ROC (m/sec)*	*Peak JW in UD (g/m³)*	*Peak JW out UD (g/m³)*	*Peak RUS in UD (g/m³)*	*Peak RUS out UD (g/m³)*	*Peak Vap D in UD (g/m³)*	*Peak Vap D out UD (g/m³)*
1	72	0.39	25	47	28	2.3	1.1	5.2	1.7	1.7	10.3	11.1	5.8	5.6
2	20	0.48	29	42	29	3.9	1.3	6.6	1.7	0.9			5.6	5.2
3	22	0.47	21	47	32	4.1	1.2	7.7	1.5	1.9	13.3	11.4	5.9	6.2
4	15	0.44	34	45	20	3.3	1.2	6.4	2.4	2.8	11.3	15.5	5.6	6.0
5	20	0.52	28	41	31	4.1	1.5	9.3	1.8	2.0	13.8	10.0	5.7	5.7
6	4	0.44	44	18	38	3.9	1.2	4.5	2.1	2.1	10.0	14.6	5.0	5.0
7	3	0.28	14	43	42	1.8	0.7	3.5	1.4		8.5		5.7	
8	7	0.52	15	54	31	2.8	1.4	5.8	1.4	0.9	11.0	14.5	5.6	
Total	163													
Average		0.44	26	42	32	3.3	1.2	6.1	1.8	1.8	11.2	12.8	5.6	5.6
Median		0.46	26	44	31	3.6	1.2	6.1	1.7	1.9	11.0	13.0	5.6	5.6

Table 24. Location of Updraft (in Percent of Cloud) from Edge of Cloud for Given Quadrants

Cloud type	Number of clouds	Cloud quadrant 0-90°	91-180°	181-270°	271-360°
1	67	26.1	28.2	23.5	22.9
2	16	37.0	27.0	14.2	15.5
3	19	33.5	26.8	24.6	18.7
4	14	28.7	43.6	31.0	25.4
5	15	27.1	26.8	30.0	13.5
6	1	60.0		0	
7	3	28.1	39.0	8.5	44.0
8	7	33.8	31.2	20.2	23.1
Total of clouds	142				
Weighted average of all clouds		29.3	29.4	23.4	21.0

Although based on slightly different clouds, the cloud base and mid-cloud updraft analyses reveal that the mid-cloud updrafts are about twice as strong as the cloud-base updrafts. This suggests that the smaller and weaker updrafts at cloud base somehow consolidate at mid-cloud to provide the larger and stronger updrafts. The location analyses of the two types of updrafts indicate that the updraft is slightly tilted from east to west as it extends up into the cloud. This is determined from the knowledge that cloud base updrafts are located on the front of echoes and the mid-level updrafts are slightly displaced into the western quadrants of the cloud.

F. SUPPRESSION HYPOTHESIS AND SEEDING TECHNOLOGIES

The establishment of a hail-suppression seeding hypothesis requires:

1) A description of the evolution and structure of hailstorms in terms of their internal and near-environmental airflow and the characteristic distributions of the three phases of water substance which are transported by or suspended in the flow
2) A description (as quantitative as possible) of the microphysical processes which determine the distribution in space, by particle size and by phase of the water substance in the cloud
3) A description of a feasible treatment by which the natural balances existing within 2) and between 1) and 2) can be altered in such a way as to produce more favorable weather (less hail damage, no anti-economic alteration of rainfall, no other dangerous or economically negative lateral effects)

STORM STRUCTURE AND AIRFLOW

Current thoughts on the airflow structure of hailstorms center on certain model types of storms exhibiting varying degrees of complexity (from highly organized to disorganized) and temporal steadiness (from steady to randomly pulsating). One model is the 'bubble' or air mass hailstorm described by Ludlam (1958) that is believed capable of producing small hail. This storm type consists of a pyramidal mass of convective elements called bubbles or thermals, whose individual properties were investigated by Scorer and Ludlam (1953). The bubble storm takes place in an atmosphere of great instability with little or no vertical wind shear. Accumulation of precipitation in the updraft eventually overcomes the buoyancy leading to formation of a downdraft and finally to dissipation of the cell. However, a thunderstorm area can consist of several adjacent cells, each in a different stage of development.

Next on the scale of organization is the 'feeder-cell' model [the concept seems to have first appeared in Vickers and Goyer (1966)] . It consists of a series of small growing towers ranged in a line which, one after the other, merge with a large, mature 'parent storm.' It is not quite clear whether the new towers merge with the parent storm and thereby lose definition, or whether the parent cell dies and is replaced by the newly arrived cell. This hailstorm model was derived from visual observation of feeder cell systems in action. At times the state of the atmosphere is such that surrounding middle and high clouds obscure the growing towers and it is difficult to identify the ongoing feeder cell process.

The model which embodies the greatest simplicity and highest state of organization and steadiness is the 'supercell' or steady state storm first introduced with observational support by Browning and Ludlam (1962) and subsequently refined by Browning and Donaldson (1963). It is infrequent in Illinois. The supercell is the largest, most severe storm, capable of producing very large hail as well as other forms of severe weather. The supercell storm consists of a single large updraft and an adjacent organized downdraft. It develops in the strongly sheared baroclinic environment of frontal or prefrontal zones and in the vicinity of the jet stream. The dynamic pressure-drag forces on the rising updraft air are such as to produce updraft streamlines which are sloped in the lower and middle levels. This sloped airflow allows the fallout of precipitation which would otherwise accumulate in the updraft and counteract its buoyancy. This same precipitation falls into dry mid-to low-level air which is cooled by evaporation and sinks to form the organized downdraft. At higher levels, the updraft air is drawn away from the storm by the strong jet winds. The downdraft acts as a mesoscale cold front, furnishing strong lift to the inflowing air and strengthening the updraft.

The strength of the updraft in the low- to mid-levels is such that drops which form there do not have time to grow to large sizes, and larger drops cannot enter it. This results in an absence or weakness of the radar echo in the updraft and the formation of a characteristic 'wall,' 'vault,' and 'overhang' structure of the echo, which in certain cases becomes hooked or notched in shape. Hail embryos form in the forward overhanging part of the radar echo. The embryos sink into the sloping updraft as they grow and are able to 'recycle' to remain suspended in a growth environment until attaining large size. It has been suggested in Morgan (1972) that the vault or weak echo region is only indicative of a strong (over 20 m/sec) updraft, so it is not necessarily a guarantee of a supercell storm.

SUPPRESSION HYPOTHESIS

Though there are several ways to attempt to modify hailstorms, the only extensive attempts at tests or applications have been based on some type of ice phase seeding.

It is important to stress that there is as yet no adequate and widely accepted theory for the nucleation of ice. The most often cited theoretical treatment is that of Fletcher (1966) which rests on some rather approximate simplifications and assumptions (the theory is built up in the same manner as that for water droplet nucleation with ice crystals assumed spherical in shape).

Though resting on a fairly firm empirical base, the artificial inducement of ice formation in the free atmosphere is always somewhat vulnerable to controversy. This arises from poor reproducibility of measurements by different techniques (though this aspect of the problem seems to be moving toward some clarification) and the influence of poorly understood phenomena of poisoning or activation by trace substances and deactivation by high humidity, exposure to liquid water at warm temperatures, and exposure to solar radiation. Additional complications of concern are scavenging of artificial ice nuclei by ice particles or of numerous ice nuclei by single particles and the turbulent diffusion of the ice nuclei from the point and time of release.

Specifically problematic in attempting to arrive at a scientifically based choice of a hail prevention hypothesis is the fact that though it has not been found possible to reliably predict ice crystal concentrations in clouds based on measurements of concentrations of ice nuclei in the inflowing air, such nucleation measurements are the basis for establishing the seeding rates for hail prevention (or rain enhancement) applications.

SEEDING TECHNOLOGIES

Among the most significant hail suppression field test programs are those carried out in the Soviet Union, Project Hailstop in Alberta, South African Project, and NHRE (National Hail Research Experiment) in northeastern Colorado. All of these are going on currently; in general, some procedural changes have been made in the course of each project and none has yet been sufficiently evaluated to determine its effectiveness. Descriptions of the current procedures of each of these projects are given.

The hail prevention projects employing cloud-base seeding have not been extensively described in the literature except for Henderson (1975), and Changnon (1974). This approach has been covered by means of an interview with a cloud seeding expert, and a summary of this interview appears in Appendix D of this report.

It should be noted that all the projects except that in South Africa base their hail suppression techniques on increasing the number of hail embryos by seeding the cloud with ice nuclei (most frequently Agl, but the Russians also use PbI_2). The operators of the South African project hypothesize a glaciation effect as being the principle underlying their approach. Based on observations and information available, we do not accept this hypothesis and have grouped this project among those operating on the augmented embryo concentration principle. Seeding agents other than Agl, such as NaCl and CuS, have been used very infrequently. The problem is how, when, and where to get the seeding agent into potential hail clouds and how to identify such clouds.

Soviet Projects

Several operational programs are under way in the Soviet Union. The Soviets believe that rapid hail growth occurs in what they call the accumulation zone (AZ) (Sulakvelidze, 1967; Marwitz, 1973). The AZ is believed to be just above the level of maximum updraft as computed by the 'slice method.' The AZ can have a liquid water content of up to 40 g/m^3. To get significant hail, the AZ must be between 0 and -25° C. Upper large droplets freeze and grow by combining with lower large droplets. Growth from 0.1 to 2 or 3 cm takes only 4 to 5 minutes. The AZ forms 30 to 60 minutes after the start of the cloud. The maximum updraft should be greater than 10 to 15 m/sec to yield significant hail.

The VGI (region) hail suppression technique begins with a hail forecast based on synoptic and radiosonde data. When thick cumulus appear, the 3.2-cm PPI radar starts scanning clouds to a distance of at least 100 km. An echo is seeded if the reflectivity (77) exceeds $5x10^8$ /cm and the echo top reaches -30° C. The silver iodide is injected at -6 to -8° C. If the hail focus is approaching the target area, the treatment is applied somewhat ahead of the strongest echo. If the storm reaches the hail stage over the target area, the maximum echo is treated. Four 100-g Agl missiles are used and repeated in 3 to 4 minutes if 17 does not decrease or the reflectivity zone does not sink. If there is still no effect, the seeding altitude is raised 500 to 700 m and the treatment repeated. An average of 6 to 7 missiles (either rockets or anti-aircraft shells) are used for each hail cloud. Over an extensive frontal process, 160 missiles may be used. The region of hail formation and growth is in the front part of the cloud.

Seeding will result in 150 to 400 hailstones/m^3, reducing hailstone size by a factor of 3 to 7. Assuming 10^{12} nuclei/g Agl and that it takes 500 nuclei/m^3 to seed a hail nucleus, 10 to 100 g AgI/km^3 of cloud air is needed. If PbI_2 is used, 11 to 12 PbI missiles are introduced at -9° C. Pb is not a significant pollutant.

The Alazani Valley operation uses rockets containing 1 kg PbI_2, which is distributed over a 6-km flight path giving 10^{15} active nuclei per km at -5° C. The number of rockets fired in a volley depends on the hail probability and the diameter of the high reflectivity zone. On 19 July 1972, volleys were fired at 2- to 5-minute intervals, with the center rocket through the Zmax core. In all, 51 rockets were fired.

The Transcaucasian Hydrometeorological Research Institute uses 15 anti-aircraft guns in one area. Storm dosage typically consists of 2 shells, each with 200 g NaCl, and 1 shell with 75 g Agl. The NaCl is injected in the Zmax region between 0 and -5° C, the AgI in the Zmax between -8 and -14. Sets of 3 shells are fired at 1-minute intervals until the threat ceases.

Alberta Hail Project Field Program

The Alberta project has also been called Project Hailstop. The design calls for hail suppression over a 'protected area,' and the newly appearing cells or rapidly growing towers close to the 'parent' storm are to be seeded (Deibert and Renick, 1975). Several such cells may exist at any one time, 20 to 50 during a system lifetime. It was desired to increase the number of hailstones by a factor of 100 or more in order to decrease their size. In a 1970 pilot study, a T-33 aircraft seeded each new cell from above as the cell passed through the 20,000 foot level. One 1-oz (28 g) AgI flare was dropped every thousand feet, and from 5 to 20 flares were used in each new cell.

In 1973 a more extensive and detailed effort was carried out. Three turbocharged aircraft carried four 26-unit Lambert flare racks on the bottom of the fuselage controlled by two Olin flare-firing control panels. The target area covered 7460 mi^2 with 429 stations consisting of a simple raingage, hail-collection bags, volunteer hail observers, and a prototype hailpad network. Telephone surveys were made after a hailstorm. On a day forecast as a potential hail day, one seeding aircraft was launched for patrol as soon as weak echoes or cumulus congestus were sighted approaching the target area. If either the radar or the patrol aircraft noted an increase in intensity, the remaining aircraft were launched. Growing towers were identified usually. When a decision to seed was made, a 50-g AgI flare was dropped every 1000 feet. Seeding runs were continued as long as new towers developed. The seeding material was injected in the -12° to -5° C layer. Experiments were also carried out with cloud-base seeding using 100-g AgI flares (32 per rack) burning for 5 minutes each.

In 1974, an area of 18,500 mi^2, centered on a C-band radar site, was used in a field test running from 20 June to 10 September. The network was divided in half; in the southern half, all growing towers were seeded if a storm's reflectivity exceeded 35 dbz. In the northern half, only half the potential hail days were seeded on a randomized basis. Here, a radar reflectivity exceeding 45 dbz was required before any seeding occurred, but thereafter all growing towers were seeded as long as the reflectivity remained above 35 dbz. Five turbocharged aircraft were available for on-top seeding, and two non-turbocharged aircraft for cloud-base seeding of growing cells that were embedded in the parent storms so that their cloud tops could not be observed (or seeded aloft). Altogether, 3018 droppable 50-g AgI flares and 1476 70-g wind-mounted flares were used during the 31 seeding days. The turbocharged aircraft were equipped with four 26-unit ejector flare racks mounted on the bottom of the fuselage. All seven aircraft were equipped with two wing-mounted cloud-base seeding flare racks, each rack holding 16 flares.

Each morning a hail-potential briefing was given. When hail was forecast, the radar was turned on and crews alerted. When weak radar echoes were detected or cumulus congestus sighted upwind of the target area, a seeding aircraft was sent on patrol. When radar indicated an increase in storm activity, or the patrol aircraft sighted vigorous convective activity, additional aircraft were dispatched. If visible towers were observed, cloud-top aircraft were sent; if cells were embedded, cloud-base aircraft were deployed. Each aircraft was assigned an individual storm. Cloud-top flares were dropped every 1000 feet; cloud-base flares were ignited one at a time (each burned 7 minutes) unless the updraft exceeded 1000 ft/min in which case two or more were ignited. Seeding runs were continued as long as new towers developed and Z remained above 35 dbz. Again the seeding agent was injected between -12 and -5° C with the droppable flares. An attempt was made to produce 100 nuclei/liter effective at -10° C.

A network of 540 stations was set up in the area of 12,200 mi^2 with 224 (1/23.5 mi^2) in the northern half and 219 (1/29.5 mi^2) in the southern half, plus a 468 mi^2 'dense' network with 97 stations (1/4.8 mi^2) in the northern half. Simple raingages and hailpads were used. Farmers were asked to note the time rain started and to put out clean beakers to sample each rainfall. Hailpads were changed after each hailstorm or once a week. Where possible, hail samples were to be picked up off a clean surface and put into a small freezer for later collection and analysis.

No conclusions were drawn as to the effectiveness of seeding, but a denser network was recommended for the following season. *Hail forecasts based on synoptic data were found to be more accurate than those based on radiosonde data.*

South Africa Project

The South Africa project (Colorado International Corporation, 1974a and b) has attempted, as did the Alberta Project, to seed rapidly rising turrets from above. The project was run on a strictly operational basis. Two turbocharged Aztec aircraft were used in 1971/72 and 1972/73. One Lear jet and one Aztec were used in 1973/74 and 1974/75 for cloud-top seeding, and in 1975/76, they are using two Lear jets and an Aztec. A Pacer 5-cm radar with computer has been used to monitor the clouds. The peak of the hail season in South Africa is from mid-November to the end of January, so that seasons are shown as 1971/72 etc. and the total hail season is 8 months beginning in September.

Go, standby, or no-go days were decided largely on the basis of the morning (0830 LST) radiosonde data. The atmosphere had to be unstable (approximately dry adiabatic above the low-level inversion) with at least 2 to 4° C buoyancy at a 'parcel' cloud temperature of -15° C. Most major storms are prefrontal, associated with an organized cold front approaching from the southwest. Northeast surface winds often back quickly to the west and increase in speed to greater than 50 kt above 500 mb. There has to be sufficient moisture to give a relatively low CCL. The current 1975 criterion for seeding is a Zmax of over 45 dbz extending above 25,000 feet MSL. Each new turret that passes through the 25,000-foot level on the active development side of the larger mature storm is seeded.

The Lear rack holds 108 of the 60-g AgI (Sierra Research SR-1) flares with an effectiveness of 10^{12} nuclei/g AgI at -10° C. The jet can descend, depressurize, and interchange flare racks one time without landing. It generally drops its flares from about 30,000 feet with a 30-second delay burn in order to bracket the -10° C isotherm with the AgI nuclei.

Case studies were described (Colorado International Corporation, 1974a and b). On 22 January 1974, 20 flares were dropped into a rapidly rising turret on the flank of a storm reaching 60,000 feet. The turret had no echo, but the major echo (viewed on RHI) had a reflectivity value of 30 dbz extending above 50,000 feet with Zmax occurring at 25,000 feet. On 1 April 1974, four developing turrets were seeded. The 40-dbz contour of the mature storm reached 35,000 feet at 1607 LST and hail was reported. The four turrets were seeded as follows: turret 1 — 16 flares at 1608 LST; turret 2 - 5 flares at 1611; turret 3 - 8 flares at 1613; turret 4 - 5 flares at 1614. The seedings did not occur in turrets giving echoes. At 1625, only spots of the 30-dbz contour extended above 29,000 feet. The low-level 40-dbz area and values did not decrease, so it was inferred that rainfall had not diminished.

In total, there were 43 seeding days for 1973/74, 598 seeding passes, and 5063 flares were used. Radar surveillance of the target area is being recommended even on the no-go forecast days, in case of a bad forecast. The Lear jet was used to seed 104 storms, the Aztec 39.

Over 1700 hail cards were distributed to farmers throughout the protected areas to obtain hail data in addition to the insurance loss data. Good results were obtained from solicited observers within 20 n mi of the city of Nelspruit. The fraction of the total registered (insured) crop area hit by hail in the season was compared to the total registered area. Also the severity of the hail was determined by counting the number of tobacco leaves with hail-caused holes and reducing the 'area hit' to an equivalent area of all the tobacco leaves that had been damaged. This result also was compared to the total registered area. The operations of the 1973/74 season appear to have been fairly effective in reducing hail damage, but more operations are needed to establish seeding effectiveness.

The considerable potential for using this jet seeding approach in the complex storm systems of the Midwest led the principal investigators of DESH to visit the South African project during 6-10 December 1975. As part of DESH, we had done a statistical evaluation of the project data and found the results encouraging (see the section "Evaluation of Hail Suppression"). The pre-frontal storms appear to be quite similar to those in Illinois and the seeding system has obvious advantages. However, seeding of inner cells in a complex cell and nocturnal storms is very difficult.

National Hail Research Experiment

As in the Soviet operations, South African project, and Alberta experiments, NHRE has attempted to inject seeding material into the supercooled portion of the cloud (Lovell and Sanborn, 1974). Early in the experiment, it was decided not to use ground-based rockets or artillery shells because of various U.S. air space regulations. Firing into the critical storm region (taken as -5° C) with horizontal rockets was considered initially, but eliminated after expensive testing because of range and accuracy problems. Cloud-base seeding was accepted as a back-up system, but there was concern over deactivation of the AgI nuclei by the cloud droplets at the lower (warmer) levels. It was finally decided to use spin-stabilized rockets carrying 100 g AgI launched vertically from an aircraft flying at cloud base, and dispensing nuclei in the supercooled portion of the cloud. However, delays in rocket delivery led to sole use of cloud base seeding in 1972 and 1973, and a mixture of rockets and cloud base seeding was used in 1974. Cloud-top seeding was eliminated because of the presumed difficulty of seeing the rising turrets in the masking clouds. Also considered was horizontal seeding at the -5° C level, with an armor-plated T-28, but this appeared to be too expensive. The vertically launched rockets finally used in 1974 rose 6500 feet above the aircraft. There is said to be no hazard from falling fragments.

It was decided that for evaluation purposes it was not possible to use past historical data because adequate past data were lacking and because of the variability between years. Similarly, it was not possible to find a control area whose hail records were well correlated with those of the target area. Therefore, only a small (600 mi^2) area was selected, and randomized seeding was used on declared hail days.

Hail days appear to occur in sequence. If no hail occurred on the previous day, a random list was used to determine if a day was to be a seed (S) or no-seed (NS) day. If hail occurred, days were alternately seeded and not seeded until that particular hail-day sequence was broken by a non-hail day, and the operator returned to using his random list to determine S or NS days.

Hail days were declared on any day with a 10-cm radar reflectivity equal to 45 dbz between -5 and -30° C and when the 35-dbz contour was within 20 minutes of the protected area. Unfortunately, poor radar calibrations led to differences in the radar seeding criteria in each of the 3 years (NSF RANN, 1974). This has greatly affected the viability of the results. An operational day started at 1000 LDT and ran until dark (~ 2000).

A radar watch was established at 1000, and if the day was a potential seed day, the aircraft were notified to take off when storms were within 50 miles of the target area (i.e., before declaration of a hail day). If storms began to develop over the target area, the aircraft were also called out to be ready to seed in the event a hail day was declared. Peak hail frequency is at 1400 and 1630-1800; about 4% presumably occur from 2200 to 1000.

On a seed day, each seeding aircraft was deployed to the region of the storm determined by maximum overhang of the 35-dbz radar contour. The pilot established two parallel seeding legs, each 6 miles long and separated by 1 to 1.5 miles. Distance of the seeding pattern from the precipitation wall was determined by characteristics of air inflow and radar overhang. When a hail day was declared, the aircraft flew its seeding pattern, firing rockets and burning flares (in 1974 only) at alternate 1-minute intervals. Seeding continued as long as the reflectivity remained above 35 dbz above the -5° C level, or until cells no longer endangered the target area, or until 2015. In 70% of the cases, several storms occurred simultaneously in the target area.

On a no-seed day all operations were carried out as on a seed day except that no aircraft were dispatched for cloud seeding even if a hail day was declared.

With an assumption that 10 nuclei/liter was desired, the seeding rate was established on the basis of an average updraft of 3×6 miles, an updraft speed of 10 m/sec, the aircraft flying at 130 kt, a 100-g flare being fired each minute, and each gram of AgI producing about 5×10^{12} nuclei. This yields slightly over 10 nuclei/liter. An additional aircraft was required for every additional 18 mi^2 of updraft. The seeding rate was decreased for the weaker systems.

The 1974 NHRE program ran from 13 May through 9 August, 7 days per week. To determine the likelihood of hail, the project had available hourly surface observations, hourly sectional charts, 3-hourly radiosonde observations, teletype, and facsimile. Each morning several hourly sectionals were plotted with pressure, relative humidity, wind, streamline analyses, and once-a-day θ_e analysis. The morning (0730) sounding was used to compute cloud-base height. This incorporated the mixing ratio, the forecasted dry adiabat below cloud, temperature of the CCL, magnitude of the positive area, height and temperature at the top of the positive area, tropopause height and temperature, and height of the -5°C level for a rising parcel. The Air Force Global Weather Center forecast was obtained each day. Regardless of the final forecast, all systems were set to go in case a hail threat materialized that was not forecast.

Among the hail parameters measured to determine the effectiveness of seeding were total mass of hail per unit area, maximum stone size, number of stones per unit area, impact momentum per unit area, and areal extent of hail. Hail mass was the primary measure because it was felt it could be most reliably measured with hail/rain separators which can be economically produced in large numbers. Plans to supplement these devices with new electro-optical devices which would provide a hail size spectrum were offered in 1975. The network alterations and variety of hail instruments used during 1972-1974 also have complicated the interpretation of the results (NSF RANN, 1974).

Approximately 16 hail days can be expected to occur annually in the protected area. About 1 or 2 will be extremely severe storms, 3 or 4 will be moderate, the remainder light. The few heavier storms dominate the statistics. Over 400 stations were in and around protected areas. Four twin engine Aztecs were used for seeding.

G. DESIRABILITY STUDIES

Desirability studies, considered essential to the design of a hail suppression experiment for Illinois, include social, ecological, and economic aspects, plus legislative activities (see figure 1). Public attitude sampling, summarized in this section, was the principal study concerning social impacts, although various public information activities were also carried out (Appendix F). Also reviewed here, for one potential ecological question, is a study concerning background data on levels of silver in hail, important because of likely use of silver iodide in seeding. Although prior economic studies of hail have provided the basis for economic-related decisions, more recent studies give additional useful information, also summarized here.

A sound legal framework for the control of weather modification in Illinois was provided by a newly enacted state law promoted by the Water Survey (Ackermann et al., 1974). In addition, a 1974 assessment of weather modification in the Illinois area by agricultural specialists calls for the initiation of hail and rain modification experiments. The 1974 statement of the North Central Region Committee (NC-94) for Weather Information for Agriculture is presented in Appendix C.

PUBLIC ATTITUDE SAMPLING

The Weather Attitude Sampling Project (WASP) was planned and initiated during January-March 1974 and completed in September 1974 as a part of milestone 31 (see figure 2). Milestone 31 was concerned with possible society, economic, and environmental impacts, and with the need for this information if an Environmental Impact Statement were to be prepared prior to an experiment. The WASP goal was to sample an adequate number of central Illinois citizens to gain accurate information *a)* on the impact of weather on their lives, and *b)* on their attitudes toward hail suppression specifically and weather modification in general. Such information was considered an essential part of the design of any future experiment, the advice given the state on the desirability of such a project, and proper means of local institutional arrangements.

WASP was jointly conducted under the direction of Human Ecology Research Services, Inc. (HERS), a Colorado firm experienced in sampling and interpreting weather modification attitudes, and the Water Survey. This work was directed by Dr. Eugene Haas. The project staff at the Water Survey helped with many of the logistics including devising interview questions, getting sampling information, developing lists of residents, and making arrangements for those who did the interviewing to use Survey telephone facilities.

The WASP sampling effort was conducted in April 1974, the start of the second year of the project. Under direction of HERS personnel, some 274 citizens chosen at random from the proposed hail project area in central Illinois were questioned at length (a typical interview took 45 minutes for 108 questions). These answers were interpreted by HERS, and a report was furnished to the Water Survey (Krane and Haas, 1974).

The citizen sample used in this study was a random sample selected from telephone directories in a 5-county area of central Illinois. Residents in the following counties were sampled: DeWitt (entire county); Piatt (northern one-half); Macon (northern one-third); Logan (southeast corner); and Champaign (small section of the western edge surrounding Mahomet). A total of

274 interviews were completed by telephone during a 2-week period in April 1974. Since there was a total of approximately 15,600 residential listings in the directories, this was a 1.8% sample for the designated area of central Illinois.

[It should be noted that the sample is biased in favor of telephone subscribers with published listings. As in any sample drawn from telephone directories, it is not possible to estimate the amount of bias introduced. Illinois Bell has provided an estimate that 94% of all households in this region of Illinois have telephones.]

The interview schedule was composed primarily of items used in previous and ongoing field research on public response to weather modification. Most of the items had been pre-tested in face-to-face and telephone interviews in Colorado, Florida, Montana, New York, South Dakota, and Utah. Items which pertained only to WASP were pre-tested in Illinois.

Interview schedule items were designed to elicit information on the following key variables:

1) Attitudes toward weather, weather modification, and science
2) Belief in the efficacy of cloud seeding technology
3) Awareness of weather modification activity
4) Awareness of the Illinois State Water Survey
5) Evaluation of proposed local programs
6) Preferred decision-making.and funding procedures
7) Socio-demographic characteristics

This survey is the first systematic attempt to measure public awareness and attitudes toward weather modification in the central portion of the United States — a climate regime considerably different from the plains and mountain states where most research on social aspects of weather modification has been undertaken. Additionally, it is important to reiterate that the survey was conducted prior to the start of any local cloud seeding. Thus, Illinois residents had not experienced a weather modification program to date.

Basically, attitudes about weather and nature (God) in Illinois were found to be similar to those found in other states. Results for 6 of the 108 questions appear in table 25. The majority, 54%, favored an experimental hail suppression program, whereas only 33% favored an operational program. Answers to questions about successful weather modification indicated that 54% believed that moisture could be increased, but only 20% thought hail could be decreased. In fact 62% just did not know about a hail suppression capability. With regard to decision-making about weather modification, half thought local residents should decide, but only 20% believed locals would decide. There also was a strong indication that the state, rather than the federal government, should and will decide on weather modification in Illinois.

Table 25. Attitudes of Illinois Citizens toward Weather Modification Issues

(In percent of the total in each column)

	Position toward types of hail suppression program			Can weather modification			Decision making about experimental hail or rain program in Illinois	
	Experi-mental	*Opera-tional*		*Increase moisture?*	*Decrease hail?*		*Who should decide?*	*Who will decide?*
Strongly oppose	5	9	No	11	14	Don't know	7	13
Oppose	16	19	Perhaps, doubt it	4	4	Local residents	49	20
Neutral	25	39	Don't know	31	62	Federal alone	1	4
Favor	48	30	Think so	15	7	State alone	28	44
Strongly favor	6	3	Yes	39	13	State + federal	6	8
						Scientists & others	9	8

The summary of findings in the report from HERS (Krane and Haas, 1974) is reproduced here because it highlights all the other major findings. Their more detailed discussion of the findings appears in Appendix B.

Summary of 16 Key Findings about Public Attitudes in 1974

1. The public view toward weather modification in Illinois before any experimental program is favorable.
2. Studies in Colorado and South Dakota prior to the start of local seeding programs resulted in findings very similar to those from Illinois.
3. Although general attitudes toward weather modification in the three states (prior to any seeding program) are comparable, a major difference is that Illinois residents are not as likely to anticipate personal economic benefit from effective cloud seeding programs.
4. Expressions of support for cloud seeding in Illinois:
   a. The majority favored experimentation with cloud seeding to find out if it works (63%). Only one out of five expressed disagreement with the concept of experimentation.
   b. Nearly three-fourths agreed that Illinois state agencies should use such things as cloud seeding if it could help farmers avoid crop losses.
   c. Two-thirds agreed that it is appropriate to try to directly control extreme weather conditions by using the most effectual techniques known.
5. Some expressions of concern or doubt about cloud seeding technology in Illinois:
   a. As many as half agreed with the statement, ". . . cloud seeding is very likely to upset the balance of nature." However, when asked specifically if cloud seeding might damage the ecology of an area, the proportion dropped to less than one-third.
   b. Nearly one-half (48%) agreed that cloud seeding probably violates God's plans for man and the weather.
   c. The sample was equally divided on the statement, "Man should take the weather as it comes . . . " (45% agreed; 44% disagreed). A little more than half agreed that alternatives such as cheaper insurance and improved weather forecasting might be preferable to modifying the weather.
6. Belief in the efficacy of cloud seeding:
   a. A little more than half (54%) believed that cloud seeding can be effective for increasing rainfall; only 15% indicated doubt.
   b. With respect to hail suppression, the clear majority felt uncertain about the effectiveness of the technology; only one out of five believed it can be efficacious.
7. Anticipated benefit or harm from a local program:
   a. Few persons felt they would be economically harmed from effective programs for hail suppression (2%), for increasing rainfall (8%), or for decreasing rainfall (15%).
   b. Clearly, more persons anticipated personal benefit from a program which could effectively reduce hail-fall (60%) than from programs to manage rainfall, either for increasing rain (47%) or for decreasing rain (33%).
8. Relatively few Illinois respondents were aware of weather modification efforts in general. However, as many as 43% claimed to have heard of programs which attempted to increase rainfall, and 29% claimed to be aware of hurricane modification efforts.
9. Only one respondent (of 274) was aware of Illinois' comprehensive weather modification law.
10. The majority were uncertain or doubted that inadvertent weather modification is changing the weather, but as many as 37% felt that this may be the case. Nevertheless, an overwhelming majority felt that unintended cloud seeding should be better understood before undertaking planned modification efforts.
11. Awareness of the Illinois State Water Survey (ISWS):

a. A little more than half of the sample claimed they were aware of the ISWS prior to this survey.
b. Among those claiming knowledge of the agency's existence, one-third said the ISWS is responsible for water resources and water control; 18% said the agency collects weather data; 11% felt the agency engaged in research related to weather and water.
c. Only one out of 10 knew that the ISWS is conducting a hail research project.
d. About 60% indicated confidence in the agency to conduct experimental cloud seeding, while one-third were uncertain.
e. Although one-fourth either did not want such a program or didn't care whether it is for hail suppression or rainfall management, the most frequently expressed preference was for the program to include both types of experimental cloud seeding.

12. Decision making regarding local cloud seeding programs:
    a. Nearly half indicated that *local* input should be involved in the decision about a local cloud seeding experiment (32% said local residents, 17% said agriculturists). However, a large proportion felt that the state government or the ISWS should decide (28%).
    b. With respect to who *will* decide, only one-fifth felt that local imput will be considered, while more feel that the state (32%) or the ISWS (11%) will make the decision.
    c. The preferred procedure in Illinois for decision-making regarding an *operational* program was seen as "a referendum submitted to the vote of all citizens in the proposed affected area."
13. Funding regarding local cloud seeding programs:
    a. The most frequent response for both *preferred* and *predicted* funding of a local experiment was the "state government." However, more persons felt that local residents *will* have to contribute (26%) than felt that they *should* pay for such a program (12%).
    b. The most satisfactory arrangements for financing of an *operational* program were thought to be "federal taxes" or "voluntary subscription of farmers." This would seem to indicate that for the present most non-farm respondents would not want support for an operational program to come from a local or state tax base.
14. Evaluation (favorableness toward) of proposed local cloud seeding:
    a. More than half (54%) were in favor of a cloud seeding *experiment* for central Illinois while only one-third favored the notion of an *operational* program at this time. A large number were undecided about both types of programs, while at least one-fifth indicated opposition.
    b. For those favoring the experiment, most felt that it is desirable to determine if cloud seeding is effective for reducing hail damage. Among those opposing the experiment, the major reason given was fear that negative effects on the weather or nature will occur.
    c. Twenty-nine percent anticipated they might take supportive action for an experimental program, while only 8% felt that they would do anything to oppose an experiment.
    d. If the issue of an experimental program came to a vote, 50% felt they would vote in favor compared to 23% who felt they would vote against the program.
15. Factors contributing to evaluation of a proposed local program:
    a. The best predictors of favorableness toward local cloud seeding experimentation were general attitudes toward weather, weather modification, and science.
    b. Anticipated economic benefit or harm from an effective program predicted moderately well acceptance of an experimental program.
    c. Belief that cloud seeding is efficacious also predicted evaluation of a proposed local program. That is, persons believing that cloud seeding can be effective for reducing hail and increasing moisture were likely to favor a local experiment.
    d. Knowledge of weather modification activities elsewhere in the country showed weak correlation with favorableness toward a local program.
16. Socio-demographic characteristics and their relationship to evaluation of weather modification:
    a. Younger persons were more likely than older persons to be favorable toward the technology and its

application; more likely to believe that cloud seeding can be effective; and less likely to feel that adverse side effects might occur from cloud seeding.

b. Males tended to be more favorably inclined than females toward weather modification. They were more knowledgeable of cloud seeding activities, and less skeptical about potentially disruptive effects resulting from the technology.

c. Higher educated respondents were generally more favorable toward weather modification, were more knowledgeable, had greater belief that the technology can produce desired results, and were in favor of local experimentation.

d. Respondents in low income families tended to be opposed to the technology in general and to proposed local programs. Additionally, they did not anticipate personal benefit from the application of cloud seeding, and were likely to feel that cloud seeding may have adverse side effects.

e. Rural residents were more likely than small town or city residents to perceive economic benefit from effective hail suppression and rainfall management programs. Also, rural residents were the most likely to favor a local experiment at this time, but they were the least likely to favor direct application of the technology (an operational program).

SILVER SAMPLING

Hailstones were collected in central Illinois during March-June 1974 as part of DESH. This effort was performed to gather background data on levels of silver in hail. This effort was based on the belief that a future experiment will likely use AgI as a seeding agent, and that pre-experiment baseline values will be useful in evaluating and interpreting silver values during an experiment. This information was also deemed desirable in achieving milestone 31 (see figure 2) and in addressing potential ecological questions.

Rainfall sampling for silver analysis was also performed in Illinois during 1973 and 1974. The silver in 138 rain samples (taken at 4 sites) in 1973 exhibited sizeable temporal and spatial variability, but always with very low concentrations (Gatz, 1973). The rainfall-weighted mean concentrations of all samples was 73 ng/1. Rain samples (38) in 1974 had a weighted mean of 89 mg/1.

The silver in the inner portions of hailstones collected in 1974 was determined to check for spatial and temporal variations (table 26). Extremes for hailstones from one storm collected in 5 different locales in a square mile area denote a considerable micro-variation. Fourteen samples from various hailstorms over a 2000 mi^2 area on 3 April 1974 showed a 20:1 variation. Comparison of the averages for the four sample dates also reveals great temporal variability. The 4-day median value was 107 ng/1 and the average was 178.

The values for silver in rain and hail are considered adequate to furnish meaningful baseline values.

Table 26. Observed Silver Concentrations in Hailstone Samples in Illinois

Dates of hail	*Silver, ng/liter* Average	*Highest*	*Lowest*
3 April 1974			
5 sites on 1 mi^2	210	670	80
14 sites over 2000 mi^2	94	410	20
21 April 1974 (1 sample)	410		
8 May 1974 (3 samples)	120	206	22
11 June 1974 (4 samples)	90	116	64

ECONOMIC STUDIES

Although most of the economic investigations pertinent to DESH were done in prior years, more data on the relationship between hailfall parameters (energy, amount of ice, etc.) and the amount of loss (%) to individual crops were desired. Although a suppression experiment would be partially evaluated with crop losses, several surface hail characteristics would come from hail sensors. Thus, there is a critical need to quantitatively relate these characteristics to crop loss. Earlier research (Changnon, 1971) provided useful initial relationships, but more high loss values (> 50%) were collected for study. This research effort was increased during 1975 as part of a 1-year research project supported by NCAR to collect additional measurements in Illinois on crop loss and hailfall characteristics.

Another hail project somewhat allied to DESH was pursued in 1974-1975 with support from the hail insurance industry. The project investigates the feasibility of assessing crop-hail damage with aerial photographs, a technique recommended from earlier Survey research (Changnon and Barron, 1971). The capability to quantify hail losses at different stages of growth of wheat, corn, and soybeans is being determined from photographs taken at different heights and times after the storms. Results to date (Towery et ah, 1975) are extremely encouraging for developing a technology for adoption by the industry.

The site of the proposed hail suppression experiment would be in central Illinois between Bloomington and Decatur, in a square area of 2000 mi^2. Assessments of the crop-hail losses in this rural area were updated and translated into 1973 dollars. Values for the 1952-1973 period were developed from hail insurance loss data that were converted to estimates of the total area loss through knowledge of the percent of the area insured (varying from 65 to 75% in different years).

The average annual loss was $265,000 with extremes ranging from a high of $1,458,000 (1965) to a low of $22,680 (1959). Only five years (1953, 1965, 1966, 1968, and 1973) had losses exceeding the average with three of these more than $1 million.

Conversely, many low loss values existed. Six values (1952, 1957, 1959, 1963, 1969, and 1971) were less than $35,000, only 13% of the average. Clearly, the loss values were very skewed. The median annual loss value is $118,000, less than half the average. Long periods of low losses tend to occur. For example, from 1955 through 1959 (5 years) all annual losses were less than the median.

The years of major loss are infrequent but tend to be statewide. Illinois led the nation in crop-hail losses in 1973 with $40 million in losses, and in 1974 Iowa, another midwestern state, led the nation with $35 million in losses. In 1975 Illinois again led the nation in crop-hail losses. Preliminary figures suggest $50 million for 1975 (2% of the 1975 crop value).

Major parts of the planned DESH activities related to *a)* the evaluation of hail prevention techniques (milestones 6, 13, 20, and 28, see figure 2) and *b)* the evaluation of potential undesirable meteorological effects (milestones 14, 21, and 29). However, a major unplanned evaluation task area of DESH evolved in 1973 for three reasons.

First, the lack of NHRE results on a variety of key subject areas became apparent in 1973-1974, and this meant that decisions to launch an experiment would have to rely heavily on unevaluated results from other hail suppression projects. Second, our earlier evaluation-oriented research gave us the experience and reputation such that we were sought by others to evaluate and/or give advice on evaluation and design for projects in South Dakota, South Africa, Canada, Colorado, and Europe. In responding to these needs, we used new statistical techniques and discovered more efficient hail parameters. These innovations then required the updating of our earlier (1967-1969) extensive evaluation-related research for Illinois (Changnon and Schickedanz, 1969; Schickedanz and Changnon, 1970).

This section of the report describes the major evaluation efforts for South Africa and Texas, reports on the key results from the 4-year North Dakota Pilot Project, and then presents the latest results for Illinois on detection of seeding effects in surface hail data.

SOUTH AFRICA PROJECT

A South Africa hail suppression effort was initiated during December 1971 by the Lowveld Tobacco Cooperative (LTK), Nelspruit, Republic of South Africa. The suppression effort was reported on by Colorado International Corporation (1974a and b) and by Davis and Mielke (1974). An evaluation of the suppression efforts was made by Davis and Mielke with the use of historical crop insurance data collected by the Lowveld Tobacco Cooperative (Laeveldse Tabakkooperasie Beperk). Davis and Mielke concluded there were indications that

1) The most probable value of the distribution of the severity ratio (total damage amount/hectares hit) was decreased for seeded observations
2) The area hit by hail was increased for seeded observations
3) For crop damaged to '100% data' there was a decrease in the large values and an increase in the small values (i.e., shape change). [The '100% data' term is a damage summation; that is, when the assessors report 50% damage to 10 hectares, it is logged as 5 hectares damaged to 100%.]

The Water Survey, as a part of its Illinois program, decided to evaluate a South African project. After discussions in 1974 with G. K. Mather of the Colorado International Corporation, the Company performing the seeding, we obtained the crop damage data to perform an independent study. The extensive evaluation of these data was reported by Schickedanz and Changnon (1975) and is summarized here.

Data

The basic data used in this study were daily and annual crop insurance records of hail damage to tobacco. Since the hail season usually begins in September and ends in April (warm season), the seasons of data are referred to as 1961/62, 1962/63, etc. The daily insurance data were from a protected area encompassing 800,000 hectares (3000 mi^2) of which 30 to 40% was farmland. Approximately 6000 hectares of tobacco within the protected region were registered with the LTK. The daily insurance data for 100% damage and the 'registered hectares,' the area insured, for the non-seeded period prior to 1972 were obtained from G. K. Mather (personal communication), and that for the seeded period from Davis and Mielke (1974). Also, the data on hectares hit by hail for the 1967/68 season were obtained from Davis and Mielke (1974) and for the years prior to 1967/68 from Davis (personal communication).

Annual damage statistics for 7 areas outside the target area were also obtained from Davis (personal communication). These areas are located at various distances from the target area (up to 250 miles away), and are considered by Davis and Mielke (1974) to be in a different climatic-geographical area.

If one adjusts the data to compensate for the year-to-year variation due to increased registered (insured) crops (Schickedanz and Changnon, 1970), it is possible to use the earlier period of record. Since the number of hectares of registered crops are available, the most direct adjustment is to divide the daily values of 100% damage and the hectares hit by hail by the yearly registered crop values. That is,

$$\text{Adjusted damage} = (\text{100\% damage/registered hectares}) \times 10^5 \quad (9)$$

$$\text{Adjusted hectares} = (\text{hectares hit/registered hectares}) \times 10^5 \quad (10)$$

Also, the severity ratio as defined by Davis and Mielke represents an adjusted series of data and is defined by:

$$\text{Severity} = (\text{100\% damage/hectares hit}) \times 10^5 \quad (11)$$

Adjusted data samples of damage, hectares, and severity were computed and these were the basic data used in all subsequent analyses of the daily insurance data for this project.

Since the change in registered crop is less abrupt for the 1967/68 season to the present, and thereby represents a potentially superior source of data, the historical period was divided into three data samples, as follows:

Control 1 (C1) sample - data from 1961/62 through 1966/67
Control 2 (C2) sample - data from 1967/68 through 20 December 1971 (seeding began 21 December 1971)
Control (C) sample - data from 1961/62 through 20 December 1971

There were a few days during the seeded period which had damage but which were not seeded for various reasons (Davis and Mielke, 1974). These data were included in the C2 and C samples as non-seeded data.

Two turbocharged Aztec aircraft were used for seeding during the period from 21 December 1971 through 1972/73, while a Lear jet and one Aztec were used during 1973/74. Thus, the data from the seeded period were also divided into three samples:

Seeded 1 (S1) sample - data from 21 December 1971 through 1972/73
Seeded 2 (S2) sample - data during 1973/74
Seeded (S) sample - data from 21 December 1971 through 1973/74

Analysis and Results

Since daily insurance data are poorly correlated and since there were no randomized data, the continuous-historical design was the only appropriate evaluation scheme to use. It addresses continuous seeding (on all potential hail days) with the historical record being the control. It would have been highly desirable to use predictor variables from atmospheric soundings, but there were no historical sounding data on which to base such a predictor equation. The nearest sounding is at Pretoria which is about 100 miles away and generally in a different air mass regime.

In the continuous-historical design-evaluation scheme, the lack of areal control and/or predictor variables creates a formidable evaluation problem. If predictor variables from the areas outside the protected area cannot be found (due to poor correlation and/or different geographical' area) or from the meteorological variables, it is extremely difficult to determine whether a *statistically detected* change in the distribution of hail damage is due to *seeding* or to a *general change in the overall areal hail climate.* Nevertheless, empirical distributions of hail damage were determined for the adjusted damage, adjusted hectares, and severity data. The log-normal distribution was fitted to the hail data for the C1, C2, C, S1, S2, and S samples and the results are listed in table 27. The non-transformed means and standard deviations are also listed, along with the sample sizes.

Table 27. Distributional Parameters and Goodness of Fit Probabilities for Daily Insurance Data in South African Seeding Region

Sample	*Sample size*	*Mean*	*Standard deviation*	*Log mean*	*Log standard deviation*	*GFP for log-normal*
Adjusted Damage						
Control	214	528.3	949.4	5.26	1.45	> .20
Control 1	89	401.4	528.5	5.24	1.31	> .20
Control 2	125	618.7	1153.3	5.27	1.55	> .20
Seeded	40	491.1	627.1	5.51	1.23	> .20
Seeded 1	27	544.2	726.8	5.52	1.30	> .20
Seeded 2	13	381.0	337.7	5.48	1.09	> .20
Adjusted Hectares						
Control	213	958.0	1513.1	6.07	1.26	> .20
Control 1	89	875.3	1112.5	6.17	1.11	> .20
Control 2	124	1017.3	1747.1	5.99	1.36	> .20
Seeded	40	937.8	1034.7	6.18	1.29	> .20
Seeded 1	27	980.2	1164.3	6.12	1.40	> .20
Seeded 2	13	849.8	728.0	6.31	1.08	> .20
Severity						
Control	213	50.3	21.3	3.81	.51	.06
Control 1	89	45.7	19.9	3.70	.55	> .20
Control 2	124	53.6	21.7	3.88	.47	.15
Seeded	40	50.5	16.4	3.87	.31	> .20
Seeded 1	27	53.3	18.3	3.92	.34	> .20
Seeded 2	13	44.8	9.5	3.78	.21	> .20

Adjusted damage = (100% damage/registered hectares) x 10^5
Adjusted hectares = (hectares hit/registered hectares) x 10^5
Severity = (100% damage/hectares hit) x 10^5

Clearly, the log-normal distribution describes the data quite well with the goodness of fit probabilities (GFP) all greater than the often cited 0.05 level of significance used for rejection of fit.

For the adjusted damage data, the seeded period had a value of 491.1 which was slightly less than the control period value of 528.3. For adjusted hectares the seeded period had a value of 937.8 compared with control period value of 958.0; for severity data, the means were 50.5 and 50.3, respectively, for the seeded and non-seeded periods. Thus, *there was very little difference between the means of control and seeded periods.*

The comparison of means for the seeded period with the earlier control period (C1) indicated that the means during the seeded period were all greater. However, the comparison of the means for the seeded period with the means of the later period (C2) indicated that the means during the seeded were all less. Similar relationships existed with the standard deviation, with the exception of the comparison between the seeded and control values of severity in which the standard deviation for the seeded period was less than that for the control period.

Results of another important comparison are worthy of note. The means and standard deviations during the second seeded period (S2) were less than those during the first control period (C1). In general, the decreases in the standard deviations were much greater than the decreases in the means, and this strongly suggests a decrease in the standard deviation (shape parameter), particularly for the severity data during the S2 period. In this period (S2) the Lear jet was used for seeding and it has a much quicker response time in getting to hailstorms for seeding than the Aztec (cloud-base seeding) aircraft.

Summary

Analysis of the daily insurance data indicated that the seeding produced a significant reduction in hail severity, as reflected by the shape parameter of the log-normal distribution (figures 43 and 44). The change in shape was caused by a decrease in large values of severity (above 48) and an increase in small values of severity (below 48) as shown in figure 44. The reduction in the log-normal standard deviations was 40% which was significant at the 0.01 level.

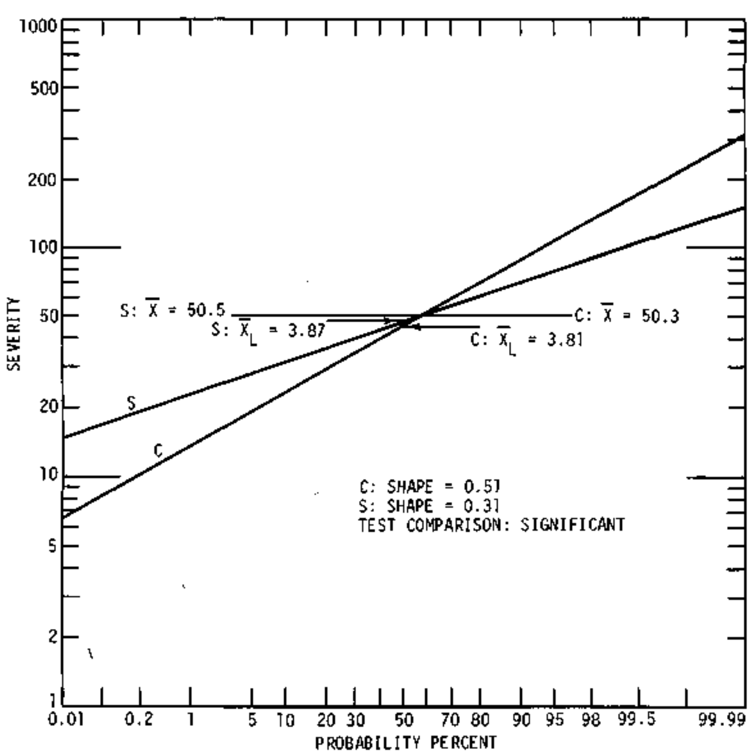


Figure 43. The log-normal distribution functions of severity for the control (C) and seeded (S) periods

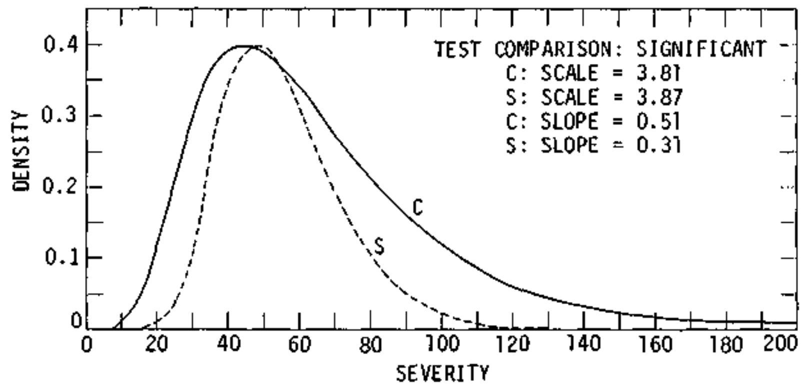


Figure 44. The log-normal density functions of severity for the control (C) and seeded (S) periods

Although non-significant, there were also results which indicated that *a)* larger daily values of (adjusted) damage were decreased, while small values were increased, and *b)* values of adjusted hectares (area hit by hail) were increased. Differences in 'adjusted' damage would be significant in approximately two more years (1975-1976). However, the present differences in adjusted hectares (area) would require many more years to be declared significant (25 years for scale and 200 years for shape).

Since it was impossible to obtain predictor (meteorological) variables for the protected area, and since the experiment was not randomized, it was extremely difficult to determine whether statistically detected changes in the distribution of the hail insurance data were totally due to seeding or to general space-time changes in the overall hail climate. Tyson et al. (1975) found a slight long-term (1880-1972) downward trend of rainfall in parts of South Africa which would likely mean less hail with time. They also found 20-year cycles in the seeded area such that the 1968-1972 period was one of the 5-year low rainfall periods, further support for less hail at the time when seeding began.

In order to partially assess whether the differences were due to the seeding, annual insurance data from another rather distant area were used as an areal control. Loss values of this area and the seeded area correlated well for the pre-seed (1961-1971) period. The use of the control area data as a predictor variable indicated that the observed differences in hail insurance values in the protected area during the seeded period may have been the result of seeding activity during the period 21 December 1971 through the 1973/74 hail season (figure 45). If the trend of expected and actual values of annual hail severity within the protected area were to continue into future years, the difference would be significant in two more years (by May 1976). No rain data were evaluated.

The above hail results could be stated with more confidence if predictor variables other than annual insurance data in the control area were available. In order to strengthen the conclusion that the change in hail severity during the seeded period was due to seeding, the reasons for the correlation of the control area values with those of the protected area should be explored. If this correlation is found to be spurious, then one is left with a significant hail reduction for which no cause is known.

The analyses of this seeding project underscore the importance of obtaining predictor variables (hail, rainfall, etc.) in surrounding areas, or variables from atmospheric soundings, to aid in the evaluation and interpretation of results. This is particularly true when one uses the continuous-historical design.

The apparent success of this project involving a jet seeding system that offers apparent

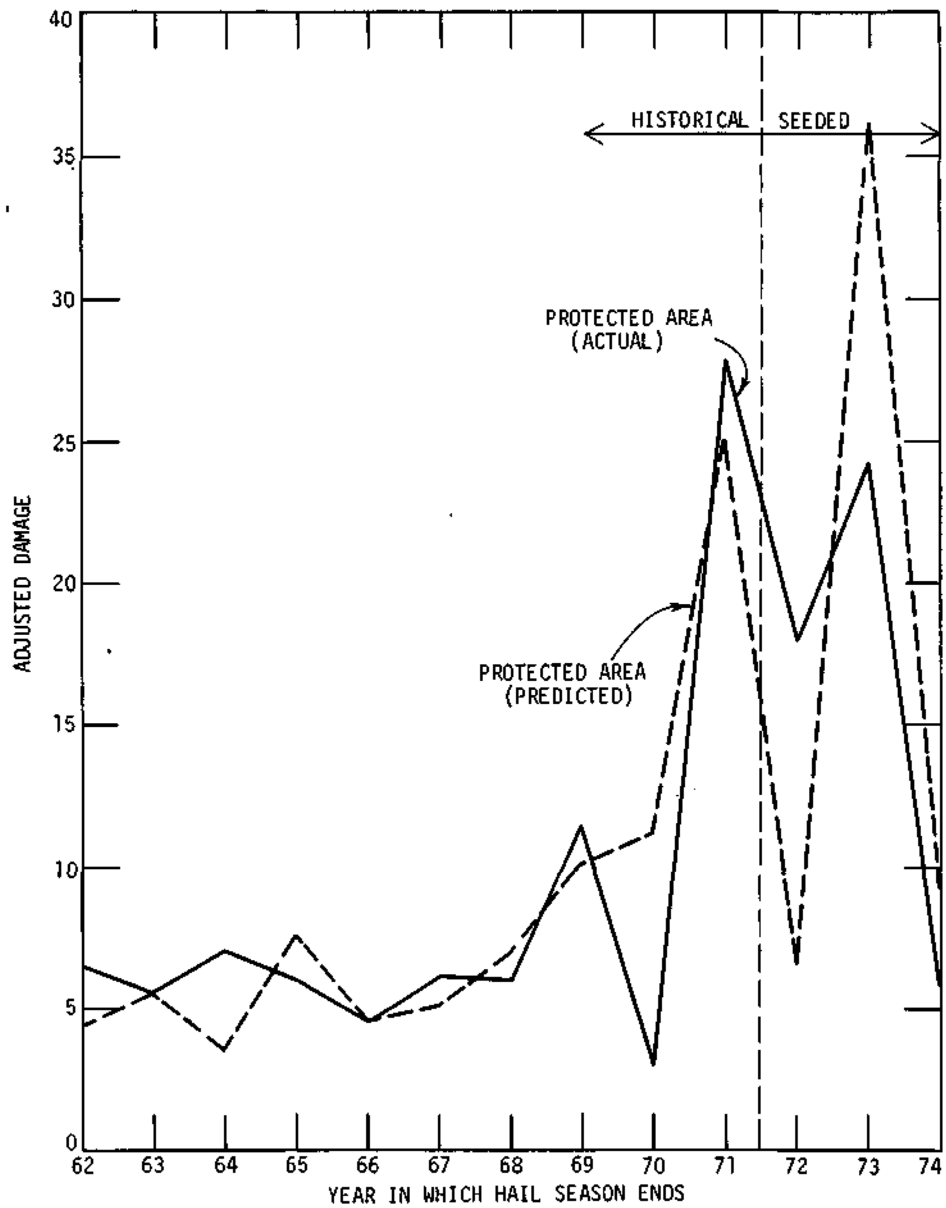


Figure 45. Actual and predicted values of the protected area adjusted damages for the historical and seeded periods as determined from control area

advantages for seeding the complex, multi-storm systems of the Midwest, led us to visit the South African project during 6-10 December 1975. The trip goals were *a)* to carefully inspect the operation of the seeding system, *b)* to compare the South African storms with those of Illinois, and *c)* to inspect the tobacco loss data collection system to determine how it might have influenced the outcome of the statistical evaluation. Information from goals *a* and *b* verified our earlier decisions that the jet cloud-top system was a functional approach suitable for testing in Illinois. Their adoption of 2 jets for seeding all storms over an area of 3000 mi^2 in 1975/76 substantiates our design decision for use of 2 jets in an Illinois experiment for an area of 2000 mi^2. Inspection of radar and meteorological data for South African storm days also indicated that storm dimensions, echo behavior, and storm systems on prefrontal storm days were quite similar to those in Illinois.

The Lowveld Tobacco Cooperative (LTK), which pays the Colorado International Corporation to perform the seeding project (about $1 million for the 8-month 1975/76 season), also is the local crop insurance company. Lloyds of London is willing to re-insure and cover the catastrophe levels of hail loss because of the presence of the hail suppression project, so it is to their (LTK) advantage to have a suppression project even if it does little. There has been a rapid expansion of tobacco grown because of local agricultural expansion as irrigation water became available through new impoundments and because tobacco has economic advantages over the existing citrus crops. This explains the growth in insured areas in the statistics we evaluated. The LTK has its own adjusters who assess all losses on the some 300 farms currently covered by the Cooperative. Inspection of the data system and discussions with farmers and adjusters did not indicate how the statistical results could have been affected by the data collection system.

The strong local belief in the project was reflected by the fact that a new 8-year contract between Colorado International Corporation and LTK was signed during our visit, and this contract is coupled to the effort of the past 5 seasons, 1971/72 through 1975/76. The visit to South Africa and study of the local weather conditions and climate indicated that the high correlation we found between the 1961-1971 hail loss values in the seeded area and those of the control region were likely spurious.

During the visit, we were able to inspect an unpublished report of the South African Weather Bureau that deals with an evaluation of the daily rainfall in the protected area for 1971-1975. Values for seeded days and areas were compared with those which were not seeded for a variety of operational reasons. The results show a slight, 4%, decrease in rainfall in the seeded situations but the difference is not statistically significant.

TEXAS PROJECT

A statistical evaluation of the results of the first 4 years of an on-going hail suppression project in Texas was performed to gain information related to the decision on a future hail suppression effort in Illinois. Continuous hail suppression operations over a 4-year period and in a fixed area offered a good opportunity to assess the effects of cloud-base seeding as reflected in surface hail data. Two sets of hail data with long-term historical records in and around the 2-county area in Texas with hail suppression projects in the 1970-1973 period were investigated. The results are discussed in depth elsewhere (Changnon, 1975b).

Hail-Day Results

Two National Weather Service stations with quality hail-day records were located in and around the seeded area, which comprises Hale and Lamb counties in the Texas Panhandle area. The stations included Lubbock in the non-seeded area and Plainview in the seeded area, and both had records that showed only the occurrence of hail by day. However, hail-day data have been and can be used to evaluate hail suppression experiments, and were investigated.

Table 28 expresses the Plainview and Lubbock hail-day values for the 1970-1973 period in relation at all other 4-year values of two past periods, 1947-1973 and 1919-1973 (records began in 1919). There were 24 possible 4-year combinations (1947-1950, 1948-1951, 1949-1952, etc.) and only 2 of the 24 (8%) at Plainview had values lower than the 9 hail days in 1970-1973. These values were 7 hail days for 1947-1950 and 8 days in 1948-1951, which are not mutually exclusive

Table 28. Comparison of May-October Hail Days in 1970-1973 with 4-Year Frequencies in Past Record Periods

	1970-1973 hail days	Number of 4-yr periods with hail-day totals < 1970-1973 values: 1947-1973 period, Number	1947-1973 period, % of time	1919-1973 period, Number	1919-1973 period, % of time
Lubbock (no seed area)	10	4	17	22	42
Plainview (seed area)	9	2	8	17	33

years. This evaluation shows the general infrequency of the low hail-day value of 1970-1973. The low 1970-1973 value at Plainview is a relatively less frequent event (8% of the time) than the low Lubbock value (17% of the time). This further suggests that the 1970-1973 value in the seeded area was quite low and lower than those in nearby non-seeded areas.

Extensive studies using Illinois hail-day data have been performed to determine the length of time to detect various levels of reduction in hail day frequencies (Changnon and Schickedanz, 1969). Although these were based on Illinois data, and were done for areal and not point frequencies, the results offer some opportunity to assess the Texas results. The historical data for a 1000 mi^2 area in western Illinois (based on data from 5 stations) showed an average summer frequency of 2.5 hail days, which is somewhat comparable to the point average at Plainview. If one accepts the assumptions necessary in the use of sequential test (no major trends in the historical data, which is not a bad assumption for the 1947-1969 period in the Texas station data), the Illinois results suggest detection of a 40% (Plainview had 41%) reduction in 3.2 years at a significance level of 0.05 (5% chance that reduction is due to natural causes). If this test is tightened to the 1% level of significance, then the detection time increases to 4 years. Hence, if one accepts translation of Illinois area results to Texas and the sequential test assumptions, one would conclude that the Plainview hail-day data indicate that hail-day frequency has been suppressed by about 40%.

Crop-Hail Insurance Results

Crop-hail insurance data from the Crop-Hail Insurance Actuarial Association for the 1946-1973 period were also investigated. Data available for each county included *a)* the annual amount of liability ($), *b)* the annual amount of losses ($), and *c)* the annual loss cost value (loss, $/liability, $ x 100). Loss cost is the best means of comparing losses, either on a spatial or temporal basis, because it normalizes the losses to the fluctuations in the liability which can be large (see figure 47). Data analyzed included that of the two counties (Lamb and Hale) in the seeded area in 1970-1973, and that from the 10 surrounding counties.

The total crop liability of the seeded counties (Hale and Lamb) and the nonseeded counties (Hockley and Lubbock) were compared (figure 46). The liability fluctuated considerably, and it decreased greatly in both areas between 1962 and 1966. In the seeded area and period, 1970-1973, the values reached their lowest on record, whereas in this same period, the nonseeded liability was increasing. The seeded area liability values in 1971, 1972, and 1973 were the three lowest ones in the 1946-1973 period. The 1970-1973 liability in the nonseeded area was 82% of the $3.8 million area average, whereas that in the seeded area was 19% of that area average. Comparison of their percentages of average (82 vs 19) shows a 63% reduction in liability in the seeded area. Thus, liability values and losses (figure 47a) both reached extremely low levels, as defined on a temporal and on a spatial basis, in the seeded years of 1971-1973. Values of both in 1970, the first year of seeding, did not exhibit an exceptional difference from those of prior years.

Losses and liability are not the best means to evaluate the temporal or spatial changes in

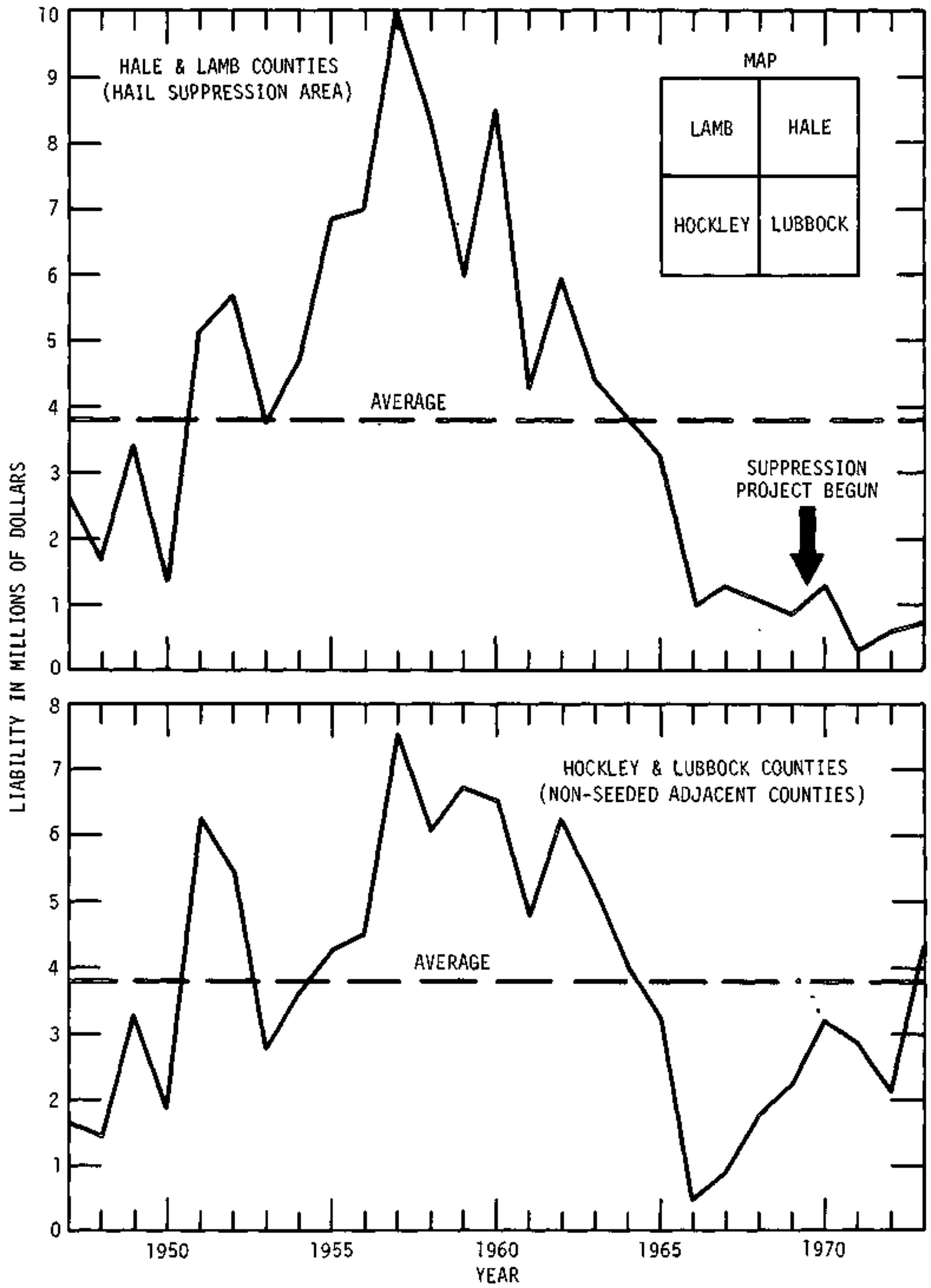


Figure 46. Comparison of crop (wheat-cotton) hail liability in 2-county areas of Texas

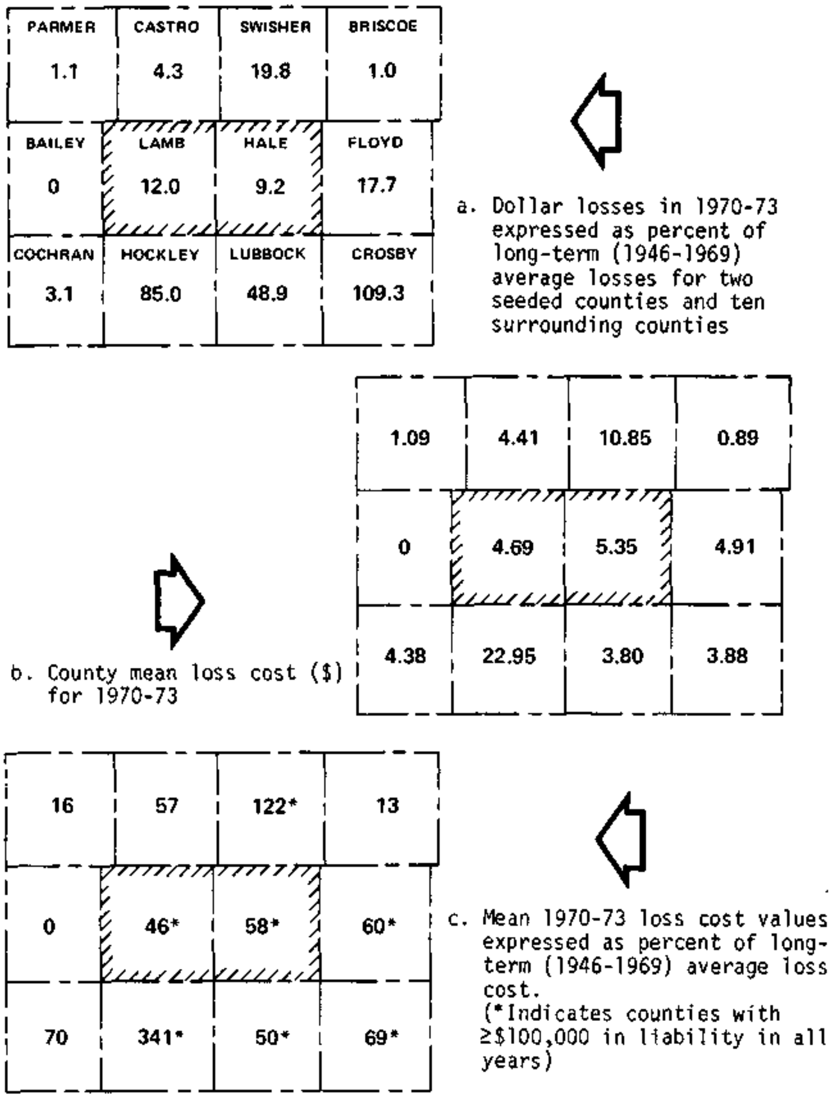


Figure 47. Mean 1970-1973 loss cost expressed as percent of long-term (1946-1969) average loss cost

crop damaging hail during 1970-1973. The county mean loss costs appear in figure 47b. This shows that the target (seeded) counties were higher than those in all but two surrounding counties (Hockley with $22.95 and Swisher with $10.85). A more meaningful regional comparison involves use of the 1970-1973 mean loss costs adjusted for the departure from the long-term (1946-1969) averages. Figure 47c shows that the seeded counties have values (46 and 58%) that are lower than 2 of the surrounding values (57 and 50%), and higher than 3 of the county values (16, 13, and 0%). The tendency for low values in the northwest portion of the area and high values in the southern portion in figure 47 suggests a climatic trend surface across the area for this 4-year period.

However, in evaluating the loss cost percentages (figure 47c) it is important to consider that the liability (area coverage) in 5 surrounding counties was at very low levels in this period. Their liabilities are so low as to suggest their results (losses and loss costs) in 1970-1973 are not too representative. Comparison of the seven counties with adequate liability (considered to be ⩾ $100,000 liability or ~5% of the area insured) indicates that the losses in the seeded counties were quite low, with Lamb the lowest and Hale lower than all but one (Lubbock County) of the five surrounding counties.

The county loss cost data were also inspected on a temporal basis. Hale County's 1970-1973 average loss cost of $5.35 (figure 47b) was compared with all other possible 4-year loss costs in 1946-1973 (25 possible values) which showed only one other lower value, $3.00 in 1949-1952. Lamb County had a 1970-1973 average loss cost of $4.69, and it was lower than any other in that county during the 25 4-year periods beginning in 1946. The next lowest cost was $4.85 in 1946-1949. Hence, each of the 1970-1973 values of the seeded counties was extremely low, one the second lowest on record and the other the lowest. These represent occurrences in the lowest 4 to 8% of the time.

The loss costs of the two seeded (target) counties and the two adjacent counties (Hockley and Lubbock) to the south were compared. Since storm motions are largely west-to-east and activity varies longitudinally, hail activity in Hockley and Lubbock should be comparable to that in Hale and Lamb. A cumulative plotting of the two sets of annual losses appears in figure 48. If the relationship between their annual losses was perfect, the dots would follow the 1:1 dashed line. They do closely approximate it up through 1970, but there are periods of 5 to 10 years when slightly different relationships appear, as noted by fitted straight lines and the individual years when each started (1946, 1952, 1963, 1967, and 1971). The shift which began in 1971 has the greatest difference in their relationship. It shows that the losses in the seeded area were not increasing as rapidly (or became relatively low) in reference to what they had been in any previous 4-year sequence.

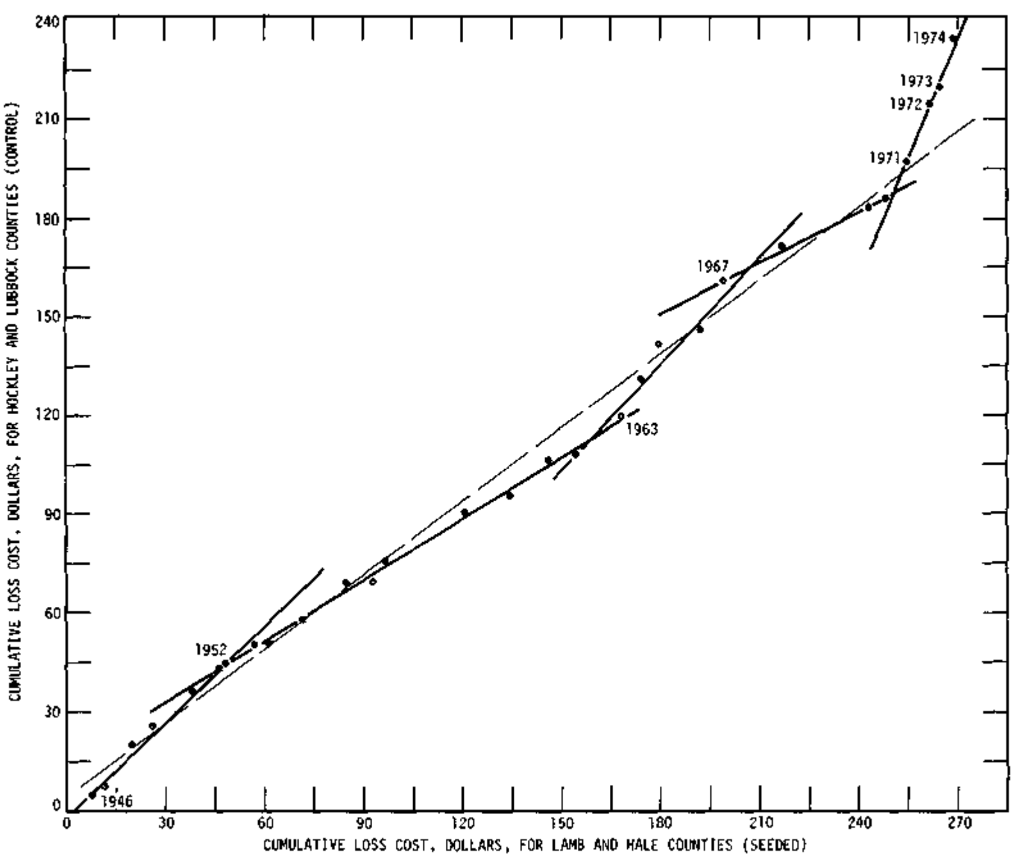


Figure 48. Relationship between cumulative loss cost values in 2-county seeded area and in the adjacent 2-county control area

Table 29. Evaluation of Various 1970-1973 Hail Values in 2-County Seeded Area

Evaluation basis	*Plainview hail-day data*	*2-county liability values*	*2-county losses*	*2-county loss costs*
Temporal	41% below average, 3rd lowest on record*	81% below average, lowest on record*	89% below average, lowest on record*	48% below average, lowest on record*
Spatial	12% reduction on Lubbock; 94% based on Levelland (50 mi SW)	63% reduction by comparison to 2 adjacent counties	80% below mean of 5 counties with adequate liability	43% reduction by comparison with Lubbock-Hockley; 5% with Lubbock-Swisher

*Record period is 1946-1973

Conclusions

The percentage reductions in hail found in the seeded (2-county) area for a variety of parameters (hail days, liability, losses, and loss cost) are summarized in table 29. First, all 10 values show a reduction below that expected from time or space expectations, and 8 of the 10 values are reductions of 41% or more. All of the temporal departures are quite great (41, 81, 89, and 48%) and are record lows or near record values. From a temporal standpoint, it appears that the 1970-1973 hail reductions in Hale and Lamb Counties reflect suppression activities, and probably at a significant level (if the Illinois and Colorado test results are translatable and the necessary statistical assumptions are met).

From a regional standpoint, the low hail values in the seeded counties show a greater variation (5 to 80%), which probably reflects the typically poor regional relations found in hail data. A few other counties in the area experienced near record low hail values, although all of these were from counties with such low liability as to be considered questionable values. There is some suggestion of a natural, regional-scale hail pattern that would lead to low values in the seeded counties. However, this probably exists because of the low liabilities in all counties west and northwest of the target area. A question that could be asked and difficult to answer, is whether the low loss cost values in the three counties east and southeast of the seeded counties (figure 47c) were due to *a)* a natural period of low hail incidence in the area, or *b)* seeding effects leading to the suppression of hail in the downwind areas as well as in the target area.

Most of the data examined strongly suggest that the hail suppression was successful. The best single measure is considered to be the 48% temporal reduction in loss costs (table 29). Another estimate is afforded by the simple average of the 10 values in table 29 which is 56% (the median is 55.5%). An independent analysis of the rainfall data in the target and control areas indicated no significant change in the target area.

NORTH DAKOTA PROJECT

The South Dakota School of Mines and Technology conducted a 4-year (1969-1972) randomized (75% seed days and 25% control days) hail suppression experiment in a 2000 mi^2 area in western North Dakota. The detailed results of this North Dakota Pilot Project are presented elsewhere (Miller et al., 1975). Presented here are various comparisons of the seed and no-seed results based on *a)* the hailpad data, *b)* the crop-hail insurance losses, *c)* hail-rain relations, and *d)* radar echo characteristics.

Table 30. Percentage Changes in Hail and Related Parameters in North Dakota

	Hailpad Hail volume	Hailpad Energy	Crop-hail losses	Hail-rain ratio
Reduction [1 – (S/NS)]	–4	21	60*	40

*Significant at 0.92 confidence level

The hailpad data showed a 21% non-significant decrease in energy on seeded days and a 4% decrease in hail volume (table 30). The insurance loss data (representing about 10% of the area) showed a 60% reduction on seeded days, and this value approaches significance at the 5% level. The ratio of hail (energy) to rain (quantity) for the seeded days, after adjusting for rain chances, revealed a 40% hail energy reduction by comparison with the no-seed ratio. The regression lines (for seeded and non-seeded storms) comparing maximum radar reflectivity and maximum hail diameter showed the seed curve to be significantly different (at 0.1 level). Analysis of various seeding rates indicated that heavier rates (> 400 g/hr) were more effective in reducing hail than light rates (< 200 g/hr).

The rainfall results indicated an average increase of 23%on seeded days. NHRE results, albeit preliminary, suggest a slight increase in rain and hail, not an increase in rain and a decrease in hail as shown in the North Dakota Pilot Project. The Texas results show a decrease in hail and no change in rainfall. The South African results show a shift with a decrease in large hail losses and an increase in small losses with no change in rainfall.

ILLINOIS SAMPLING REQUIREMENTS

Previous studies have provided information regarding the statistical design and evaluation of hail modification experiments in Illinois (Schickedanz et al., 1969; Changnon and Schickedanz, 1969; and Schickedanz and Changnon, 1970). In particular, sample size requirements were presented for a variety of designs, data types, and statistical tests. The purpose of the present study was to investigate crop-insurance parameters not used in the previous studies and the potential use of predictor variables. This new work was motivated by studies in Colorado (Schickedanz and Changnon, 1970, 1971) in which additional crop-hail parameters were shown to have shorter detection times than those used in the Illinois study. Also, it was considered desirable to include sample size requirements for experiments when more than one seeding treatment (i.e., cloud-base and cloud-top seeding) is employed.

Basic Data and Crop-Insurance Parameters

The basic data used were part of the crop insurance data used in the previous Illinois study (Schickedanz et al., 1969). In particular, data from area 1 (1531 mi^2) and area 2 (1598 mi^2) in east central Illinois were used to form the basic data sample. These areas are adjacent, located in a general N-S position.

Previously, adjusted hail parameters of dollars, acres, and acres > 10% loss were used in the studies involving crop insurance data. To obtain a greater refinement of the intensity of the hailstorm, and to circumvent some of the difficulties inherent in the adjustment process, the following additional hail parameters were derived.

Table 31. Distributional Parameters and Goodness of Fit Probabilities for Daily Insurance Data in Area 1

Sample	*Sample size (days)*	*Log mean*	*Log standard deviation*	*GFP for log-normal*
Actual dollar loss	315	6.08	2.05	.17
Actual acre loss	315	5.11	1.74	.17
Actual acre loss > 10%	156	4.72	1.66	>.20
Adjusted dollar loss	315	2.38	2.18	>.20
Adjusted acre loss	315	2.27	1.97	>.20
Adjusted acre loss > 10%	156	1.64	1.93	>.20
Dollar extent	315	4.30	.94	>.20
Areal extent	315	3.34	.63	>.20
Severity	315	3.96	.84	>.20

Dollar extent = actual dollar loss/number of claims (12)

Areal extent = actual acre loss/number of claims (13)

Severity = actual dollar loss/actual acre loss (14)

It was believed that the dollar extent and areal extent parameters would be relatively free of liability and area size variability problems since the number of claims should vary with the amount of liability and the amount of area in crop land. The severity parameter provides a measure of the intensity of the hailstorm in relation to the number of acres hit and should also exhibit less variability than actual dollar or acre loss.

The log-normal distribution was fitted to the new hail parameters, and the results are listed in table 31 along with results for the hail parameters used in the earlier Illinois study. The sample sizes, as well as the goodness of fit probabilities (GFP), are also listed. Clearly, the log-normal distribution describes the data quite well with most of the goodness of fit parameters greater than 0.20. Since the data are well described by the log-normal distribution, the distributional parameters in table 31 were used for subsequent computation of sample size requirements.

For the study of atmospheric predictor variables, the 0600 radiosonde data from Peoria, Illinois, for the years 1957-1962 were used, since these data were already available on magnetic disk storage at the Water Survey. From the radiosonde variables of pressure, temperature, and relative humidity, the variables of height, dew point, mixing ratio, saturated mixing ratio, and equivalent potential temperature were computed for the surface and for the 950-, 850-, 700-, 600-, 500-, and 400-mb levels. The Peoria radiosonde is located 40 miles west of area 1 and 30 miles northwest of area 2. It would have been highly desirable to have had radiosonde data from within or nearer the hail study areas, or at midday, but such data were unavailable.

For the study of areal predictor variables, the data from area 1 were used as the dependent variable, while the data from area 2 were used as the predictor variable. The predictor variables were used as a control variable to reduce the sample size.

Experimental Design

The choice of a proper experimental design in a weather modification experiment is most difficult. It is not hard to obtain estimates of sample size required to detect a given difference between seeded and nonseeded parameters at a given level of sensitivity. Rather, the difficulty lies in the fact that these estimates of sample size must be judged with respect to the important considerations of the data collection system, the economics of obtaining the larger number of experimental units required in a very efficient statistical design compared with the smaller number required in a less efficient design, and the likelihood that the assumptions of the design can be met.

In an experimental research program, the basic requirement that is placed on the design is that of *randomization.* We first consider the random-experimental design which involves the randomization of the experimental unit (usually days or some sub-set of days) over a single target area into seeded and nonseeded units. This design does not incorporate historical data, and the evaluation is based strictly on data collected during the experimental period. The total number of units needed to obtain significance for a specified difference and level of precision is given by Schickedanz and Changnon (1970) as

$$N = [(\mu_\alpha + \mu_\beta)^2 \sigma^2]/[D^2 \pi(1 - \pi)] \tag{15}$$

where:

μ_α = the normal deviate for α probability level
μ_β = the normal deviate for β probability level
D = the difference in means it is desired to detect
σ^2 = the variance of the nonseeded sample (assumed to be equal to the seeded variance)
π = the randomization factor (equal to 0.5 for a 50-50 randomization)

If the data are normally distributed, σ^2 is a non-transformed variance and D is equal to $\delta\mu_{ns}$ where 5 is the percentage difference it is desired to detect and $\delta\mu_{ns}$ is the nonseeded mean. In order to apply the equation, estimates of μ_{ns} and σ^2 are needed prior to experimentation and these estimates are obtained from historical climatological data. The estimates from equation 15 then provide information on the expected duration for a specific level of precision under the assumption that the future experiment will be performed in the same conditions as those reflected in the historical data. Thus, one limitation is that the weather conditions of the historical period will not necessarily be duplicated during the period of the experiment; hence, the required sample size will not be exactly as estimated. But, projection of past experience into the future is still the best estimate available. It is emphasized, however, that in the actual evaluation of the experiment, only data from the experimental period are used.

If the data are log-normally distributed, σ^2 is the log-transformed variance. If sample size requirements are desired for a reduction in the non-transformed mean, then D is equal to the logarithm of $(1 - \delta)$. For the computation of sample sizes involving daily insurance data in this report, the log-normal estimates of σ^2 and D were used since the daily insurance data were found to be log-normally distributed.

The random-experimental design often requires long periods of time to verify a given reduction depending on the hail parameter used. The number of units to verify a given reduction can be shortened theoretically by using the random-historical design in which a random choice is made of the unit to be seeded with the historical record as the control. In this design, the sample size is reduced because the historical record is assumed to be the population and a one-sample test is employed. The total number of units required is given by Schickedanz and Changnon (1970) as

$$N = [(\mu_\alpha + \mu_\beta)^2 \sigma^2]/[D^2 \pi] \tag{16}$$

It is easily seen that for a randomization factor of 0.5, the random-historical design requires one-half the number of observations required by the random-experimental design. However, the random-historical design requires that the data measurement system be the same in both historical and experimental periods. Another difficulty is that trends, cycles, and abnormally wet and dry years are a part of the historical record and the comparison with a long-term average may not be valid. However, the nonseeded data during the experimental period can be used to assess whether the experimental period is abnormally wet or dry so that a more valid comparison can be made.

If the randomization factor is set equal to 1 in equation 16 (i.e., no randomization), then the equation provides the number of units needed for the continuous-historical design. In this design, all experimental units are seeded and the historical record is the control. If the randomization factor is 0.5 in the random-historical and random-experimental designs, the number of observations for the continuous-historical design is one-half of the number required for the random-historical and one-fourth of the number required for the random-experimental. However, the data collection system must be the same for both the historical and the experimental periods. Also the problems of trends, cycles, and abnormally wet and dry years are more severe than for the random-historical design. This places doubt on the validity of the continuous-historical design.

For all three designs, predictor variables (covariates) can be included in the design to increase the sensitivity of the test. The predictor variables can be atmospheric or areal variables. The number of units required for the random-experimental design can be obtained by multiplying equation 15 by $(1 - R^2)$

$$N = [(\mu_\alpha + \mu_\beta)^2 \sigma^2 (1 - R^2)]/[D^2 \pi(1 - \pi)] \qquad (17)$$

where R is the multiple correlation between the hailfall parameter in the target and the predictor variables, or in the case of one predictor, the simple correlation coefficient. Similarly, the number of units for the random-historical design can be obtained by multiplying equation 16 by $(1 - R^2)$

$$N = [(\mu_\alpha + \mu_\beta)^2 \sigma^2 (1 - R^2)]/[D^2 \pi] \qquad (18)$$

The number of units for the continuous-historical design can be obtained from equation 18 by setting $\pi = 1$.

The classical target-control design is a special case where only 1 control area is used for a predictor. Since the correlation between daily hailfall of nearby areas is usually low, the classical target-control design is impracticable. Such a design would require a similar measurement system in the target area, with little or no reduction in the number of units required. In fact, if $R = 0$, the target-control and random-experimental designs have the same sensitivity.

It should be noted that, for the continuous-historical and random-historical designs, the estimate of R is derived from the historical period. The use of the historical correlation relationship during the seeded period for daily insurance data has an inherent difficulty in that the correlation relationship in the seeded period may be different from that of the historical period.

Often it is desired to employ more than one seeding treatment (e.g., cloud-base seeding and cloud-top seeding). The nonseeded data are also considered to be a treatment, thus the addition of another seeded treatment results in a 33-33-33 randomization instead of the usual 50-50. The additional treatment can be incorporated into the random-experimental design in the following manner.

Even though the randomization is 33-33-33, there are an equal number of units in each treatment, and each seeded treatment is related to the nonseeded treatment through a 50-50 randomization. Thus, if N' (50-50 randomization) is determined from equations 15 or 17 it will require N'/2 additional observations in order for each treatment to have a 50-50 randomization with the nonseeded sample. This ensures a 3 3-3 3-33 randomization when all three treatments are considered. If we let the total number of treatments (i.e., nonseeded treatment included) be equal to k, then in general the number of observations (N_k) required is given by

$$N_k = N' (k/2) \qquad (19)$$

Theoretically, it would be possible to obtain N_k for the random-historical design through the multiplication of k/2 by N' (50-50 randomization) as determined from equations 16 or 18. However, because the validity of the random-historical design is questionable under certain conditions, this final calculation is not recommended.

Table 32. Comparison of Sample Size Requirements for Various Hail Parameters for the Random-Experimental Design in Area 1 (Randomization = 0.5, a = 0.05)

		Sample size required for differences of:					
		20%		30%		40%	
Parameter	Power	Days	Years	Days	Years	Days	Years
Actual dollar loss	0.7	1574	94.8	616	37.1	300	18.1
	0.5	907	54.7	355	21.4	173	10.4
Actual acre loss	0.7	1140	68.7	446	26.7	217	13.1
	0.5	657	39.6	257	15.5	125	7.5
Actual acre loss > 10%	0.7	1033	125.8	404	49.2	197	24.0
	0.5	595	72.5	233	28.4	114	13.9
Adjusted dollar loss	0.7	1788	107.7	700	42.2	341	20.5
	0.5	1031	62.0	403	24.3	197	11.9
Adjusted acre loss	0.7	1459	87.9	571	34.4	278	16.7
	0.5	841	50.7	329	19.8	160	9.6
Adjusted acre loss > 10%	0.7	1400	171.0	548	66.8	267	32.6
	0.5	807	98.4	316	38.5	154	18.8
Dollar extent	0.7	328	19.8	128	7.7	63	3.8
	0.5	189	11.4	74	4.5	36	2.2
Areal extent	0.7	151	9.1	59	3.6	29	1.7
	0.5	87	5.2	34	2.1	17	1.0
Severity	0.7	266	16.0	104	6.3	51	3.1
	0.5	154	9.3	60	3.6	29	1.7

Results

The log-normal estimates of a^2 and equation 15 were used to compute the number of days (experimental) to obtain significance for various percentage decreases at the 0.7 and 0.5 power $(1 - \beta)$ levels, as shown in table 32 for the random-experimental design. Computations for parameters used in the previous Illinois study (Schickedanz et al., 1969; Schickedanz and Changnon, 1970) have been included for comparison with the new parameters.

The new parameters (dollar extent, areal extent, and severity) are far superior for use in the evaluation of hail suppression. Dollar extent requires 24% of the sample size required for adjusted acre loss > 10%. Furthermore, dollar extent requires the largest sample size of the new parameters, while the adjusted acre loss > 10% requires the smallest sample size of the adjusted parameters used in the earlier study. Thus, other comparisons between the adjusted and new parameters are even more favorable. This is an expected result in view of the findings from the Colorado study (Schickedanz and Changnon, 1970, 1971) and because the division (loss per claim) required to obtain these parameters removes much of the variability inherent in the adjusted loss data (see table 31). In a sense, this division is also a more meaningful figure for individual farmers because it is more representative of circumstances on an individual farm than is the gross amount of loss per county or multi-county area.

To convert the number of experimental units to the number of years required for detection of a given decrease, the number of units expected per year and the ability of the forecast scheme to predict hail must be considered. From prior experience, it is expected that 75% of the operational days (forecasted hail days) will in fact have hail. From the historical insurance records, there was an average of 8.21 hail days per year for the acre loss > 10% parameters and 16.58 hail days per year for the other parameters shown in table 31. Furthermore, it is assumed that the forecasting scheme will forecast all hail days, although 25% of these days will in fact have no hail. Thus, it is assumed that the number of operational hail days required per year will be 10.95 and 22.11 days, respectively, for the acre loss > 10% parameters and for the other parameters. However, in

Table 33. Comparison of Sample Size Requirement for Various Hail Parameters for the Random-Experimental Design in Area 1

Three-treatment randomization, a = 0.05

		Sample size required for difference of:					
		20%		*30%*		*40%*	
Parameter	*Power*	*Days*	*Years*	*Days*	*Years*	*Days*	*Years*
Dollar extent	0.7	492	29.6	193	11.6	95	5.7
	0.5	284	17.1	111	6.7	54	3.3
Areal extent	0.7	227	13.7	89	5.3	44	2.6
	0.5	131	7.8	51	3.1	26	1.5
Severity	0.7	399	24.0	156	9.4	77	4.6
	0.5	231	13.9	90	5.4	44	2.7

order to convert the number of hail days for a given decrease to the number of years required, it is sufficient to divide the number of hail days by the expected (average) number of hail days per year.

For a 70% chance of detection (power = 0.7) 3.6 years are required to detect a 30% decrease in areal extent, 6.3 years for severity, and 7.7 years for dollar extent. For a 50% chance of detection, 2.1 years are required to detect a 30% decrease in areal extent, 3.6 years for severity, and 4.5 years for dollar extent. All other parameters require more than 5 years for a 40% decrease at both power levels and, therefore, are not considered further in this report. It is clear that the parameters of areal extent, severity, and dollar extent are the most efficient of the daily insurance parameters.

Equation 19 and the results from table 32 were used to compute the sample size requirements for a three-treatment randomization (33-33-33), as shown in table 33 for the most efficient parameters. For a power level of 0.7, 2.6 years are required to detect a 40% reduction in areal extent, 4.6 years for severity, and 5.7 years for dollar extent. For a 30% reduction, over 5 years are required for all three parameters.

For a power level of 0.5, a 40% reduction is detectable for all three parameters in less than 5 years. However, a 30% reduction is detectable only for areal extent in less than 5 years.

The sample requirements for the three-treatment randomization (table 33) are 50% greater than the requirements for two-treatment randomization (table 32). For a 40% reduction at the 0.7 lower level, the three-treatment randomization requires 15 additional hail days for areal extent, 26 for severity, and 32 for dollar extent. Since the hail days constitute only 75% of the number of operational days, the three-treatment randomization requires 20, 35, and 43 additonal operational days, respectively, for areal extent, severity, and dollar extent.

As noted previously, the inclusion of predictor variables can reduce the sample size requirements for the experimental-random design. In order to explore the possibility of the use of area 2 as an areal predictor, the correlation coefficients between area 1 and area 2 were determined (table 34).

Table 34. Correlation of Daily Hailfall Parameters between Area 1 and Area 2

	Areal size	*Areal extent*	*Severity*	*Dollar extent*
All days	565	-.29*	-.09*	-.05
Hail days in area 1	315	-.02	.01	.04

*Significant at the 0.05 level

In general the correlation between area 1 and area 2 is quite low. There is a significant correlation for areal extent and severity when days with hail in at least one of the two areas are considered. However, the amount of variance explained for the largest coefficient is only 8% (-0.29^2) and so severity by itself is too small to be of use as a predictor. More importantly, since the log-normal distribution can be applied only to days with hail, it is the predictors for damage on the hail days in area 1 that are critical. Clearly, the correlations are essentially zero for these days, and area 2 cannot be used as an areal predictor.

All of the atmospheric variables previously mentioned from the Peoria radiosonde (page 105) were investigated for their potential use as predictor variables. If one considers the three most efficient hail parameters, two of them (dollar extent and severity) were significantly correlated with some of the radiosonde variables, whereas one (areal extent) was not significantly correlated with any of the variables. The variables which have significant correlation with area 1 dollar extent and severity are listed in table 35 along with their associated correlation coefficients.

Table 35. Correlation of Daily Hailfall Parameters in Area 1 with Variables from the Peoria Radiosonde

	Surface	950	850	Levels (mb) 700	600	500
Dollar extent						
Pressure						
Wind speed				.21	.25	.24
Temperature	-.29	-.26	-.29	-.22	-.20	
Dew point	-.28					
Mixing ratio	-.26					
Saturated mixing ratio	-.29	-.23	-.28	-.21	-.20	
Equivalent potential temperature	-.28	-.21				
Severity						
Pressure	.21					
Wind speed						
Temperature	-.27					
Dew point	-.30	-.22				
Mixing ratio	-.31	-.22				
Saturated mixing ratio	-.28					
Equivalent potential temperature	-.30	-.22	-.20	-.21		

For dollar extent, temperature and the four moisture variables indicate that the air was cooler and drier on days with heavy loss intensity than on days with light loss intensity. The windspeeds between the 700 and 500 mb levels were greater on the hail days with heavier loss intensity than on the hail days with lighter loss intensity. A similar relationship exists for severity data, although the windspeed correlations between the 700 and 500 mb levels were insignificant and are not listed in table 35.

The relationships between damage, temperature, and moisture present a surprising result. However, it was noted in the objective analyses schemes described elsewhere in this report that hail does occur in central Illinois on post-cold-frontal days. Dynamic destabilization was postulated to be the cause of hail on one set of post-cold-frontal days, whereas deep convection due to overrunning was postulated to be the cause of hail on the other set of days. Certainly, another possibility is that on cool and dry days, there is less chance for the hailstones to melt before reaching the ground.

Although it is not clear that the hail damage should be greater on post-frontal days, widespread hail has often occurred on these days; this may influence the overall correlations.

The multiple linear regression between dollar extent and the 17 corresponding radiosonde variables listed in table 35 was determined. Similarly a multiple linear regression was determined for severity and its 11 corresponding radiosonde variables in table 35. The multiple correlation coefficient for dollar extent is 0.53 and is significant at the 0.05 level of significance. The multiple correlation for severity is 0.43 and is signficant at the 0.10 level of significance.

The multiple regressions were used as predictor equations for the dollar extent and severity in area 1. The reduced sample size requirements due to the inclusion of predictor variables were determined from equation 17 and the results are listed in table 36.

Table 36. Comparison of Sample Sizes to Obtain a 40% Reduction in the Random-Experimental Design with and without Predictor Variables

		Without predictor variables		*With predictor variables*	
Parameter	*Power*	*Days*	*Years*	*Days*	*Years*
50-50 randomization					
Dollar extent	0.7	63	3.8	45	2.7
	0.5	36	2.2	26	1.6
Severity	0.7	51	3.1	42	2.5
	0.5	29	1.7	24	1.4
33-33-33 randomization					
Dollar extent	0.7	95	5.7	68	4.1
	0.5	54	3.3	39	2.4
Severity	0.7	77	4.6	63	3.8
	0.5	44	2.7	36	2.2

The sample size for dollar extent is reduced the most and severity is reduced the least. This is a direct consequence of multiplying the previous sample size by $(1 - R^2)$ or reducing the previous sample size by R^2. Since dollar extent has the largest correlation coefficient (0.5 3 compared with 0.43 for severity) it is reduced the most. The net result of the inclusion of the predictor variables is to reduce the sample sizes for dollar extent and severity (50-50 randomization) to values less than 3 years for both power levels. For a 33-33-33 randomization, dollar extent has a sample size of 4.1 years for a power level of 0.7 and severity has a sample size of 3.8 years. Although the sample sizes for dollar extent and severity are now closer to those for areal extent, they still have larger sample sizes than does areal extent (see tables 32 and 33).

Although the total number of treatments may be greater than 2, each seeded sample is still related to the nonseeded sample through a 50-50 randomization in the random-experimental and random-historical designs (see discussion of equation 19). Therefore π equals 0.5 in equations 15 and 17, and an inspection of these equations reveals that in order to obtain the number of observations for the random-historical design without predictor variables, it is sufficient to multiply the sample sizes (random-experimental) in tables 32 and 3 3 by 0.5. That is, the number of observations for the random-historical design is always one-half that of the random-experimental design. However, the lack of equal data quality in the historical and experimental periods negates the usefulness of this approach to the design, if data measurements other than the insurance data are used. In practically all experimental research programs, several other data (such as hailstone size distribution, hailstone frequency, hailfall energy, and storm-echo charactersitics) are measured during the experimental program and such measurements are being recommended for any future experiment in Illinois.

Thus, we do not recommend the random-historical design as the basic design for a hail experiment in Illinois, but rather the random-experimental design with predictor variables. This does not negate the possibility of performing tests related to the random-historical design during an experiment, as they provide useful and pertinent supplementary information.

Summary and Conclusions

The main purpose of this research was to investigate crop insurance parameters not used in previous Illinois studies. The results indicate that the three insurance parameters of areal extent, severity, and dollar extent are far superior to the various parameters used in the previous studies. For a 70% chance of detection with a 50-50 randomization scheme, 3.6 years are required to detect a 30% decrease in areal extent, 6.3 years for severity, and 7.7 years for dollar extent. For a 50% chance of detection, 2.1 years are required to detect a 30% decrease in areal extent, 3.6 years for severity, and 4.5 years for areal extent.

Another purpose of the research was to obtain sample sizes for more than one seeding treatment (specifically, cloud-base and cloud-top seeding) which results in a 33-33-33 randomization scheme. The addition of one extra treatment increases the sample size requirements by 50%. For a power level of 0.7, 2.6 years are required to detect a 40% reduction in areal extent, 4.6 years for severity, and 5.7 years for dollar extent. For a power level of 0.5, a 40% reduction is detectable for all three parameters in less than 5 years. For a 30% reduction, over 5 years are required for both power levels with the exception of areal extent at a power level of 0.5 which is detectable in 3.1 years.

The third purpose of this research was to obtain sample sizes when predictor variables are included in the design. Since the correlation between hailfall of nearby areas was extremely low, areal predictors could not be used. The use of predictors from atmospheric sounding variables reduced the sample size requirements 28% for dollar extent and 18% for severity. The lack of significant correlation prevented the use of predictors for areal extent. The predictors were obtained from the 0600 sounding which was from a radiosonde station 40 miles from the area of interest. It is quite possible that the use of predictors from afternoon soundings or from soundings nearer (or within) the area of interest would reduce the sample sizes by a higher percent. In an Illinois experiment, predictors such as these could be explored by using the data from special radiosonde observations on the nonseeded days.

The sample size requirements presented in this text are for a random-experimental design (i.e., randomized days over a single target area with the non-seeded days as the control). These sample sizes could be reduced somewhat by using a random-historical design, *if all assumptions were met.* In the earlier Illinois study, the random-historical design was recommended as the most likely candidate. However, this recommendation was based on the fact that the random-historical design required sample sizes which were a compromise between the large sample sizes required by the random-experimental design and the questionable validity of the continuous-historical design. However, with the availability of more efficient hail parameters (areal extent, severity, and dollar extent), the random-experimental design with predictor variables provides reasonable detection times. Thus, the random-experimental design with predictor variables is the recommended design for an Illinois experiment, thereby avoiding some of the possible pitfalls of the random-historical design. Certainly, tests involving the random-historical design should be performed during the experiment to provide useful and pertinent supplementary information.

SUMMARY

Inspection and review of the evaluations for South Africa, Texas, and North Dakota reveal a variety of results, but *they all indicate reductions in hail due to suppression effects.* The reductions vary, depending on space-time comparisons and types of data, from 5 to 80%. Most reductions are in the 40 to 50% range. Most are *not statistically significant* at the 5% level, largely because the size of the reductions and sample sizes (length of project) are (or were in North Dakota) as yet too small. If the 40 to 50% reductions of the Africa and Texas projects are sustained through 1976, they will be significant. It is unfortunate that the North Dakota Pilot Project was terminated with only 4 years of data. Yet, the internal consistency of the results suggests that the 31% average of the 4, 21, 40, and 60% reductions shown in different types of data would be a reasonable approximation.

Thus, the 55% average of the Texas reductions, the 31% of the North Dakota values, and the 40% in South Africa point to a 'best estimate' of 40%. Admittedly, these three projects have used different seeding technologies.

The results on rainfall changes with the hail are less clear. The Texas project, which was only trying to suppress hail, did not produce a rainfall change. The North Dakota project, which was attempting to increase rainfall and decrease hail, got a 23% rain increase. The South African project shows no change in rain. Inadvertent modification of summer hail and rain at St. Louis and other major midwestern cities suggests they both are increased. Hence the available results and evaluation do not point toward a given rainfall outcome with hail suppression. Again, differences in seeding techniques may account for the differences in the rainfall results.

Part 2. Design of an Experiment to Suppress Hail in Illinois

INTRODUCTION

Part 1 of this report summarized the results of the Water Survey's latest project in a series of projects focused on the potential of hail suppression in Illinois. Nine years of suppression-oriented research in Illinois, coupled with research and component testing in Colorado as part of NHRE, have provided most of the information needed to design a hail suppression experiment for Illinois. This part of the final report addresses the key components of the Suppress Hail Experiment (SHE) in Illinois.

Experimental Goals

The goal of SHE would be to discern the degrees of alteration of various hail characteristics including:

1) Hailstone size distribution and derived parameters (volume of ice, kinetic energy, and momentum)
2) Amount of crop-hail loss (dollars)
3) Hail day frequency
4) Storm-echo characteristics
5) Area of crop loss
6) Combinations of the above characteristics

It would also discern changes in associated rainfall characteristics including:

1) Rain day frequencies
2) Rainfall quantity
3) Rain intensity
4) Amount of seeded material in rainwater
5) Raincells

'Proof of concept' would be achieved when any three of the surface hail characteristics, including one or more of the three insurance parameters (dollar extent, areal extent, severity or dollars divided by area) have been reduced 40% or more (from the nonseeded sample) for either of the seeding methods (cloud base or cloud top) over a period of 4 years. This ensures a 70% chance of detection at the 0.05 level of significance. In addition, at least one of the three hailpad parameters (hailstone size distribution, hailstone frequency, and hailfall energy) must exhibit a significant decrease at the 0.05 level of significance over the 4-year period (two seeding methods employed), or over a 3-year period (if only one seeding method were employed in a 50-50 randomization). Furthermore, it is considered highly desirable that the direction of the difference for non-significant parameters should be consistent with the known physical theory and with the direction of the significant differences. In the above context, the historical data would be used in the role of crucial and supplementary data to strengthen the conclusions reached concerning the proof of concept.

Key experimental features basic to the goal of SHE are:

1) Employment of advanced statistical-physical evaluation techniques using control data obtained through randomization and from historical data (1947-1975)
2) Utilization of the best established modification hypothesis and seeding techniques
3) One-area experimentation in a heavily cropped and densely insured region

4) Involvement of all types of users (local, state, federal) of the potential suppression technology directly or indirectly (information exchange) in the experiment

Design Philosophy

The design of SHE is founded on a philosophy (and approach) identified in 1967 that before launching of SHE there will be sufficient scientific information and evidence of suppression and its mechanisms presented elsewhere to launch a 'proof of concept experiment.' The perceived need to establish the potential of hail suppression for the nation (NSF, 1968) led to this philosophy.

The approach chosen for satisfying this national goal was *a)* to initiate an extensive scientifically oriented experiment in the High Plains (northeast Colorado) to perform the necessary fundamental research and to test suppression techniques there; and *b)* if successful, to subsequently test certain results and modification technologies in other hail climatic zones (NSF, 1968; NCAR, 1969). NHRE became the first part of this sequential approach, and Illinois with its quite different hail climate prepared to become the site for the second part.

Under this approach, however, the expensive scientific investigations of all facets of hailstorms, particularly those concerning the near-storm dynamics and in-storm microphysical processes, were never to be pursued in the Illinois studies. These results were to be obtained in NHRE and translated to Illinois conditions, a condition reflected in the prime goal of the Survey's radar-related involvement and hail research in NHRE.

Thus, the proof of concept approach for SHE in Illinois was to be based upon four sets of information, as follows:

1) All results from the extensive, 15-year studies of hail in Illinois
2) Available data from below-cloud and in-cloud measurements obtained from other Water Survey flight programs in 1970-1975
3) The achieved suppression levels revealed by well-conducted commercial (non-randomized) hail suppression programs (Texas and South Africa)
4) The scientific findings about hailstorm modification processes and the actual suppression results achieved in well-conducted randomized experimental research programs (North Dakota and NHRE)

These four information sources not only affect the design of SHE but also directly relate to decisions to implement SHE. A critical summary of the key weaknesses in each of these information sources is relevant to understanding the design of SHE and the ensuing recommendations for its implementation.

The 15-year effort in Illinois (source 1) was hurt most by the various delays of the components in the complex CHILL radar system plus its use on NHRE during the spring and summers of 1972, 1973, and 1974, which together resulted in too few 10-cm and dual wavelength data on Illinois hailstorms. The Water Survey flight programs of METROMEX (Semonin and Changnon, 1974) and PEP (Changnon, 1973a) furnished some useful data, particularly about below-cloud updrafts, but the unexpected cessation of the PEP aircraft program due to federal funding cuts led to only limited in-cloud information and none for nocturnal storms (Ackerman, 1974). The evaluation of commercial hail suppression projects was largely completed, but as expected, it is limited by uncertainty about results due to the lack of randomization.

Finally, the results from scientific projects have been helpful in identifying alterations in surface hailfalls, as in North Dakota (Miller et al., 1975). However, critical problems within NHRE for 1972-1974 (NSF et al. NHRE Panel, 1974) have led to *a)* no believable identification of hail alteration, and *b)* more tragically, too little comprehensive and integrated research into the scientific aspects of hailstorms *that only NHRE was supported to provide.* Other hail reserach projects in Illinois and South Dakota were not supported for in-depth hailstorm studies involving aircraft.

Application of Results

A design of SHE is offered, even with the limitations to desired information, because any pursuit of hail suppression in the Midwest in the near future should be based on the best design concepts and information available at this time. A failure to develop a design at this time because certain information elements are missing is not considered justifiable, particularly if socio-economic pressures lead to a decision to start a suppression project (experimental or otherwise) in the Midwest.

The results of SHE, if it were conducted in Illinois, would be applicable to other parts of the Midwest. A study of the hail climate of the nation (Changnon, 1975c) reveals that an area roughly from east of the 100th Meridian (eastern Kansas and Nebraska) to the Appalachian Mountains (eastern Ohio) and north from Tennessee to Minnesota and Michigan would be included. This is an area where most hailstorms are produced by macroscale weather disturbances with only local urban and minor topographic effects on storm frequency.

Design Components

The design of SHE is based on four components and the following portions of this section describe these.

The first component is the *modification hypothesis and the related seeding technologies.* It addresses the choice of hypothesis to be tested and the seeding technologies.

The second component is the *statistical-physical design and evaluation.* It concerns the basic area, randomization, experimental area, data for evaluation, and likely times required for detecting changes in hail.

The third component involves the *operational aspects.* Here, the subcomponents of operations including the operational center, the forecast needs, radars, and communication system are described.

The fourth component is the *impact monitoring and interactions* effort. This entails monitoring of impacts to crops, public attitudes, and ecology. It also involves the interactions with institutions of all types, the public, and all users of the results.

MODIFICATION HYPOTHESIS AND SEEDING TECHNIQUES

Hypothesis Choice

Some major a priori constraints had to be placed on our freedom of choice of hypothesis and seeding method in arriving at the design of SHE. First, systems employing artillery, ground-based rockets, or horizontally fired air-to-air rockets are not viable in the Midwest at the present time. Second, although we cannot rule out the eventual utility of ground-based emission of seeding material in operational programs, such an approach would introduce unnecessary uncertainties into the most critical element of the experiment. Hence, ground-based seeding was considered unsuitable for a proof of concept experiment at this time.

Third, the hypothesis and method chosen could not be avant-garde. It must be readily available without the need for developmental programs. Ideally, there must be experienced companies available, willing and capable of pursuing the operational aspects. Although not necessarily accepted by a majority of the scientific community, the method chosen must have been visible to the scientific community for a time sufficient for it to be considered a 'mature' idea. Though not proven, it also must have found sufficient approval and acceptance through statistical evaluation to represent a 'reasonable gamble' to those paying for its application.

Conceptual Models

Synoptic stratification of hail days has shown that the occurrence of hailstorms under simple air mass conditions is of very small import in Illinois. Hailstorms of consequence tend overwhelmingly to be either associated with synoptic scale systems or organized into mesoscale systems. This is probably not specific just to Illinois and is a result of the nearly constant convectively unstable state of warm summertime air masses over the continent. This suggests that the simple, unsteady bubble model of the air mass hailstorm need not be considered of importance for a hail prevention experiment.

Illinois hailstorm echoes tend to occur largely in lines and organized areas, and from this and results on their associated synoptic weather conditions, it is reasonable to infer that the storms of importance will resemble the multi-cell feeder cloud system or the supercell long-traveling storm. The prevalence of the multi-cell type of storm over the other is clear. As in other areas, the hail damage through the growing season in the Midwest is dominated by just a few days of very severe damage out of many more (on an areal basis) of moderate or light damage. It would be tempting to say that these heavy to severe damage cases are due to steady state supercell storms, but that is not correct. Massive, long-track storms typical of the so-called supercell storm have occurred only twice (15 May 1968 and 3 April 1974) in the 2000-mi^2 project area in the 1967-1975 period. In fact, a colossal storm, the worst summer hailstorm in Illinois since 1964, occurred in the East St. Louis METROMEX reserach area on 12 August 1973 and it was stationary, lived an hour, and was not at all typical of the supercell type of storm. Clearly, the storm type of consequence and high frequency is the multi-cellular type.

Statistics on the absolute frequency of supercell hailstorms and other types of storms in the Midwest are needed. This problem is to be confronted as a subtask in a new 15-month Survey project aimed at assessing the future technology of hail prevention. For the moment this must be considered a serious lacuna in our background knowledge about hailstorms in the Midwest.

Basic Modification Hypothesis

Considerations of feasibility and reasonable economy rapidly rule out the total glaciation approach to hailstorm suppression in the Midwest and probably elsewhere. The augmented embryo concentration (competition) approach appears both feasible and economical at the present moment. It is an approach which is, within our present knowledge of the hail process, logical and scientifically sound. It has an encouragingly high degree of credibility within the scientific community. It is also being applied in a number of regions of the world with some statistical indications of success.

There are two distinct approaches to operational application of the competing embryo technique to Illinois hailstorms: *a)* cloud-base updraft seeding of feeder cells and, when necessary, of mature parent storms; and *b)* mid-level seeding of the tops of the new or feeder cells as they grow through a critical height-temperature level.

Seeding Techniques

Delivery Systems

The above-mentioned distinctly different approaches to essentially the same modification hypothesis differ radically only in the system of delivery of the seeding agent. Each suffers in its own way the uncertainties of ice phase seeding: *a)* uncertain diffusion of the particles through the required volume; *b)* deactivation by exposure to above-freezing water cloud; *c)* adverse scavenging by water; and *d)* adverse scavenging by natural and artificial ice crystals. The proponents of the two systems can cite operational advantages of one over the other and the disadvantages of the other. Each system operates within the conceptual framework of the same model of the hailstorm. The choice arrived at for SHE utilizes both systems, separately, in a three-way randomized design.

The high-level system is being applied in hail prevention programs in Alberta (Canada) and in South Africa. Our analysis of the results of the latter project has indicated that it may be reducing the hail damage. The cloud-base approach has been applied in Texas, North Dakota, and Kenya. Our analysis of the Texas data indicates the possibility of a successful reduction of hail damage. The mechanics of both approaches are fully worked out so that no developmental work need be undertaken in order to apply them in Illinois. Lastly, there is a reasonable level of acceptance of the soundness and credibility of both methods within the scientific community.

There is no clear basis for choosing one method over the other, and our analysis of the requirements for a three-way randomization does not predict an unreasonable lengthening of the experiment over the time required to test a single method. The spirit of a proof of concept experiment is to answer questions that are being asked about services which are being used and offered. These two approaches to hail prevention have been applied in highly visible programs with sizeable investment of funds by farmer groups and with the prospect that this will continue. There is clearly need for an evaluation of both.

Seeding Material and Rate of Seeding

The hail prevention methods selected for trial in Illinois both make use of silver iodide as the ice nucleant. Both utilize the combustion of pyrotechnic mixtures for the production of the AgI particles. The cloud-top technique would use droppable pyrotechnic flares containing 50 to 70 g AgI. These are to be dropped every 1000 feet during top penetrations at the -15 to -20° C level. The cloud-base approach would utilize end-burning flares which contain 100 g AgI and burn from 5 to 7 minutes each, permitting seeding rates of from 15 to 20 g/min and greater in cloud base updrafts.

STATISTICAL-PHYSICAL DESIGN AND EVALUATION

The extensive Survey research into designs and means of evaluating hail suppression projects, coupled with the experimental goals and the design philosophy chosen for the experiment, plus a review of past project evaluation techniques, lead to a central point: *the experiment must be designed around a comprehensive evaluation involving surface hail data.* A proof of concept experiment *must provide clear proof that crop-damaging hail has been altered.* Hence, the evaluation must include *a)* crop-hail loss data (as derived from a heavily insured area), and *b)* surface hailfall characteristics directly related to crop and property loss. The hailfall data are needed to supplement insurance data for areas where it is lacking and where crop loss occurs more than once in a season.

Proof

Proof of an effect can only be established satisfactorily with a form of control data collected at random during the experimental period. This requirement does not neglect the use of historical crop loss and hailfall data derived from the past 9 years of study in the Illinois experimental area. This historical control data coupled with control data obtained randomly in the experiment will shorten the time to detect an effect in hail, a very desirable goal in an expensive field experiment. The level of significance to be sought for any three of the surface hail characteristics (of those recommended for collection) is a probability of 0.05 for alpha (false assertion of a seeding effect) and 0.3 for the beta value (a false assertion of no seeding effect). The recommended hail evaluation data include hail days, hail intensity, hailstone size and frequency, crop-haii losses ($)', crop loss area, and various combinations of these.

Evaluation must also entail a careful statistical analysis of the rainfall in the experimental area. This would include the frequency of rain days, the daily amount of rain, rainfall intensity, raincell analyses, and areal analyses of the seeding material in rain and hail samples. These rainfall data and seeding material information, coupled with the six hailfall data units (see Introduction), must be interpreted jointly with *a)* 3-dimensional echo (reflectivity) data and *b)* synoptic weather conditions to get information as to any physical processes being altered by the seeding.

Detection of Effect

Detection of the effect of modification is a critical design issue. Past studies clearly point to hail experimentation in one area since area-to-area correlations of hail are weak and the various target-control approaches for getting control data for evaluating are just not acceptable.

Detection of possible hail changes with single-area experimentation, involving randomized seeding of some experimental unit (hour, day, etc.), is partially a function of area size. The larger the area, the less the time required to detect an effect.

Detection is also a function of sampling which rests on dimension of the verification elements Prior Survey studies show that area mean hail values and hailstreaks necessitate one sampling instrument per square mile to insure a representative measurmeent of all hailfall parameters over an area of 100 mi^2 or larger. Similar hail-rain studies since 1967 reveal that all desired rainfall expressions require one raingage per 9 mi^2 , each raingage to be adapted to also record the time of hail. Optimization of costs of these two factors (area size and instrument density) with a realistic expectation of project support funds indicates choice of an experimental area of 2000 mi^2 with hail samplers every 1 mi^2 and recording raingages every 9 mi^2.

Experimental Unit

A key part of the experimental design and evaluation for hail suppression is the choice of the experimental unit. Various evaluation data and a variety of operational considerations affect the unit chosen, and failure to define realistically the criteria to declare an experimental unit can produce serious evaluation complications. The large size of the experimental area derived, plus the large number of measurement sites, together point toward use of daily units for realistic servicing of instrumentation. Proper management of the extensive airborne seeding system required in any highly time-limiting design (such as seed for x hours, no seed for y hours, then seed for z hours, etc.) is unrealistic. Another critical consideration is the use of crop-hail loss data (necessary for evaluation) which is acquired only on a daily basis. Study of past hailfall periods in the 2000 mi^2 experimental area shows them to have durations of 1 to 12 hours (often the hailstorms are intermittent in this period but produced by one major weather condition), and about 30% of the time these periods extend into the nocturnal hours or begin at night. Clearly, the minimum of hail activity is in the 0600-0900 CDT period, *but it can hail at all times.* Thus, the *experimental unit chosen is a 24-hour period.* It will typically embrace all the hail produced on the area by one major synoptic weather system (a feature desired on the evaluation process). .

The 24-hour unit choice, coupled with the logistical problems of servicing a large network, plus the fact that hail days have a weak tendency (0.3 probability) to occur in pairs in the area, means that the 2000 passive hail samplers (hailpads) must be changed after each 24-hour period. A simple device that will remotely alternate exposure of dual hailpads at each site is easily available.

The definition of a 24-hour experimental period will be on an objective forecast basis. Essentially, analysis shows that the use of our technique for forecasting thunderstorms in the area will result in forecasts that include all area hail days, and in an 'over forecast' of hail days by about 30%. That is, all potential hail days will be included in the experimental units, but they will be 70% of the total forecast 24-hour experimental units (or 30% of the units will not be hail days due to natural processes). The forecasting will be updated every hour with the use of objective techniques, and when the criteria are met at any time, an experimental unit will be declared.

At this stage in the decision process, the three-way randomization (one-third seeded with cloud-base release systems, one-third seeded with releases at mid-cloud levels, and one-third of the units not seeded) would be employed. The randomization process would be designed to ensure a similar number of hail-producing weather conditions in each class. For example, 65% of all area hail days are with squall lines and zones, 15% with cold fronts, 17% with warm-stationary fronts, and 3% are due to local instability with no major frontal features. Such distributions (65, 15, 17, and 3) must be sought in the samples of each category to ensure against a 'bad draw.'

Once a given alternative (seecbor no seed) is made for a given day, that alternative is eliminated from the choices for the next forecast experimental unit. This will ensure against runs of similar treatment, particularly when hail occurs on consecutive days.

A third contingency in the forecast and choice of days for experimentation concerns elimination of days with atmospheric conditions capable of *extremely severe weather events,* major tornadoes (tracks > 15 miles) and short duration flood-producing rainstorms (> 3 inches in 2 hours or > 6 inches in 12 hours). Although most of these also are hail days, discussions with state officials about experimentation on such days, plus the lack of specific knowledge of seeding effects on such events, and the attitudes from the public sampling effort collectively indicate that truly extreme events should be excluded from experimentation. Where possible, atmospheric conditions conducive to such events, which occur in the experimental area on an average of 1 day in any 3-year period (1 day of 48), will be used to forecast and to separate out such days from the experiment. Furthermore, if a 24-hour period has been put in the experimental unit and, because of a forecasting error, starts to become such a potential severe event (as evidenced from atmopsheric conditions and/or radar data), it will immediately be dropped as a unit and no seeding will be pursued until a new unit is declared.

After a unit has been declared for seeding, another deicsion process will be used to initiate the actual seeding operations during the 24-hour period. Costs prohibit the 24-hour surveillance flying of seeding aircraft, so their activation will be determined by monitoring echo and cloud activity. The development of any detectable (> 20 dbz) echoes and/or cumulus congestus clouds (using satellite data) in the area will be the criteria used to launch seeding aircraft. Number and positions of seeding aircraft will be determined by the developing situation. Seeding is to be performed on any cloud (cell) entities which have

1) A reflectivity in the spring (March-May) that exceeds 35 dbz anywhere above the freezing level, or in the summer-fall (June-October) exceeds 39 dbz anywhere above the freezing level
2) Tops growing at ⩾ 1000 ft/min

Seeding in the 24-hour unit randomly chosen for a seeding experiment will continue on all such candidate clouds (echoes) in and approaching the experimental area. Clouds (echoes) chosen for seeding beyond the area will be those whose track and life stage (based on near real-time calculations of echo average characteristics for that period) indicate they will persist into the area. *The goal is to seed all possible hail-producing clouds.*

Summary

This section has defined the experimental area (2000 mi^2), its instrument density (1 per mi^2 for hail, 1 per 9 mi^2 for rain), and the experimental unit (24-hour) chosen and the reasons for these choices. Proof of hail suppression must come from surface hail data directly related to crop losses. However, it must be accompanied by a meaningful interpretation of the processes altered by using a comprehensive analysis of all data. All the hail data, rain data, information on the deposition of seeding material, and radar echo results will be interpreted according to synoptic weather conditions.

Statistical proof will utilize these data types analyzed on the basis of a combination of single area randomization and area historical data to yield two sets of control data. Rigorous significance levels must be reached by at least three of the hailfall characteristics.

Declaration of 24-hour experimental units will occur when weather conditions reach a pre-set area thunderstorm forecast criteria. Three-way randomization (seed aloft, seed at cloud base, and no seed categories) will then be used with built-in sampling regulations to ensure representative samples of weather conditions in each category. Extreme tornadic and flash flood-producing events will be excluded from the experiment for a variety of scientific and socio-political reasons. Once a seed unit has been declared, seeding activity will be launched on the basis of certain cloud activity (satellite detected) and achievement of radar echo criteria (reflectivity and growth).

The decisions as to area size, sampling density, 24-hour unit, three-way randomization, level of statistical significance, and forecast declaration system all integrate to affect the time required to detect a change in hail. Since such an experiment is an expensive undertaking, all design choices have been made within a cost-scientific optimization framework with *a goal of minimizing the length of the experiment.*

Given all these factors, the length of the experiment depends on the level of reduction sought. Use of the two most powerful surface hail factors found (amount of loss, or intensity, coupled with area of loss) reveals the following detection times for either seeding system. Detection of a 20% reduction (at an alpha = 0.05 and a beta = 0.3) would require 24 years; a 30% reduction, 10 years; a 40% reduction, 5 years; and a 50% reduction, 4 years. A year is defined by the crop loss season (mid-May through September) which averages 16 hail loss days in the proposed 2000-mi^2 area. As noted in the evaluation section of Part 1 of this report, it appears that 30 to 50% reductions have been achieved in other hail climates with the use of the seeding technologies advocated for this experiment. Hence, a 40% reduction in two or more hail variables seems to be a reasonable goal of the experiment. This would require a 5-year or shorter experiment for each seeding system. At this time no predictable shift in rainfall quantity or rate can be stated.

OPERATIONAL ASPECTS

The operational aspects of the hail experiment must function to fulfill the project goal, the design, the modification hypothesis, and evaluation needs set forth in the prior three sections. Operations must resemble a well-organized, military-type, 24-hour effort with a staff and facilities adequate to eliminate major failures during the experimental period (mid-May through September). For this reason, operational personnel should be chosen on the basis of experience with past successful field operations. The operational phase of the experiment has five components:

1) An operational headquarters
2) A forecast system
3) A seeding system
4) An evaluation system
5) A data processing, preliminary analysis and interpretation effort.

Headquarters

A structure must be established in a locale readily accessible to the field operations and located where *a)* the project radars can scan adequately the experimental area, and *b)* the project aircraft can be based. The space should include offices for the project director, a radar operational-communication center for aircraft, two forecast rooms, electronic shops, a ready-room for briefings, a network operational room, analyses space, data and equipment storage, radar antenna sites, and a radio transmission facility. The aircraft must be at an airport where facilities are adequate for their storage and maintenance and for the storage of the seeding devices and material.

The experiment would be supervised by a Project Director housed at the Headquarters. He must have an assistant. Their major duties are to oversee the field project effort from May-September, to oversee at all times the ongoing analyses, to conduct daily briefings, to supervise the choice of experimental units, and to prepare all reports for the project.

Forecast System

The basic functions of the forecast system were defined in the previous section on design and evaluation. Basically, the forecast system comprises the staff and facilities functioning within the Headquarters to:

1) Develop 'alerts' on time scales of 3 to 48 hours before experimental units
2) Declare the 24-hour experimental units on any given clock hour
3) Utilize radar data, satellite data, and all other forms of weather data to monitor and forecast the onset of storm activity just beyond and inside the experimental area during an experimental unit.

Standard area thunderstorm objective forecast criteria developed in DESH should be used to declare an experimental unit. They will result in a forecast of 22 days (units) per season (mid-May through September), on the average. They will over-forecast the hail events (16 days on the average), but will include all hail events.

As part of declaring the 24-hour unit, this system must perform two other key tasks. It must interact with the random choice of treatment (seed or ho seed) process of the Project Director to furnish the basic synoptic weather condition that is about to produce the hail. This is then combined with past seed or no seed unit information and random tables to ensure a comparable distribution of conditions sampled in each experimental category (seeding at cloud base, seeding at upper cloud levels, and no seed days).

Second, the forecast system, in declaring the 24-hour units, must indicate whether the conditions are those capable of excessively severe weather (defined as tornadoes $\geqslant$ 15 miles in length or rainstorms capable of $\geqslant$ 3 inches in 2 hours or $\geqslant$ 6 inches in 12 hours). This potential is also to be monitored during a 24-hour unit, and if it develops, the unit is to be discarded from the sample and any ongoing seeding is to stop.

To perform these functions, certain key facilities must exist. One is a continuous (24 hour) operating radar facility capable of showing, at the desire of the duty forecaster, the position, maximum reflectivity, and height of any or all storms within and 50 miles W, SW, and NW of the experimental area. Also required is a synchronous satellite data terminal capable of displaying the 30-minute satellite photographs. Other weather equipment include facsimile and teletype circuits. The incoming hourly weather data is to be fed into a mini-computer, located at the operational headquarters or at a nearby locale. Here, the objective analysis and forecast techniques are used to make on each hour the forecast of all critical conditions.

The DESH objective forecast analysis study also revealed that the forecast system, to be effective, would require a weather observation station to be established in the Vandalia area to furnish data in a region too void of data sources. A rawinsonde site needs to be operated in east-central Illinois to form a triad of stations (Salem, Peoria, and Champaign). Releases every 6 hours at all three stations would be needed, requiring additional, on-call releases at the Salem and Peoria NWS stations. A pibal facility would also be operated by the forecast system at Headquarters.

Personnel must be adequate to perform the 24-hour forecast effort from May through September. This includes a forecast system director, 4 duty meteorologists, and 4 assistants to plot data, to feed input to the computer, and to operate the rawinsonde.

Seeding System

The seeding system would consist of the aircraft and their equipment (racks and pods) for transporting and releasing the seeding material. The system also includes the seeding materials, a radar for aircraft guidance and tracking, a radar-to-aircraft communication system, and all required personnel.

The aircraft requirements, based on discussions with operational weather modifiers and careful considerations of the storm frequency and storm period durations in the experimental area, would be 10 aircraft available for cloud-base seeding activities and 2 jet aircraft (3 crews) available for the high-level seeding. The cloud-base seeding aircraft should be capable of measuring updraft velocities in storms, and the high-level aircraft should have on-board radar and scope photography. All aircraft should have position recording devices and transponders to the base station radar. The often multi-cellular and multi-line nature of hail-producing periods will frequently necessitate pre-storm distribution of these aircraft at 2 or 3 airports around the area after the experimental unit has been declared. Such a distribution would be based on project forecasts. The forecast group would also alert (3 to 48 hours ahead) and advise the seeding system group as to the operational times and locales in the area during a unit. It would also declare the initiation of seeding (if it is a seed unit).

An aircraft-related effort initiated well before the experiment would be planning with the Federal Aviation Agency. The operation of project aircraft with ability to go into thunderstorms must be understood and cleared by the FAA. A system of routine communication with FAA on operational periods must be established so that aircraft operations are not restricted.

Seeding Materials

The silver iodide seeding would be conducted with the use of pyrotechnic devices. These would be wing-mounted on the 10 cloud-base aircraft. Droppable pyrotechnics would be carried on the 2 high-level jet aircraft in pods. The racks, pods, and pyrotechnics have already been developed and tested. Adjustments to the burn time (vertical distance) of the droppable flares would be made according to predicted storm heights and likely flight levels so as to burn in the -5° C to -15° C level. Since the presence of the seeding materials (silver) would be studied from rain and hail samples, care must be used in the storage and handling of the pyrotechnics. This storage must be in a facility well separated from the locale where rain and hail samples are kept.

Radar

Once operations involving actual seeding have been declared by the forecast group, a radar is used for directing the seeding aircraft. A radar must be devoted to this task and it must be capable of 3-dimensional (RHI) scans to search for high reflectivity areas and echo configurations indicative of updraft areas. Every effort must be made on any operational period to rapidly discern the general placement of updraft areas (front, back, etc.) and to identify new echo formation zones. The positions of at least 5 project aircraft should be monitored on this radar system through use of transponders and a receiver mounted on the radar antenna.

The personnel for the seeding system would include 2 skilled radar operators, the necessary aircraft crews (13 pilots and 13 crewmen), and a radar technician. Major consideration must be given to the employment of a group skilled in aircraft operations and weather modification to handle the entire seeding system.

Evaluation System

The goals set forth require an elaborate, smoothly functioning system to evaluate the experiment. The basic evaluation tools include *a)* a series of surface networks (hailpads, raingages, observers, rainwater samplers), *b)* crop loss data, *c)* atmospheric data that describe the mesoscale environment, *d)* a weather radar system, and *e)* geostationary satellite data on clouds.

Networks

Four basic networks devoted to sampling the hail and rain in the experimental area are needed. First is the hailpad network comprising 2000 pads ($1/mi^2$). These would be a 'dual sensor' type, either center pivoted (with a pivot timed to occur at 0600 each day), or a dual pad site with a simple movable shield that covers one of the two pads for a 24-hour period and also shifts at 0600 each day. Simple springwound timers would suffice to allow this remotely controlled sampling of two 24-hour hail units in sequence before servicing (changing of pads). Past studies show no cases in 9 years of 3 hail days in sequence. Servicing of the 2000 hailpads would be handled by 20 local residents with each assigned 100 pads, a number easily serviced in a day. Servicing can be on an 'on-call' basis, but would be done at least once a week.

The rainfall would be measured in 220 recording raingages located 3 miles apart. These would be modified to record hailfall times by the use of a new inexpensive timing device designed by the Survey which records hail time on the raingage chart with a second pen. Each raingage is at a hailpad site. Available recording hailgages, such as the 15 possessed by the Water Survey, should be distributed evenly throughout the area. The raingages and hailgages would be serviced by 4 trained technicians on a weekly basis.

Rainwater-hail samplers (plastic bottles attached to fence posts) would be installed at every other raingage (110 total). These data will allow tracing of silver seeding material through its geographical positions. These would be serviced in an 8-hour period by 3 local field residents on an 'on-call' basis with routine bottle changes weekly. In addition, one sampler must be located in each of the six downwind regions (2000 mi^2). These would be serviced by a paid observer.

A fourth network would be composed of volunteer hail observers sought in and around the experimental area. About 300 to 400 such observers should be organized and furnished with reporting cards. These give standard hailfall information and any crop or property damage data. These observers should also be furnished with plastic bags and asked to collect any hailstones that occur, to be used in analyses of seeding material.

Crop Loss Data

The experimental area is to be located where hail insurance coverage is extensive (> 60% insured). All hail insurance companies and associations would be contacted and asked to furnish detailed information on all hail loss claims in and around the area and also to furnish copies of the detailed work sheets of the adjusters.

Further crop loss data would be collected by use of an aerial (color and IR) photographic technique developed by the Survey. Flights over the loss areas should be made 5 to 15 days after each storm period at an optimum height, 5000 feet AGL. These photographs would be analyzed by the Survey's technique to develop loss patterns and area mean loss values for each crop and field. Hence, these mapped values would aid in the detailed estimates of loss in the adjusted fields and would furnish desired data in the uninsured areas. An adjuster would be needed to get ground-truth point data to calibrate the loss values obtained from the photographs.

Atmospheric Data

Certain field operations are required to obtain surface weather and upper air data to aid in the evaluation involving classification of the hail periods by a variety of atmospheric conditions. This would necessitate the installation and operation of 15 surface weather stations located in a grid pattern in the experimental area. Each would record temperature, dew point, and winds. These would be serviced by the raingage network technicians.

In addition, the previously described data produced for the forecast system would be used in the evaluation. This includes the hourly surface weather data from the station to be established to the south of the experimental area, plus the pibal and radiosonde data from the Peoria, Salem, and Champaign sites. These data coupled with other routinely available from the NWS would constitute the atmospheric data.

Radar

A weather radar (10-cm wavelength) must be available and dedicated to use in the evaluation process. If possible, the radar should have a capability to detect hail in the storms. The dual wavelength CHILL system has such a capability. Operations must be conducted on all experimental units (24-hours) and in a fixed, 3-dimensional scan pattern over the experimental area. The scans must sample all levels (based on beam width) from the surface to the -25° C level and enough additional levels to encompass the echo tops. Every effort must be made to develop a complete scan series in 5 minutes or less. Personnel needed include 3 radar operators, an operational director, and an electronic engineer.

Satellite

The evaluation effort would also utilize the 30-minute cloud data furnished by geostationary satellites that are used in the forecast effort. These data should be routinely collected and retained for all convective cloud days. They would be used in the experimental area and in six downwind areas to monitor cloud behavior on the mesoscale. Personnel in the forecast system would store these data.

Data Processing and Preliminary Analysis

A key aspect for a successful operation and evaluation effort is rapid data processing. Quality of all data (raingage, radar, radiosonde, etc.) must be determined as quickly as possible to detect problems. Hence, facilities (computers and film readers) and staff must be sufficient to allow for routine processing of the data. It is extremely important that the data of all types be digitized. The digitization should be on magnetic tapes such that all data from an individual day can be easily studied, and so that all data of a single device (say radar) can be examined for a whole season. The personnel needs (editing, checking, reviewing, and digitizing) include 3 them. people for raingage data, 3 for the hailpad, hail loss, and observer data, and 3 for the radar data. Other more complex data can be evaluated by off-duty forecasters.

Project leaders and subsection directors should spend all available time in the operational period (May-September) performing preliminary analysis of the initial processed data. In the off season (October-April), the 4 field technicians and 7 radar operators can assist in routine analyses, as well as repair/calibration of equipment. The project forecast staff should be used to perform a variety of analyses in the off season. A key effort of the off-season analyses would be *a)* to stay current in the evaluation, and *b)* to discover errors or problems that require revisions in the operations of the next season.

IMPACT MONITORING AND PUBLIC INTERACTIONS

This fourth and equally essential component of a midwestern hail suppression experiment concerns how the meteorological efforts (the first three parts —hypothesis, design, and operations) interface with users and the public. It also addresses actual and potential impacts on the social attitudes, on the economy, on ecology, and with any institutional-legal arrangements.

Interactions

Before the experiment can be launched, a carefully presented program to inform the public must be initiated. A social attitudes study (Krane and Haas, 1974; Appendix B) pointed to a favorable public attitude toward *weather modification experimentation* in Illinois. However, it also revealed a great lack of knowledge about hail suppression. It showed that for a complicated, difficult to understand science like weather modification, the majority of the public tends to depend on key local (township, city, and county) decision makers for opinion development. These decision makers can vary and may include key farmers, bankers, clergy, mayors, elected county officials, extension agents, and conservation district directors. Thus, one major interaction effort concerns local (people in and around the experimental area) users and interests.

In Phase 1 of this local interactive effort, the key people must be identified in and around the 2000 mi^2 area, and then systematically informed about all aspects of the experiment. Presentations to these small groups have to be honest and internally consistent. A short concise project information document should be developed for wide distribution. If reasonable, a 'citizens committee' could be developed as a focal point for a continuing interface throughout the project. A project information person is needed at all times to give talks and to answer questions.

Phase 2 of this local public interactive effort involves working with the local decision makers to develop a series of public presentations to key groups (service clubs, 4-H groups, farmer unions, etc.). The experiment should not be launched until Phases 1 and 2 are well initiated and a favorable and understanding local response is obtained. Among other things, this will aid in the local arrangements for instrument siting, a major effort.

The public in and around the area should be routinely and continuously informed through the news media about the progress of the project (Phase 3). The project forecast regarding experimental days could be aired over local radio stations, and summaries of annual results must be delivered to the public and to the local and state officials. All possible existing means for distributing information, such as the University of Illinois Extension Service, should be used to distribute project information, both on a regular basis and about specific items of lay interest.

The other major interactive effort concerns *non-local users* of the project results. First is the crop-hail and property insurance intersts (companies and their associations). Successful hail suppression could have a major impact on this industry, and they will wish to be closely informed of the progress and performance of the experiment. Further, their involvement is sought in the form of furnishing detailed daily loss claims and adjustments for the project area. Their endorsement of the experiment is also sought so that local insurance agents will understand the project and its potential value to them.

Another group of users includes various agriculturalists at universities in and around Illinois, agricultural associations (such as the IAA), the Farm Bureau, and major agri-businesses related to the region's agriculture. Hail suppression, if successful, would affect them in various ways. The strong influential reputation of the agriculture experiment station and agricultural groups like IAA also means they must be informed about the project so as to secure their understanding and to utilize their communication systems. Key officials in these agricultural groups must be contacted and the experiment explained before it is launched. State experiment stations commonly serve as key information sources for most farmers in the state, and being able to give an honest appraisal of hail suppression is in the interest of the experiment stations.

A third group of users to be informed before, during, and after the experiment are governmental officials. At the state level, this begins with the Governors Office. It would also include key staff in all state departments affected by the experiment (Registration and Education, Agriculture, Conservation, and Insurance). As part of this, the State Weather Modification Control Board must be informed about the project according to state regulations. Also, local area legislators should be informed about the project.

At the federal level, all agencies providing support must be informed of all stages, generally more often than grants or contracts require. The project activities would be routinely reported to NOAA (Department of Commerce) according to federal laws on weather modification. Presentations about the project should also be scheduled for the Interdepartmental Committee on Atmospheric Sciences so that all federal agencies involved in weather modification will be aware of the project and its progress. An Environmental Impact Statement may be necessary, depending on the funding source(s) and those conducting the experiment.

Another user group includes all atmospheric and agricultural scientists and engineers. The results of the project must be distributed to these two user groups. Specific attention should be given to the exchange of information with the weather modification industry. This group would be the main users of the proven technologies, and the project performance and results are of considerable importance to this industry.

Impact Monitoring

The second portion of this part of the experiment relates to the monitoring of social, legal, economic, and ecological impacts. Recommended monitoring efforts are described below.

Public Attitudes

The 1974 sampling in central Illinois of public attitudes toward weather modification provides a unique 'baseline' of information prior to any experimentation. Similar sampling of public attitudes, both in and near the project area, should be conducted annually during the hail suppression experiment. This would be a valuable sociological experiment, and would also serve as a means for detecting any trends in attitudes toward the project. Effectiveness of the public information activities can also be judged from the monitoring of public attitudes. The results would be valuable in any future application of a successful technology in Illinois and elsewhere. This questioning should include perceived attitudes toward economic and other impacts.

Economic Impacts

The crop loss data collected from insurance companies would be analyzed in detail as part of the evaluation. The dollar losses and areas of loss can be used to monitor the economic aspects. In particular, the loss data should be compared with historical loss values from the project area. Loss in surrounding similar-sized areas and for the entire state should be monitored for qualitative assessments of the effects in the experimental area.

Impacts beyond the Project Area

The potential for altering the precipitation (rain or hail) beyond the project area is of concern to the public and to atmospheric scientists. The lack of mesoscale numerical models adequate to predict and understand such large-scale effects means that "Extra Area Effects" (EAE) must be monitored on a descriptive, not causal, basis. Six sets of data available on a daily basis should be collected from the surrounding area (50 miles north and south of the experimental area and 100 miles east of it). These extra-area data sets include *a)* the daily and hourly rainfall data from the Environmental Data Service, *b)* hail data from cooperative hail observers established by the project, *c)* the daily crop-hail insurance loss data, *d)* hourly radar data of project radar systems and those of the NWS, *e)* the cloud data of the SMS satellite, and/) rainwater samples for monitoring silver with one sampler in each 2000-mi^2 area. Each of these would be separated according to the seeding criteria for each experimental unit (day), and compared by daily means and totals for six 2000 mi^2 areas including one adjacent to the north of the experimental area, one to the south, one to the northeast, two to the east, and one to the southeast. The cloud, radar, and hourly rainfall data would also allow sequential quantitative analyses of the behavior (areal extent and intensity) of mesoscale systems that pass through the experimental area. A rainwater sampler must be installed in each of the six extra areas to collect water for analysis of the seeding material.

Ecological Impacts

The alteration of hail is considered to have little or no detectable long-term effects on the Illinois ecosystem. Water from melted hail is an insignificant part of the growing season rainfall, and normal damage of hail to the non-crop flora and to the fauna is largely insignificant. Studies of weather (temperature and precipitation) impacts on rabbits in Illinois shows that the warm season weather factors, which are obviously more critical conditions than hail, explain less than 10% of the variation in rabbit populations.

The only environmental consequence that can be imaged from the hail suppression experiment is that from the seeding material, silver. Silver can be toxic to certain species if ingested in sufficient quantities. The amount of silver iodide to be released into clouds is relatively low but should be apparent in levels of 100 to 200 ng/l in rainwater. However, these levels are 3 orders of magnitude below toxic levels. Nevertheless, rainwater samples should be collected throughout the experimental area (one site per 18 mi^2) and used *a)* to evaluate the seeding effectiveness, and *b)* to monitor the amount of silver deposition. Soil samples should be collected from 6 locations at the end of each season and analyzed for silver content. Research is on-going at Colorado State University to provide indications of levels at which silver might become a problem in the ecosystem. Results to date do not suggest any possible ecological effect from the quantities of silver found in soils of Colorado where weather modification has been performed.

ADDITIONAL ISSUES REQUIRING RESEARCH

If possible, three areas of research need to be pursued further before a hail suppression experiment is launched in Illinois. Two of these needs relate to inadequate information from other Survey projects involving cloud studies with aircraft. The flight programs of METROMEX and PEP were expected to gather sufficient cloud data (on updraft characteristics and in-cloud conditions like super-cooled water and nuclei) to negate a cloud sampling effort in DESH.

First, the PEP effort involving mid-cloud sampling was suddenly restricted to 2 months of summer data because of funding cuts. Too few hail-producing storms (prior to their development) were sampled. Hence, available background cloud data critical to seeding rate decisions is more limited than desired. More such flights and data are needed.

Second, the cloud base updraft measurements and tracer experiments for METROMEX were totally restricted to daytime efforts. Hence, little useful information is available on *a)* the updraft characteristics of nocturnal storms, and *b)* the aircraft operational problems associated with night-time cloud-base seeding. This lack of nocturnal storm data and the obvious operational difficulty is a critical issue since 30% of the hailstorms in the experimental area occur at night. The operational problem can only be solved by sophisticated use of radar data (an understanding of likely updraft positions based on real-time interpretation of radar echo data) and excellent aircraft-radar operator communications. Data on nocturnal clouds and storms should be collected to ascertain cloud base characteristics and their relation to radar echo behavior. On-top cloud seeding by jets also is based on visual observations and is also restricted nocturnally unless lightning is adequate to illuminate the growing cells.

The third need derives from inadequate information on the various possible relationships between hail (surface and aloft) and 10-cm radar data. The limited CHILL radar operations for DESH coupled with the loss of the radar to support NHRE in Colorado in the springs and summers of 1973 and 1974 yielded too small a sample of hailstorm data over the Illinois hail network.

Hence, a variety of radar-hail relationships (echo reflectivity, growth, volume, and rates of change) cannot be established with certainty.

Recommended efforts, if possible, prior to launching a hail suppression experiment in Illinois would concern research of data collected in a full hail season (April-September). Efforts would include

1) A surface hail network
2) A good 10-cm digital radar
3) A good cloud physics penetration aircraft to collect in-cloud data on all possible hailstorms
4) A second aircraft to measure cloud base conditions (in concert with radar operations)
5) A high-level capability jet aircraft (suitable for mid-cloud 15,000 to 30,000 feet seeding) to test its operational limitations (in concert with the 10-cm radar) in summer season storms at night and in the daylight

Data analyzed from these five sources would remove uncertainties relating to evaluation (with radar), seeding rates, and nocturnal operations.

Part 3. Advisability of an Experiment in Illinois

The termination of a 9-year effort to design a hail suppression experiment for Illinois calls for an assessment of whether an experiment should be done. The advisability of an experiment rests on several factors. The midwestern agricultural community has established the need for experimentation with hail suppression in the Midwest (see Appendix C).

The Illinois-located hail research, which since 1967 focused largely on the development of the design of an experiment, had the expectation that one important part of a decision to proceed into an Illinois experiment was the outcome of NHRE. Originally NHRE was intended to be completed by 1975 or 1976. The Illinois experiment would rest partially on certain fundamental research findings on hail formation processes from Colorado that would be transferable to Illinois. Certainly unsuccessful NHRE results (increased hail and/or decreased rain) would probably auger against recommending, or launching, a midwestern experiment. For this reason, the Survey sought participation in certain phases of NHRE (statistical evaluation, radar, and surface hail studies) applicable to an Illinois experiment. Because of a variety of major managerial and operational problems and analytical delays, NHRE will not be completed as planned, and a revised experiment may well extend through 1980. The Survey's initial research missions with NHRE were either satisfied or terminated by NHRE in 1974. Only preliminary inconclusive results on the hail suppression of NHRE are available, but these are not encouraging since they indicate a slight increase in hail and rain from seeding. The results are not yet classed as statistically significant.

The Illinois experiment was never envisioned to have the extensive and expensive research component that NHRE was designed to have. The NHRE research results, particularly those explaining how in-cloud processes were modified (if it occurred), were to be coupled with past research results collected in a variety of prior hail research efforts in Illinois. At this time, neither source of information is considered adequate to be used in developing a thorough scientific explanation of the outcome of any hail suppression experiment in the near future.

The Illinois experiment would have to be launched with the acceptance that a) *it would be a test of existing seeding technique(s) believed to be the most valid,* b) *decisions on their validity would have to rest on suppression results obtained elsewhere, and* c) *there would not be sufficient complementary research effort in the Illinois experiment (or from results from prior Illinois studies) to explain fully the meteorological outcome of the Illinois experiment.*

Hence, a critical issue in deciding on the recommendation for an experiment in Illinois is whether there is sufficient evidence from other suppression projects, using existing technologies, to justify an experiment which would largely answer only the question, "With technology X applied to midwestern thunderstorms, is hail increased, not changed, or decreased?" Cloud-base type seeding using AgI appears to have reduced hail losses in projects in the west of Texas and in western North Dakota, and high-level AgI seeding into clouds in South Africa also may have reduced major crop losses. However, certain storm types and systems involved in hail production in these areas are different from those in the Midwest. The question is, "How much difference is there, or with what confidence can one transfer results from these areas to the Midwest as a basis to recommend launching an experiment?"

Another issue regarding advisability concerns the attitudes and support of large and complex groups of individuals, institutions, and agencies. Clearly, the experiment deals with severe storms and the potential for public concern about the consequences of modification efforts is high. Thus a recommendation for an experiment must involve an extensive effort to discuss and explain the experiment with several high-level state officials, governmental groups, agricultural groups, and university groups. Their support is critical to a recommendation since the proper conduct of the experiment needs local and state understanding and support.

A public attitude survey of Illinois citizens conducted in 1974 showed greater belief in and interest in rain modification than hail suppression. The economic benefits of a 15% average summer rain increase outweigh those from a 80% hail loss reduction. The METROMEX results of inadvertent weather modification by St. Louis establishes that 20 to 25% more summer rain is produced and is accompanied by 50 to 75% more hail. Economic assessments prove the benefits due to the added rain exceed those losses due to added hail. Extending these results into planned efforts to reduce hail suggests the possibility of reduced rainfall, and the difference in their agricultural values suggests the net result might be a loss. Clearly, almost any modification of rainfall would be of greater economic impact in Illinois than a major modification of hail.

The meteorological results from DESH also point to the fact that successful operations in Illinois will be difficult because of the complexity of the hailstorm systems and because of the need for nocturnal operations. Evaluation needs set stringent requirements on the evaluation scheme, and the considerable logistics for successful operations will tax the forecasting scheme and the storm monitoring systems. In summary, a decision to pursue an experiment involves awareness that the operational effort will be much more complex than that of many prior weather modification experiments.

Thus, one cannot clearly and strongly recommend a type of experiment that can be envisioned as being limited both by potential funding and meteorological facilities available in the foreseeable 2 to 5 years. Critical instrumentation such as armored aircraft which can penetrate storms is needed to explain modification but such aircraft and other facilities are committed to NHRE for the next several years. Hence any modification achieved in Illinois would likely not have desired supporting physical evidence, even if unlimited funds were available. A decision to ignore this scientific issue in an experiment rests *a)* on having sufficiently clear results of suppression from activities elsewhere with existing technologies, and *b)* on making subjective decisions that "it will likely work in Illinois, and it is in the state's interest to test the concept." Economically, crop losses due to hail in a 2000-mi^2 area in central Illinois average $265,000 annually (1973 dollars), and the comparable cost of quality but standard weather modification operational efforts were and are about 10¢ per acre (1973 value), or a total of $130,000 for a 2000-$mi^2$ area. Hence, *the hail loss would have to be reduced 50% to just break even,* and a reduction of 50% is the most optimistic value to be expected. Hence, the economic aspects do not look particularly favorable unless greater reductions can be envisioned or seeding technologies of much lower cost are developed.

The considerable socio-economic, technological, and scientific uncertainties mentioned will be further addressed in another comprehensive study of hail suppression being launched in 1975 by scientists of the Survey and lawyers, sociologists, and economists of other institutions. This NSF-supported project is a 'technology assessment' of the future of hail suppression on a national scale, and as such will define the likely scientific, technological, and socio-economic factors relating to hail suppression 10 and 20 years in the future. This project, when completed in 1976, should help clarify several of the current uncertainties that face the launching of an Illinois experiment.

For these principal reasons, launching of an experiment in Illinois does not appear advisable in 1976. As new knowledge becomes available about hail suppression technologies, this decision should be re-examined.

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APPENDIX A

List of Hail-Related Papers and Reports of the Illinois State Water Survey

Major subject content	
8	Achtemeier, G. L., and G. M. Morgan, 1975: *A Short-Term Thunderstorm Forecast System: Step 1, Exploitation of the Surface Data.* Preprints 9th Conference Severe Local Storms, AMS, Boston, 18-24.
11	Barron, A., S. A. Changnon, and J. Hornaday, 1970: *Investigations of Crop-Hail Loss Measurement Techniques.* CHIAA Research Report No. 42, 67 pp.
7	Carbone, R. E., D. Atlas, P. Eccles, R. Fetter, and E. A. Mueller, 1973: *Dual Wavelength Radar Hail Detection.* Bulletin AMS, Vol. 54, 921-924.
1, 2, 3, 10	Changnon, S. A., 1975: *Scales of Hail.* Preprints Symposium/Workshop on Hail, NCAR, Boulder, Colorado, 51 pp.
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13	_____, 1973: *Summary Report of METROMEX Studies, 1971-1972.* Illinois State Water Survey Report of Investigation 74, Urbana, 169 pp.
13	_____, 1972: *Field Study of Urban Effects on Precipitation and Severe Weather at St. Louis.* Annual Report, NSF Grant GA-28189X, 20 pp.
13	_____, 1972: *Urban Effects on Thunderstorm and Hailstorm Frequencies.* Preprints Conference on Urban Environment, Philadelphia, Pennsylvania, 177-184.
2, 3	_____, 1972: *Examples of Economic Losses from Hail in the United States.* Journal of Applied Meteorology, Vol. 11, 1128-1137.

(Continued on next page)

SUBJECT INDEX

1 General information
2 Climatology
3 Socio-economic/environmental aspects of hail
4 Design and evaluation of hail research projects
5 Design of hail suppression projects
6 Evaluation of hail suppression projects
7 Radar utilization in hail studies
8 Forecasting of hail
9 Modeling (conceptual and numerical) of hailstorms
10 Surface hail characteristics and sampling
11 Instrumentation for measurement of surface hail
12 Causes of hail (synoptic, surface, and cloud scale factors)
13 Inadvertent modification of hail
14 Hail and crop losses
15 Case studies of inadvertent storms

APPENDIX A (Continued)

Major subject content

7 Changnon, S. A., 1972: *Illinois Radar Research for Hail Suppression Applications, 1967-1969.* Illinois State Water Survey Report of Investigation 71, Urbana, 23 pp.

10, 11 _____, 1972: *Studies of Hail Data in 1970-1972.* Final Report, NSF Grant GA-16917, 28 pp.

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(Continued on next page)

APPENDIX A (Continued)

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4	Changnon, S. A., G. M. Morgan, G. Achtemeier, N. G. Towery, and R. C. Grosh, 1975: *Design of a Hail Suppression Project for Illinois.* Journal of Applied Meteorology, Vol. 14, 771-782.
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6, 14	Henderson, T. J., and S. A. Changnon, 1972: *Results from an Application Program of Hail Suppression in Texas.* Preprints 3rd Conference on Weather Modification, Rapid City, South Dakota, 260-267.
2, 12	Huff, F. A., 1964: *Correlation between Summer Hail Patterns in Illinois and Associated Climatological Events.* Journal of Applied Meteorology, Vol. 3, 240-247.
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2, 10, 11	____, and N. G. Towery, 1974: *Small Scale Variability of Hail and Its Significance for Hail Prevention Experiments.* Journal of Applied Meteorology, Vol. 14, 763-770.
6, 7	Mueller, E. A., and S. A. Changnon, 1974: *Comparison of Echo Statistics for Seeded and Non-Seeded Storms in NHRE 1973.* 4th Conference on Weather Modification, AMS, Ft. Lauderdale, Florida, 114-118.
6, 11	____, and S. A. Changnon, 1968: *A Recording Hailgage for Use in Hail Modification Projects.* Proceedings of 1st National Conference on Weather Modification, 494-502.
7, 15	____, and G. M. Morgan, 1974: *Colorado-Illinois Operational and Analytical Programs Utilizing a Dual Wavelength Radar Facility.* Final Report, NCAR Subcontract 186/71, 34 pp.
7	____, and G. M. Morgan, 1972: *Colorado-Illinois Operational and Analytical Program Utilizing a Dual Wavelength Radar Facility.* Annual Report, NCAR Subcontract 186/71, 13 pp.
6, 7	Rinehart, R. E., and D. W. Staggs, 1968: *Use of Radar to Delineate Surface Hail Areas in Weather Modification Experiments.* Proceedings National Conference on Weather Modification, AMS, Albany, New York, 9 pp.

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APPENDIX A (Concluded)

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APPENDIX B

The Public View toward Weather Modification in Illinois: A Social Assessment

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FINDINGS

A. Attitudes Toward Science, Weather, and Heather Modification

Fifteen items were included in the interview schedule in order to assess local attitudes toward science, weather, and weather modification. These items do not pertain directly to the possibility of a local cloud seeding program, but rather attempt to measure general feelings of Illinois residents about planned programs to alter the weather. The fifteen items can be grouped into several categories. Three of the attitude items should be considered pro-weather modification -- agreement with these statements is indicative of a favorable feeling toward cloud seeding programs. Several other items are anti-weather modification -- agreement is an expression of opposition or doubt about the feasibility and/or outcome of cloud seeding. Another three items measure attitudes toward science and scientists, while the remaining items deal with the issues of control, decision making, and funding with respect to weather modification programs. Table 1 presents the findings for these attitude items.

Responses on the three pro-weather modification items suggest considerable support for cloud seeding technology, both on an experimental basis and on an operational basis. A clear majority of respondents agree that experimentation is desirable (Item 1). As many as 63% agree with the statement while only 20% disagree; the remaining 17% are undecided. Item 5 suggests that "Illinois State Agencies should feel free to use such things as cloud seeding if it might help farmers avoid crop losses." An even larger proportion of the sample agree with this statement (71%). A third item expressing a pro-weather modification sentiment suggests that control of extreme weather conditions by use of the most effective techniques known is quite appropriate (Item 12). As on the previous two items, about two-thirds of the sample are in agreement while only one-fifth disagree.

The next five attitude items to be discussed are expressions of negative feelings or doubts about the application of cloud seeding technology. While 37% disagree that cloud seeding may be against the **will of** the Supreme Being, almost half agree (Item 3). Concern about potentially disruptive effects which cloud seeding may have on the balance of nature are evident from Item 6. Although a sizable proportion of the sample are uncertain about cloud seeding disrupting nature's harmony (29%), far more agree with the possibility (50%) than disagree (21%). Two items suggest that it may be best for man to leave the weather alone, or to deal with weather-caused problems in ways other than through cloud seeding. The proportions agreeing and disagreeing "That man should take the weather as it comes..." are equal (45% and 44%, Item 9). With respect to finding other ways of dealing with the weather (Item 13), about half agree that such things as improved weather forecasting and cheaper insurance may be preferable to weather modification, while one-third disagree. Are attempts to modify the weather a worthy expenditure of tax money? Almost two-thirds agree that other problems should be solved before spending more tax money on weather modification (Item 10), suggesting that for the majority of those interviewed, weather-caused problems may not be a salient concern.

Three items indicate that strong positive sentiments toward science and scientists are held by the majority of the sample. Four out of five respondents agree that "Man should use scientific knowledge to deal with problems whenever and wherever possible" (Item 4), and three-fourths feel that experimentation in general is beneficial to society (Item 8). Clearly, scientists are viewed as concerned citizens, for only one out of eight respondents agree that scientists may have more interest in their experiments than they do for general social conditions (Table 5).

The remaining four attitude items pertain to control and funding of cloud seeding programs. When presented with a choice between state control and federal control for experimental programs, far more persons agree that individual states should be in control (61%) than disagree (23%), (Item 2). The sample is about evenly divided on the statement which suggests that scientists should be in complete control of weather modification programs (Item 11). The fact that as many as 46% of the sample agree that scientists should control such activities is further evidence of favorable attitudes toward scientists in general. However, even though most seem to prefer state control to federal control as well as feel that scientists should have a major role, it is evident from Item 14 that Illinois residents do not want local citizens left out of decision-making procedures. As many as six out of ten respondents indicate that local residents should have a voice in decisions about cloud seeding programs, regardless of the funding source.

One final item considers financing of weather modification. The proportions disagreeing and agreeing that all citizens should be taxed to pay for cloud seeding programs are about the same (44% and 42%). It may well be that many persons are not comfortable with the thought of personally paying something toward weather modification without having experienced benefits from a local program. Data bearing on perceived benefit from weather modification are discussed in the evaluation section of this report (Section E).

A factor analysis was computed on these fifteen attitude items to determine if some of the items might be combined into scales.* Since the purpose of the analysis was heuristic, results are not presented here. Three of the factors derived had as the highest loading items statements which are intuitively and theoretically consistent. On this basis the high loading items on a factor were combined to form a single scale. Three such scales were formed.**

The first scale is designated as the Weather Modification Scale (WXM) and is composed of Items 1, 5, and 12 which we previously discussed as pro-weather modification items. The higher an individual's score on this scale, the more favorably inclined he is toward cloud seeding technology.

Scale 2 is labelled Religio-Natural Orientation (RN2) and consists of Items 3, 6, and 9. The interpretation of this scale is that man's relationship to the weather is one of balance and harmony, and that deliberate attempts to change the weather will upset this "religio-natural" balance. The higher the scale score for a respondent, the stronger is his orientation to this view of the world.

Scale 3 is comprised of two items which measure favorability to the scientific approach for solving problems. This scale is designated as the Scientific Orientation Scale (SO1). High scores on this scale are indicative of a strong scientific orientation.

* The analysis used the minimum residual method of factor extraction and Kaiser's varimax method of factor rotation.

** For a detailed description of the scales see Appendix A.

The relationship between these attitude scales- and other important variables in the study is reported in Section G.

B. Belief in the Efficacy of Cloud Seeding

It has been hypothesized that belief in the efficacy of cloud seeding is associated with favorable evaluation of a specific cloud seeding program (Haas and Krane, 1973; Farhar and Mewes, 1974). That is, persons who believe cloud seeding can produce more moisture and suppress hail should be favorable toward the operation of a program in their geographical area. Respondents were asked if they believed cloud seeding could increase moisture and if cloud seeding could suppress hail (Table 2).

With respect to augmenting precipitation, a little more than half of the sample believe that cloud seeding may be an effective tool (39% answered "yes" and another 15% answered "I think so"). About one-third are uncertain and the remaining 15% doubt that the technology can work. Belief that cloud seeding is effective for reducing damaging hail is considerably less among the respondents. The majority (62%) claim to be uncertain, while one-fifth say "no" and another one-fifth say "yes".

The fact that such a large proportion of the sample feel cloud seeding can work for rain augmentation is surprising. Except for a few very brief efforts, no cloud seeding has been conducted in Central Illinois —either on an experimental or on an operational basis.* Lacking experience with a successful program of precipitation augmentation, it may be that belief in efficacy derives from knowledge of cloud seeding programs elsewhere in the country. (See Section C, following).

* This is substantiated by the respondents themselves, as only 4% claimed awareness of any past cloud seeding efforts in Illinois.

Belief that cloud seeding is effective for modifying the weather may also be associated with ecological concerns. Respondents were asked, "Do you think that a cloud seeding program might damage the ecology of an area -- that it might prove harmful to plant or animal life, soil or water in any way?" From Table 3 it is apparent that more respondents feel uncertain about potential side effects than feel that such occurrences may or may not develop. Four out of ten are uncertain compared to 28% who feel that cloud seeding might be detrimental to the ecology, and 31% who feel it would not be detrimental. Among those indicating fear of potential side effects, the majority mentioned things such as general adverse weather change, upsetting the balance of nature, the effect of chemicals on plants or animals, and the possibility of excessive moisture or flooding.

C. Awareness of Weather Modification Activity

Another major hypothesis in research on the sociological aspects of weather modification is that knowledgeability and awareness of cloud seeding in general, as well as knowledge about the details of a local program, contribute to favorable program evaluation (Farhar, 1974; Krane and Haas, 1974). Since no cloud seeding programs are currently in operation in Illinois, it is not possible to measure respondent levels of knowledge about a local program. However, we did ask respondents if they had heard of weather modification programs operating elsewhere. Table 4 presents the findings.

Respondents are most aware of weather modification for increasing rainfall, and for hurricane wind suppression. As many as 43% claim to have some knowledge of rainfall enhancement programs and 29% claim to be aware of research efforts on hurricanes. Very few persons indicate having knowledge of other types of weather modification programs (hail, 13%; fog, 10%; tornado, 15%). In general, the level of knowledge about planned weather modification is relatively low.

Respondents were also asked about inadvertent weather modification (Table 5). More than one-third answered "yes" or "I think so" to the question, "Do you think that unintended (or accidental) cloud seeding is bringing about changes in the weather?" Slightly less than one-third answered "no" or "I doubt it", while the remaining one-third were uncertain. All respondents were then asked if "...accidental weather modification should be better understood before anyone tries to modify the weather intentionally?" An overwhelming majority (87%) say "yes", even though only a minority (37%) had previously indicated that they felt accidental seeding may be affecting the weather.

Although Illinois has a comprehensive weather modification law which was enacted in 1973, only one respondent was aware of the law (Table 6). This is not surprising in light of the recency of the legislation and in the absence of weather modification activity in the state which would bring visibility to the law.

D. Awareness of the Illinois State Water Survey

The Illinois State Water Survey (ISWS) is a state agency heavily engaged in research related to water resources and weather within the state of Illinois. If an experimental hail suppression program is proposed and conducted in Illinois, it will be under the auspices of the ISWS. Therefore, a number of items were incorporated in the interview schedule to assess public awareness of the agency, of its purpose and activities related to weather phenomena, and to determine the degree of confidence which citizens have in the ISWS to conduct experimental weather modification.

Respondents were asked, "Have you ever heard of the Illinois State Water Survey?" Only 22% claimed to be unaware of the agency's existence while 78% claimed they had heard of the ISWS (Table 7). However, since all respondents had previously received a letter from the ISWS stating that they would be contacted for an interview, we further asked those who claimed awareness to specify whether they knew of the agency prior to this survey, or only as a result of this survey. With this stipulation there were still 52%, or about half of the total sample, who claimed they knew of the organization prior to being contacted.

Knowledgeable respondents were then asked if they know what the ISWS does — what its purpose is (Table 7). As many as one-fourth had no knowledge of the organization's activities. However, one-third said that the ISWS is in some way responsible for water resources and water control within the state; 18% said the agency collected weather data; and 11% said the agency was engaged in research pertaining to weather, water or the environment.

Very few respondents were aware of the hail research project being operated by the ISWS. Only twenty-nine (11%) claimed knowledge of the project (Table 7).

Table 8 shows the results when respondents were asked if they had confidence that the ISWS could conduct a well designed hail suppression experiment. Six out of ten respondents said "yes", one-third were uncertain, and less than one-tenth said "no". With respect to an experimental program for rainfall management, the results are nearly identical. Table 8 also gives the findings when respondents were asked to state a preference between the two types of experimental programs. The most frequent response was that the program should include both (35%), followed by preference for rainfall management (23%), and then by preference for hail suppression (18%). A sizable proportion indicated they would not want either type of program, or that they just didn't care (24%).

In general it appears that the ISWS is reasonably well known in the area. Although few persons know specifically of the hail research project, a very sizable number are aware of the agency and of the kind of activities it supports. Additionally, more than half of the sample have confidence in the capability of the agency to conduct an experimental weather modification program.

E. Evaluation of Cloud Seeding Programs

A primary objective of this study is to determine the degree of acceptance or favorableness toward a proposed experimental weather modification program. Additionally, to account for the factors which contribute to citizen evaluation is of considerable importance. The interview schedule contained a number of items to assess citizen evaluation of local cloud seeding prior to the inception of a program in Illinois.

It is hypothesized that perceived personal benefit from a local cloud seeding program is a determinant of favorableness toward the program. Therefore, respondents were asked, "If a cloud seeding program operating in this area were able to suppress hail, would you say it would probably be of economic benefit to you, harmful to you, or make no difference to you?" Well over half (60%) indicate that an effective hail suppression program would benefit them; almost none (2%) anticipate harm; the remainder feel that such a program would make no difference to them (Table 9). The same question was repeated with respect to an increase in rainfall, and again, with respect to a decrease in rainfall. Clearly, Illinois residents do not perceive as much benefit from rainfall management programs as they do from a hail suppression program (Table 9). Slightly higher proportions anticipate harm from rainfall management (8% for increase; 15% for decrease). More significant is the shift away from perceived benefit to the position that such programs would make no difference to them. Compared to 60% who anticipate benefit from hail suppression, 47% anticipate benefit from a program which could increase rainfall, and only 33% anticipate benefit from a program which could reduce rainfall.

The principal evaluation item is reported in Table 10. Respondents were asked to use one of five categories (from strongly oppose to strongly favor) in answering the following question: "As a resident of this area, how do you feel about an experimental program of hail suppression which may be proposed for this part of Central Illinois?" One out of five persons claim to be opposed to such a program; one-fourth are undecided or feel they have insufficient knowledge to judge; and a little more than half favor the possibility of an experimental program. The figure for favorability is comparable to the proportion in Colorado and in South Dakota who favored a local cloud seeding program prior to its inception. In fact, the percentage is slightly higher: 54% for Illinois, 52% for Colorado and 46% for South Dakota.* This finding should be somewhat rewarding to proponents of weather modification in Illinois since no organized resistance has developed toward the program in Colorado (after four summers of field operations) nor toward the program in South Dakota (after three operational seasons). One cautionary note: It is also the case that expressed opposition to a local program is somewhat greater in Illinois than it was in the two other states — 21% in Illinois, 15% in Colorado, and 9% in South Dakota.

Regardless of their expressed position toward an experimental program, respondents were asked "why" they felt that way (Table 11).

* See Appendix B for further comparisons and sources of data.

For those favoring the experiment, the most frequent response was "belief that research is desirable" for determining the effectiveness of cloud seeding (41%); followed by "specific benefit to the area as a whole" (such as reduced damage to crops and property in the area). Most who oppose the experiment fear that negative effects on the weather or nature will occur (48%). Other stated reasons for opposition include religious beliefs, fear that the program will be wasteful or ineffective, and fear that the program will be expensive to conduct. The clear majority who are undecided simply feel they have insufficient knowledge to judge (87%).

Respondents were asked to indicate what action, if any, they would take if an experimental program were proposed for their area. Table 12 summarizes the findings for this item. Nearly two-thirds feel they would take no action -- either to oppose or to support the program. Less than one in ten say they would actively oppose and the types of action mentioned included "talking against the program", "voting against the program", and "contacting a state official or congressman". For the 29% who claim they might take supportive action, things mentioned included talking, voting, signing petitions, an"d helping the program financially.

More specifically, we asked, "How likely would you be to sign a petition <u>favoring</u> a hail or rain experiment for Central Illinois?" Close to half (45%) indicate they would "probably" or "definitely" sign a petition if it were presented to them (Table 13). Few persons claim they would sign a petition to oppose an experiment (15%, Table 13). We also asked respondents how they would vote and how they thought most people in their county would vote if the issue were placed on the ballot (Table 14). Exactly half feel they personally would vote in favor; 27% are undecided or feel they wouldn't vote; and 23% say they would vote against the program.

One final evaluation item pertaining to an experimental program was asked: "If any persons were to suffer damages which were a result of a cloud seeding experiment, do you feel these damages should be compensated?" Table 15 indicates that a total of 84% feel compensation should be made — 57% who gave an unqualified "yes", and 27% who qualified their response with "if damages can be proven to result from the seeding." This finding differs from the Colorado study where the majority who felt compensation should be made were more likely to qualify their answer (14%, unqualified "yes"; 43%, qualified "yes").* When asked who should pay the compensation, two responses were most frequent: "those doing the seeding" (43%), and "the state government" (30%).

In addition to the evaluation items relating to an experimental cloud seeding program, respondents were asked about the possibility of an operational program. We gave a brief description of the difference between experimental and operational weather modification, and followed this by asking, "How do you feel about the possibility of an <u>operational</u> (non-experimental) program which would seed clouds on all days when hailstorms are in the area?" It is most interesting to compare the results (Table 16) to the item relating to an experimental program (Table 10). Whereas 54% favored the concept of an experiment, only one-third favor an operational program for the area. More respondents are undecided about an operational program (39% compared to 25%), and more are opposed (28% compared to 21%). What accounts for the difference in evaluation of the two types of cloud seeding programs? An examination

* It should be noted that this item was first asked in the Colorado study after respondents had experienced a summer of the National Hail Research Experiment's field activities. This could very well account for the difference in proportions (Haas and Krane, 1973).

of Table 17 provides at least a partial answer. Among those opposing an operational program, 22% suggest that it is necessary first to determine the effectiveness of hail suppression through experimentation. And among the "undecided", 12% give this same reason for their position. Although the actual number of respondents who use this basis for evaluating an operational program is small (a total of 27), it certainly contributes to the drop in favorability which was noted fpr an experimental program. It is also worth noting that the prominant reason given for favorable program evaluation has shifted from "experimentation is desirable" (41%, Table 11) to mention of a specific benefit to the area from hail suppression (43%, Table 17).

The data on program evaluation suggest that Central Illinois residents are rather open to the possibility of an experimental program of hail suppression. The proportion giving favorable evaluation far exceeds the proportion giving a negative evaluation. When asked about taking action toward a proposed experiment, more feel they would engage in supportive activity than in resistive activity. And the lower favorability toward an operational program is partially accounted for -- in the words of many respondents -- by the need for a convincing experimental program. Other variables relating to evaluation are discussed in Section G (following).

F. Decision Making and Funding Regarding Cloud Seeding Programs

An important issue in the application of weather modification technology continues to evolve around decision-making procedures. It has been suggested recently that provision for citizen involvement is not associated with incidence of resistance to projects (Farhar and Mewes, 1974a). Thus, organized public action to oppose a local cloud seeding program appears to be less likely when opportunities for citizen participation in decision-making are provided.

Illinois residents were asked who will and who should make the decision regarding a local cloud seeding experiment? The findings are given in Table 18. Clearly, with respect to who will decide, the most likely response is the "state government". One-third of the respondents answer this way and another 11% feel that the ISWS will make the decision. As many as one-fifth feel that there will be local input into the decision (12% say local residents or local government; another 8% say local agriculturists). With respect to who should decide, the response pattern is very different. The preference is for the decision to be made at the local level — nearly half indicate that local residents (32%) or local agriculturists (17%) should decide about a local cloud seeding experiment. Only 28% say the state government or the ISWS should decide.

Further evidence of the desire for local involvement comes from a previously discussed attitude item (Item 14, Table 1). As many as 60% of the respondents indicated a preference for local residents to have a voice in decisions about a weather modification program, even if local tax money were not used to finance the program.

Respondents were also asked about predicted and preferred funding regarding an experimental cloud seeding program. When asked who should pay, more indicate the state government (31%) than any other single response (Table 19). Nearly one-fourth say the local residents (12%) or local agriculturists (12%) should pay for an experiment. Additional responses include: the federal government (10%), a combination of state and federal (7%); and a combination of state and local (8%). The pattern of responses when asked who will pay differs only slightly (Table 19). As many as 26% feel that local residents will foot the bill, compared to 12% who felt they should pay. As was the case on preferred funding, the most frequent response for predicted funding is the state government (35%).

What are the views with respect to control and funding of operational cloud seeding programs? Cumulative data from research on social aspects of weather modification in different parts of the country have consistently shown that the dominant view among citizens is for local involvement in the decision-making process. Therefore, we presented to each respondent in Illinois alternative decision-making procedures which could be used in the future for deciding on appropriate counties for inclusion in an operational program. After allowing time for careful consideration of all the procedures, we then asked each respondent to select the one which was "most satisfactory" and the one which was "least satisfactory". The proportions selecting the various procedures and the rank order of expressed preferences are presented in Table 20.

Clearly, the preferred procedure in Illinois is seen as "a referendum submitted to the vote of all citizens living in the proposed affected area." Leaving the decision in the hands of "the scientists proposing and conducting the program" is seen as the least satisfactory mechanism. All other alternatives lagged far behind in the selection for most and least satisfactory decision-making procedures.

Respondents were also asked to select "most satisfactory" and "least satisfactory" funding procedures for an operational cloud seeding program. Again, we presented a list of five alternatives and asked respondents to consider carefully each one before expressing their views. The list of funding procedures and the results may be seen in Table 21. No single procedure clearly stands out, either as being the most satisfactory or as least satisfactory. "Federal income taxes" and "voluntary subscription of farmers in the affected area" are viewed more often as the preferred financial arrangements. However, "voluntary subscription of farmers" also ranks first among the least satisfactory procedures, followed closely by "taxes on all property in participating counties." Undoubtedly, many non-farm respondents select voluntary payment by agriculturists as the preferred mechanism while selecting county property taxes as the least agreeable arrangement. On the other hand, most farmers do not select voluntary subscription as their preferred procedure; but do select it as the least satisfactory arrangement.

G. Relationships Among Key Variables

Major hypotheses in sociological research on public response to weather modification suggest that the following variables predict favorableness toward local cloud seeding programs: general attitudes toward weather modification and science; belief in the efficacy of cloud seeding; knowledgeability (awareness) of cloud seeding programs; and perceived benefit or harm from application of the technology. In order to determine the relationship between evaluation of proposed cloud seeding in Illinois (dependent variables) and the predictor variables, intercorrelations among all key variables were calculated using the Pearson product-moment correlation coefficient.

Before examining the relationships between predictor and evaluation variables (Table 22), mention should be made of the scaling procedures used for combining items into single scales.* Quite simply, a number of variables used in the correlation analysis are scales formed by adding for each respondent his score (response code value) on one item to his

* For a detailed description of the scales and statistics computed on the scales, reference should be made to Appendix A.

score on a second item, then a third item, and so forth. For example, the WXM scale in Table 22 is called the Weather Modification Scale and represents the addition of three attitude items into a single variable. Thus, every respondent has a WXM score equivalent to the total of his responses on the three separate items.

Four evaluation variables are of concern here: 1) favorableness toward a proposed experimental program (EV2); 2) anticipated action to support or oppose an experimental program (AA1); 3) anticipated vote and petition signing for an experimental program (AA2); and favorableness toward a proposed operational program (EV3).

As has been found in other studies, the best predictors of local program evaluation prior to the inception of the project are general attitudes toward weather, weather modification, and science. Table 22 shows that the Weather Modification Scale (WXM) is the best predictor of program evaluation ($r = .70$ with EV2; $r = .69$ with AA2). The Religio-Natural scale (RN2) also predicts extremely well respondent evaluation of proposed programs ($r = -.62$ with EV2; $r = -.65$ with AA2). That is to say, persons adhering to a religio-natural view of the world are likely to be opposed to a local program, while persons not adhering to this view are likely to favor a local program. The scientific orientation scale predicts program evaluation moderately well. For example, $r = .53$ with AA2, .51 with EV2, and .44 with EV3. Thus, having positive feelings toward science in general leads to favorable evaluation of local programs.

The benefit-harm scales correlate moderately with evaluation. For example, the correlation between BH1 and AA2 results in $r = .47$; between BH1 and EV2, $r = .44$. Respondents anticipating that they would have personal economic benefit from an effective cloud seeding program are likely to be in favor of a proposed program. Respondents anticipating economic harm from cloud seeding are likely to oppose the program.

Belief that cloud seeding is efficacious also leads to favorable evaluation. Although the correlation coefficients between belief in efficacy variables and evaluation variables are somewhat lower, they still indicate predictive power for belief in efficacy. Belief that cloud seeding can effectively reduce hail and increase rainfall (BE1) correlates .42 with anticipated vote and petition signing (AA2); and correlates .36 with evaluation of an experimental program (EV2).

Of all the predictor variables, knowledgeability (KN1) shows the weakest correlation with program evaluation. None of the correlation coefficients exceed a value of .20, indicating very little predictive power for that variable.

The data presented in Table 22 support the findings from other studies. In general, it seems to be the case that prior to the start of a local cloud seeding program the best predictors of program evaluation are general attitudes toward weather, weather modification, and science. Anticipated economic benefit or harm from the proposed program, as well as belief in the effectiveness of the technology, predict less well but nevertheless show moderate correlation with evaluation. And finally, knowledge of weather modification activities shows weak correlation with evaluation.

Studies in South Dakota and Colorado (c.f. Farhar and Mewes, 1974; Haas and Krane, 1973) have found that after several years of program operation belief in efficacy, perceived benefit from the program, and knowledgeability tend to increase. Additionally, the relationships between these variables and the evaluation variables become stronger over time.

In addition to the correlational analysis presented above, extensive analysis was done using the socio-demographic data collected during the Interviews. This analysis is fully reported in Appendix C and is only briefly commented on here.

For each of six demographic variables we divided the sample into sub-groups and then compared these sub-groups on their responses to thirty selected items from the interview schedule. In general, a large number of significant relationships were found and a general pattern emerged with respect to each demographic variable (i.e., males vs. females, younger vs. older persons, and so forth).

With respect to age there are clear differences. Within increasing age groups we find less favorability toward cloud seeding technology and its application, less belief that the technology can be effective, and more concern that the technology, if applied, might result in adverse side effects. Older respondents are much more likely than younger ones to adhere to a religio-natural view of the world; thus, they feel it may be best to let nature take its course.

Generally speaking, males tend to be more favorably inclined to weather modification, more knowledgeable of weather modification activities, and less skeptical about potential harm resulting from the application of the technology.

With respect to educational background, the pattern of responses indicates that higher educated respondents are more knowledgeable of cloud seeding efforts, more favorable toward the technology, more favorable to a proposed experimental program, and tend to have a little greater belief that the technology may be effective for increasing rainfall and suppressing hail.

Family income differentiates responses among the sample also, with most differences occurring between lower income respondents compared to middle and upper income respondents. Briefly, low income persons tend to be unfavorable toward cloud seeding technology, do not believe the technology can be efficacious, do not anticipate much benefit even if the technology were effective, and feel that cloud seeding may have adverse side effects.

Some response differences are found among socio-economic classes as well. Where differences occur, the overall pattern indicates that the higher the socio-economic status, the greater the favorability toward the technology.

With respect to community size, the most noteworthy findings show that rural residents are most likely to perceive economic benefit from effective hail suppression and rainfall management programs, followed by small town residents and then city residents. Also, rural residents are the most likely to favor a local cloud seeding experiment, but are the least likely to favor a local operational program. This would seem to indicate that rural residents, since they are more likely to feel direct benefits from the technology, are realistically more cautious about the application of the technology until its effectiveness has been established.

H. Analysis of Program Evaluation Among Farm Respondents

Since persons who are engaged in agricultural enterprises are most likely to receive direct economic benefits (or disbenefits) from cloud seeding for hail suppression or rainfall management, we decided to do a separate analysis of local program evaluation for this set of respondents. Utilizing demographic items pertaining to farm owners or operators, we subdivided the farm respondents into different groupings and then examined responses on several of the evaluation items.

Table 23 gives the findings when farm ownership is cross classified by evaluation items. Although the majority of all farmers clearly indicate that they would benefit from an effective hail suppression program, farmers owning all of their land are not as likely to perceive benefits (67%) as are farmers who own only part of the land they tend (71%) or farmers who rent all of the land they tend (83%). However, farmers who "rent all" land are much less likely to take a position toward proposed experimental and operational programs — either to support or to oppose -- then are the "own all" and "own part/rent part" farmers. Thirty-nine percent claim to be undecided about an experimental program (compared to less than one-fifth of "own all" or "own part" farmers); and exactly half claim to be undecided about an operational program (compared to one-third or less in the ownership groups). Regardless of farm ownership, farmers are more favorable toward experimentation than toward direct application of the technology. Nevertheless, a sizable proportion indicate opposition to either type of program -- one fourth of owners or part owners oppose an experiment while more than one-third oppose the notion of an operational program.

One interview schedule item not heretofore discussed asked farm respondents to indicate how much they personally would be willing to contribute to the cost of an operational hail suppression program. From Table 23 it is clear that for the present, a large number of farmers would not want to contribute anything -- 52% of the "own all" group, 25% of the "own part" group and 33% of the "rent all" group. From one-sixth to one-third, however, feel they might pay up to $1.00/ acre for an effective hail suppression program.

Does size of farm operation (Table 24) affect evaluation of proposed local cloud seeding? Farmers with less than 400 acres are a **little** more likely than farmers with larger acreages to feel that they **would** benefit from a hail suppression program (77% compared to 67%). Farmers with medium size operations (between 200 and 400 acres) are less **likely** to oppose and more likely to favor experimental and operational programs than are farmers with either larger (400 or more acres) or smaller (less than 200 acres) enterprises. Medium size farm owners/ operators are also a little more likely to indicate willingness to share the cost of an operational program.

Length of farm residency indicates some differences in evaluation of proposed programs, as can be seen from Table 25. In general, those who have farmed from 16 to 30 years are more likely to anticipate economic benefit (82%) than are those who have farmed for more than 30 years (63%). Farmers of 16 to 30 years also are more apt to favor both types of cloud seeding programs than are farmers of either shorter or longer duration. The greatest opposition is found among farmers who have been involved in crop production for less than sixteen years -- 30% oppose an experiment and 45% oppose direct application.

We thought that whether or not agriculturists had suffered recent crop loss from hail might influence perspectives on proposed local weather modification. Farmers were asked if they had experienced crop losses to hail in the last five years. Only about one-third indicated such losses (24 of 69, Table 26). When we cross-classify the crop loss item with evaluation items we do note some differences, although relatively minor. For example, farmers with recent losses were a little more likely than those without losses to favor an experimental program (62% compared to 53%), and to favor an operational program (34% compared to 26%). Also, the proportion indicating willingness to contribute to the cost of an operational program is a little higher for the crop loss group than for the non-loss group (54% compared to 47%); but still, more than one-third of both groups would not be willing to contribute any amount at this time.

In every aspect of social life there are individuals and groups who take risks and those who do not, for whatever their reasons may be. Farmers are no exception, for we found that exactly one-third of the farm respondents normally do not purchase crop hail insurance while the other two-thirds are frequent purchasers. Although the differences in evaluation are not as great as one might expect, we do note their existence (Table 27). With respect to position toward an experimental program, the proportion of risk-takers (non-purchasers) favoring the program (562) equals the proportion of non-riskers (regular purchasers) who favor (57%). However, 35% of non-purchasers indicate opposition while only 15% of purchasers are opposed. In regard to an operational program, more in each group claim to be opposed at this time (48% for non-purchasers and 33% of purchasers). However, a higher percentage of risk-takers compared to non-riskers are fa-vorable toward the concept of an operational program (35% and 26%, respectively). Regular crop hail insurance carriers are more apt to be undecided. These findings would seem to suggest that farmers who are regular insurance purchasers feel the need for substantial evidence that hail suppression can work before they would exchange their insurance coverage for an operational program.

Table 1

Attitudes Toward Science, Weather and Weather Modification

Item 1. It is a good idea for scientists to experiment with cloud seeding so that we can find out if it really does work -- to see if it does increase moisture, and so forth.

RESPONSE:	%	(N)	
1 = Strongly Disagree	4	(11)	
2 = Disagree	16	(44)	
3 = Unsure	17	(47)	$\bar{x}$ = 3.45
4 = Agree	56	(154)	S.D. = 0.97
5 = Strongly Agree	7	(18)	
Totals	100	(274)	

Item 2. If there are going to be weather modification experiments, such as cloud seeding, individual states rather than the federal government should control and conduct them.

RESPONSE:	%	(N)	
1 = Strongly Disagree	2	(6)	
2 = Disagree	21	(59)	
3 = Unsure	16	(43)	$\bar{x}$ = 3.41
4 = Agree	54	(148)	S.D. = 0.97
5 = Strongly Agree	7	(18)	
Totals	100	(274)	

Item 3. Cloud seeding probably violates God's plans for man and the weather.

RESPONSE:	%	(N)	
1 = Strongly Disagree	4	(12)	
2 = Disagree	33	(92)	
3 = Unsure	15	(40)	$\bar{x}$ = 3.17
4 = Agree	36	(98)	S.D. = 1.15
5 = Strongly Agree	12	(32)	
Totals	100	(274)	

Table 1, continued

Item 4. Man should use scientific knowledge to deal with problems whenever and wherever possible.

RESPONSE:	%	(N)	
1 = Strongly Disagree	1	(3)	
2 = Disagree	10	(27)	
3 = Unsure	9	(24)	$\bar{x}$ = 3.80
4 = Agree	68	(187)	S.D. = 0.81
5 = Strongly Agree	12	(33)	
Totals	100	(274)	

Item 5. Illinois state agencies should feel free to use such things as cloud seeding if it might help farmers avoid crop losses.

RESPONSE:	%	(N)	
1 = Strongly Disagree	3	(9)	
2 = Disagree	15	(42)	
3 = Unsure	11	(29)	$\bar{x}$ = 3.59
4 = Agree	60	(165)	S.D. = 0.98
5 = Strongly Agree	11	(29)	
Totals	100	(274)	

Item 6. Even when carefully controlled, cloud seeding programs are very likely to upset the balance of nature.

RESPONSE:	%	(N)	
1 = Strongly Disagree	1	(3)	
2 = Disagree	20	(55)	
3 = Unsure	29	(80)	$\bar{x}$ = 3.56
4 = Agree	41	(113)	S.D. = 0.93
5 = Strongly Agree	9	(23)	
Totals	100	(274)	

Item 7. If there are going to be weather modification programs, then all citizens should be taxed to pay for them.

RESPONSE:	%	(N)	
1 = Strongly Disagree	12	(33)	
2 = Disagree	32	(87)	
3 = Unsure	14	(39)	$\bar{x}$ = 2.89
4 = Agree	39	(107)	S.D. = 1.14
5 = Strongly Agree	3	(8)	
Totals	100	(274)	

Table 1, continued

Item 8. Scientific experiments in general usually produce useful results -- produce things that are helpful to man.

RESPONSE:	%	(N)	
1 = Strongly Disagree	2	(4)	
2 = Disagree	11	(30)	
3 = Unsure	14	(39)	x = 3.63
4 = Agree	70	(191)	S.D. = 0.78
5 = Strongly Agree	3	(9)	
Totals	100	(273)	
Missing Data		(1)	

Item 9. Man should take the weather as it comes and not try to change it to suit his needs or wishes.

RESPONSE:	%	(N)	
1 = Strongly Disagree	3	(10)	
2 = Disagree	41	(112)	
3 = Unsure	11	(30)	$\bar{x}$ = 3.10
4 = Agree	31	(84)	S.D. = 1.19
5 = Strongly Agree	14	(38)	
Totals	100	(274)	

Item 10. We should try to solve other problems before spending more tax money on weather modification programs.

RESPONSE:	%	(N)	
1 = Strongly Disagree	1	(3)	
2 = Disagree	22	(60)	
3 = Unsure	13	(34)	$\bar{x}$ = 3.59
4 = Agree	46	(127)	S.D. = 1.06
5 = Strongly Agree	18	(50)	
Totals	100	(274)	

Item 11. Since scientists know most about these matters, the control and conduct of weather modification programs should be left entirely in their hands.

RESPONSE:	%	(N)	
1 = Strongly Disagree	12	(34)	
2 = Disagree	31	(86)	
3 = Unsure	11	(29)	$\bar{x}$ = 2.92
4 = Agree	43	(117)	S.D. = 1.16
5 = Strongly Agree	3	(7)	
Totals	100	(273)	
Missing Data		(1)	

Table 1, continued

Item 12. If weather is a problem to farmers, it is appropriate to try to directly control extreme weather conditions by using the most effective techniques known -- for example, cloud seeding to increase rain if moisture is needed.

RESPONSE:	%	(N)	
1 = Strongly Disagree	2	(6)	
2 = Disagree	18	(51)	
3 = Unsure	14	(38)	$\bar{x}$ = 3.46
4 = Agree	62	(169)	S.D. = 0.91
5 = Strongly Agree	4	(10)	
Totals	100	(274)	

Item 13. Instead of trying to change the weather, man should find other ways of dealing with it -- for example, improved weather forecasting, cheaper crop insurance and so forth.

RESPONSE:	%	(N)	
1 = Strongly Disagree	2	(4)	
2 = Disagree	29	(80)	
3 = Unsure	17	(46)	$\bar{x}$ = 3.29
4 = Agree	44	(121)	S.D. = 1.02
5 = Strongly Agree	8	(23)	
Totals	100	(274)	

Item 14. Local residents should <u>not</u> have a voice in decisions about a weather modification program unless local tax money is used to finance the program.

RESPONSE:	%	(N)	
1 = Strongly Disagree	11	(30)	
2 = Disagree	49	(133)	
3 = Unsure	11	(29)	$\bar{x}$ = 2.61
4 = Agree	27	(75)	S.D. = 1.07
5 = Strongly Agree	2	(6)	
Totals	100	(273)	
Missing Data		(1)	

Item 15. In general, weather scientists are mainly concerned with their experiments and don't really care about what happens to other people.

RESPONSE:	%	(N)	
1 = Strongly Disagree	8	(21)	
2 = Disagree	63	(170)	
3 = Unsure	13	(37)	$\bar{x}$ = 2.42
4 = Agree	13	(37)	S.D. = 0.92
5 = Strongly Agree	3	(8)	
Totals	100	(273)	
Missing Data		(1)	

Table 2

Belief In The Efficacy Of Cloud Seeding For Rain Augmentation And Hail Suppression

Can cloud seeding actually:	Increase Moisture[1]		Suppress Hail[2]	
	%	N	%	N
1 = No	12	(32)	14	(38)
2 = Perhaps, but I doubt it	3	(10)	4	(12)
3 = Don't Know	31	(84)	62	(170)
4 = I think so but I'm not sure	15	(41)	7	(18)
5 = Yes	39	(107)	13	(36)
Totals	100	(274)	100	(274)
$\bar{x}$ =	3.66		3.01	
S.D. =	1.34		1.09	

Questions phrased:

1. "Do you think that cloud seeding works -- that is, do you think it can actually <u>increase moisture</u>?"
2. "Do you think that cloud seeding can actually <u>suppress hail</u>?"

Table 3

Opinions About Potential Side-Effects From Cloud Seeding

1. Do you think cloud seeding might damage the ecology of an area?	%	N	
1 = No	31	(86)	
2 = Uncertain	41	(111)	$\bar{x}$ = 1.97
3 = Yes	28	(77)	S.D. = 0.77
Totals	100	(274)	

2. If yes: how might it prove harmful?	%	N
Don't Know/Just a feeling	10	(8)
Other	10	(8)
Reduction in moisture/Drought	3	(2)
Excessive moisture/Floods	17	(13)
General adverse weather change/ Upset balance of nature	40	(31)
Chemicals might be detrimental to plants, animals, or man	20	(15)
Totals	100	(77)

Table 4

Awareness of Weather Modification Programs

RESPONSE:	Rain[1] %	Hail[2] %	Fog[3] %	Hurricane[4] %	Tornado[5] %
1 = No	53	82	89	66	84
2 = Don't Remember	4	5	1	5	1
3 = Yes	43	13	10	29	15
Total	100	100	100	100	100
N =	(274)	(273)	(274)	(273)	(274)
Missing Data	(0)	(1)	(0)	(1)	(0)
$\bar{x}$ =	1.90	1.31	1.21	1.64	1.31
S.D. =	0.98	0.69	0.60	0.91	0.72

IF YES to one or more of the above: "In general, was what you heard about weather modification unfavorable, neutral or favorable?"

RESPONSE:	%	(N)
Unfavorable	16	(26)
Neutral	36	(57)
Favorable	41	(66)
Don't Remember	7	(11)
Totals	100	(160)

Questions phrased as follows:

1. "Have you heard about any weather modification programs which attempt to increase rainfall?"
2. "Have you heard about any weather modification programs which attempt to suppress or decrease hail?"
3. "What about fog? Have you heard anything about attempts to break up fog?"
4. "Are you aware of any programs which attempt to modify hurricanes?"
5. "What about tornadoes? Have you heard anything about weather modification programs which attempt to stop or reduce damage from tornadoes?

Table 5

Opinions About Inadvertent Weather Modification

1. "Do you think that unintended (or accidental) cloud seeding is bringing about changes in the weather?"

RESPONSE:	%	N	
1 = No	24	(66)	
2 = Could be, but I doubt it	6	(16)	
3 = Uncertain/Don't Know	33	(91)	$\bar{x}$ = 3.03
4 = I think so/Seems like it	17	(46)	S.D. = 1.41
5 = Yes	20	(55)	
Totals	100	(274)	

2. "Do you feel that accidental weather modification should be better understood before anyone tries to modify the weather intentionally?"

RESPONSE:	%	N	
1 = No	7	(20)	
2 = Uncertain	6	(17)	$\bar{x}$ = 2.80
3 = Yes	87	(237)	S.D. = 0.55
Totals	100	(274)	

Table 6

Knowledge of Weather Modification Regulation

"As far as you know, does the State of Illinois have any laws regulating planned weather modification activities?"

RESPONSE:	%	N	
1 = No	56	(154)	
2 = Don't Know/Uncertain	44	(119)	$\bar{x}$ = 1.44
3 = Yes	0	(1)	S.D. = 0.50
Totals	100	(274)	

Table 7

Knowledge of Illinois State Water Survey and Hail Research Program of the ISWS

1. *"Have you ever heard of the Illinois State Water Survey?"*

RESPONSE:	%	N	
1 = No	22	(61)	
2 = Yes, through this interview	26	(70)	$\bar{x}$ = 2.30
3 = Yes, prior to this interview	52	(143)	S.D. = 0.81
Totals	100	(274)	

2. IF YES: "Could you please tell me the purpose of the ISWS -- what the agency does?"*

RESPONSE:	%	N
Weather control/Rain control	3	(5)
Weather data collection (rainfall, hailfall, wind measurements etc.)	18	(32)
Research (re: weather, water, environment)	11	(20)
"Something" to do with water	6	(10)
Responsible for water control (water supply, waterways, water quality, water table levels, drainage)	36	(63)
Don't Know	26	(47)
Totals	100	(177)

3. "Are you aware of the hail research project being operated by the ISWS?"

RESPONSE:	%	N	
1 = No	89	(245)	$\bar{x}$ = 1.11
2 = Yes	11	(29)	S.D. = 0.31
Totals	100	(274)	

*This item was intended only for respondents who indicated they were aware of the ISWS prior to the interview; but was also asked of 34 of the 70 respondents who indicated awareness of the ISWS only through this study. Thus, the N = 177 rather than 143.

Table 8

Public Confidence in the ISWS to Conduct Experimental Weather Modification

RESPONSE:	For Hail Suppression[1]		For Rainfall Management[2]	
	%	N	%	N
1 = No	7	(19)	11	(31)
2 = Uncertain/Don't Know	33	(89)	31	(85)
3 = Yes	60	(163)	58	(157)
Totals	100	(271)	100	(273)
Missing Data		(3)		(1)
$\bar{x}$ =	2.53		2.46	
S.D. =	0.62		0.61	

"Do you feel such a program should be for hail suppression or rainfall management?"

RESPONSE:	%	N
Hail suppression	18	(48)
Rainfall management	23	(62)
Would prefer it included both	35	(96)
Would not want either one	12	(34)
Don't care/Don't know	12	(32)
Totals	100	(272)
Missing Data		(2)

Questions phrased:

1. "Do you have confidence that the Illinois State Water Survey can conduct a well designed program to test the possibility of suppressing hail?"
2. "How about a program to test the possibility of managing rainfall -- either to increase or decrease rainfall? Do you have confidence that the Illinois State Water Survey can conduct an experimental program of rainfall management?"

Table 9

Anticipated Benefit or Harm From Weather Modification

If cloud seeding were able to:	Suppress Hail[1]		Increase Rainfall[2]		Decrease Rainfall[3]	
RESPONSE:	%	N	%	N	%	N
1 = Harmful	2	(6)	8	(21)	15	(40)
2 = Make no difference/Don't Know	38	(103)	45	(123)	52	(142)
3 = Beneficial	60	(165)	47	(130)	33	(92)
Totals	100	(274)	100	(274)	100	(274)
$\bar{x}$ =	2.58		2.40		2.19	
S.D. =	0.54		0.63		0.67	

Questions phrased:

1. "If a cloud seeding program operating in this area were able to suppress hail, reduce damage from hail, would you say it would probably be of economic benefit to you, harmful to you, or make no difference to you?"
2. "If a cloud seeding program were able to increase rainfall, would you say it would probably be of economic benefit to you, harmful to you, or make no difference to you?"
3. "If a cloud seeding program were able to decrease rainfall, would you say it would probably be of economic benefit to you, harmful to you, or make no difference to you?"

Table 10

Position Toward An Experimental Program for Hail Suppression[1]

RESPONSE:	%	N	
1 = Strongly Oppose	5	(15)	
2 = Oppose	16	(43)	
3 = Undecided/Neutral	25	(69)	$\bar{x}$ = 3.33
4 = Favor	48	(131)	S.D. = 0.99
5 = Strongly Favor	6	(16)	
Totals	100	(274)	

[1]Question phrased: "As a resident of this area, how do you feel about an experimental program of hail suppression which may be proposed for this part of central Illinois?"

Table 11

Reason for Position Toward Experimental Program

A. Favor Experiment Because:	%	N
Research/experimentation is desirable	41	(60)
Perceive general benefit to area/Community	14	(21)
Perceive general benefit to specific group/self	11	(16)
Perceive specific benefit to area/Community	23	(33)
Perceive specific benefit to specific group/self	9	(14)
Other	2	(3)
Totals	100	(147)
B. Oppose Experiment Because:	**%**	**N**
Religious beliefs/Against God's will	10	(6)
Wasteful/Ineffective	12	(7)
Not enough hail damage in Illinois	7	(4)
Negative effects on weather/Balance of nature	48	(28)
Benefits only farmers	4	(2)
Too costly/Too many taxes already	10	(6)
Other	9	(5)
Totals	100	(58)
C. Undecided About Experiment Because:	**%**	**N**
Not enough hail damage in Illinois	3	(2)
Negative effects on weather/Nature	1	(1)
Insufficient knowledge to judge	87	(60)
Too costly/Don't know who will pay	3	(2)
Other	6	(4)
Totals	100	(69)

Table 12

Anticipated Action Toward Proposed Experimental Program

1. "If there is an experimental cloud seeding program proposed for your area, do you think you will do anything to support or oppose it?"

RESPONSE:	%	N	
1 = Yes, oppose	8	(23)	
2 = No, won't do anything or Don't Know	63	(171)	$\bar{x}$ = 2.21 S.D. = 0.58
3 = Yes, support	29	(80)	
Totals	100	(274)	

2. If "yes, oppose," kinds of action mentioned.

RESPONSE:	%	N
Vote against program	13	(3)
Talk against program to friends/farmers	22	(5)
Contact state official or congressman	22	(5)
Other/Don't Know	43	(10)
Totals	100	(23)

3. If "yes, support," kinds of action mentioned.

RESPONSE:	%	N
Vote in favor of program	13	(10)
Talk in favor of program	36	(29)
Sign petition in favor	11	(9)
Give money/taxes to support	15	(12)
Spread literature	2.5	(2)
Attend public meetings	2.5	(2)
Other/Don't Know	20	(16)
Totals	100	(80)

Table 13

Likelihood of Signing Petitions <u>Favoring</u> and <u>Opposing</u> an Experimental Program

1. "How likely would you be to sign a petition <u>favoring</u> a hail or rain experiment for central Illinois?"

RESPONSE:	%	N	
1 = Definitely not sign	14	(38)	
2 = Probably not sign	17	(46)	
3 = Uncertain	24	(67)	$\bar{x}$ = 3.18
4 = Probably sign	27	(74)	S.D. = 1.30
5 = Definitely sign	18	(49)	
Totals	100	(274)	

2. "How likely would you be to sign a petition <u>opposing</u> a hail or rain experiment for central Illinois?"

RESPONSE:	%	N	
1 = Definitely not sign	21	(59)	
2 = Probably not sign	37	(102)	
3 = Uncertain	27	(74)	$\bar{x}$ = 2.40
4 = Probably sign	8	(21)	S.D. = 1.11
5 = Definitely sign	7	(18)	
Totals	100	(274)	

Table 14

Anticipated Vote on an Experimental Program

1. "If residents in this area were to vote on whether an experimental weather modification program should be started, how do you think you would vote?"

RESPONSE:	%	N	
1 = Against experiment	23	(63)	
2 = Uncertain/Probably wouldn't vote	27	(74)	$\bar{x}$ = 2.27 S.D. = 0.81
3 = For experiment	50	(137)	
Totals	100	(274)	

2. "How do you think most people in this county would vote?"

RESPONSE:	%	N	
1 = Against experiment	27	(74)	
2 = Uncertain/Don't Know	38	(105)	$\bar{x}$ = 2.35
3 = 50-50 (about equal for and against)	7	(20)	S.D. = 1.15
4 = For experiment	28	(75)	
Totals	100	(274)	

Table 15

Opinions About Compensation for Uninsured Loss From Cloud Seeding Experiment

1. "If any persons were to suffer damages which were a result of a cloud seeding experiment, do you feel these damages should be compensated?"

RESPONSE:	%	N	
1 = No	7	(18)	
2 = Uncertain/Don't Know	9	(26)	$\bar{x}$ = 3.35
3 = Yes, if proved damages were result of seeding	27	(73)	S.D. = 0.90
4 = Yes (unqualified)	57	(157)	
Totals	100	(274)	

2. IF YES: "Who should pay for this compensation?"

RESPONSE:	%	N
Insurance companies	7	(15)
Those doing the cloud seeding	43	(99)
Those who benefit/Farmers	1	(3)
State government	30	(69)
State and federal government	5	(12)
Federal government	8	(18)
Other	1	(2)
Don't Know	5	(12)
Totals	100	(230)

Table 16

Position toward An Operational Program for Hail Suppression[1]

RESPONSE:	%	N	
1 = Strongly Oppose	9	(25)	
2 = Oppose	19	(51)	
3 = Undecided	39	(108)	$\bar{x}$ = 2.99
4 = Favor	30	(81)	S.D. = 0.99
5 = Strongly Favor	3	(9)	
Totals	100	(274)	

Question phrased:

1. "As a resident of this area, how do you feel about the possibility of an operational (non-experimental) program which would seed clouds on all days when hailstorms are in the area?"

Table 17

Reasons for Position Toward Operational Program		
A. Favor Program Because:	**%**	**N**
Research/Experimentation/Progress is desireable	14	(12)
Perceive general benefit to area/community	22	(20)
Perceive general benefit to specific group/self	12	(11)
Perceive specific benefit to area/community	43	(38)
Perceive specific benefit to specific group/self	3	(3)
Other	6	(5)
Totals	100	(89)
Missing Data		(1)
B. Oppose Program Because:	**%**	**N**
Religious beliefs/Against God's Will	8	(6)
Wasteful/Ineffective	6	(4)
Not enough hail damage in Illinois	11	(8)
Negative effects on weather/Balance of nature	32	(23)
Benefits only farmers	3	(2)
Too costly/Too many taxes already	3	(2)
Need to know if cloud seeding works (need experimental program first/ must prove results first)	22	(16)
Other	15	(11)
Totals	100	(72)
Missing Data		(4)
C. Undecided About Program Because:	**%**	**N**
Not enough hail damage in Illinois	3	(3)
Negative effects on weather/Nature	2	(2)
Insufficient knowledge to judge	70	(64)
Too costly/Don't know who will pay	1	(1)
Indifferent/Just don't care	3	(3)
Need to know if cloud seeding works (need experimental program first/ must prove results first)	12	(11)
Other	9	(8)
Totals	100	(92)
Missing Data		(16)

Table 18

Predicted and Preferred Decision Making Regarding an Experimental Program

RESPONSE:	Who Will Decide[1]		Who Should Decide[2]	
	%	N	%	N
Local residents/Local government	12	(33)	32	(89)
Local agriculturists	8	(23)	17	(46)
Local and state governments (includes local, state and federal)	8	(21)	5	(13)
State government/statewide referendum	32	(89)	20	(55)
State and federal governments	4	(10)	1.5	(4)
Federal government	4	(11)	1.5	(4)
Scientists/Researchers	2	(5)	4	(12)
Illinois State Water Survey	11	(31)	8	(21)
Other	5	(13)	4	(12)
Don't Know	14	(38)	7	(18)
Totals	100	(274)	100	(274)

Questions phrased:

1. "Who do you think will decide whether or not a hail or rain experiment will be started in Illinois?"
2. "Who do you think should make this decision?"

Table 19

Predicted and Preferred Funding Regarding an Experimental Program

RESPONSE:	Who Should Pay[1] %	N	Who Will Pay[2] %	N
Local residents/Local government	12	(34)	26	(71)
Local agriculturists	12	(34)	4	(12)
Local and state governments (includes local, state and federal)	8	(21)	8	(23)
State government	31	(84)	35	(95)
State and federal governments	7	(18)	7	(19)
Federal government	10	(28)	8	(22)
Other	9	(26)	0	(0)
Don't know/no opinion	11	(29)	12	(32)
Totals	100	(274)	100	(274)

"Other" category includes: "anyone who wanted it done;" "everyone;" "those who would benefit;" "hail insurance companies;" and "Illinois State Water Survey."

Questions phrased:

1. "Who do you think should pay for an experimental cloud seeding program?"
2. "Who do you think will pay for such a program if it is proposed?"

Table 20

Opinions About Area/County Selection For an Operational Hail Suppression Program[1]

Possible Procedures for Site Selection:	% Selecting For: Most	Least	Ranking of Decision-Making Procedures. Most	Least
Referendum submitted to vote of all citizens in proposed affected area	47	9	1	4
Referendum submitted to vote of owners or operators of agricultural land in proposed affected area	17	11	3	3
Decision by a regional weather modification control board elected by citizens	9	2	4	6
Decision by joint agreement between county commissioner and a regional weather modification control board	4	7	5	5
Decision left up to scientists proposing and conducting the program	2	48	6	1
Decision left up to scientists but with assistance of a weather modification advisory board appointed by the Governor of Illinois	19	16	2	2
Other (including combinations)	1	1		
Don't Know	1	6		
	100%	100%		
N =	(274)	(273)		
Missing Data	(0)	(1)		

1. Respondents were asked to select the procedure which they felt was most satisfactory for deciding what counties or areas should participate in an operational hail suppression program; and then they were asked to select the least satisfactory procedure.

Table 21

Opinions About Financing an Operational Hail Suppression Program[1]

Possible Procedures for Financing:	% Selecting For: Most	% Selecting For: Least	Ranking of Financing Procedures: Most	Ranking of Financing Procedures: Least
Federal income taxes	23	15.5	1.5	3.5
Illinois State income taxes	18	15	3	5
County property taxes	15	23	4	2
Property tax on agricultural land only	12	15.5	5	3.5
Voluntary subscription of farmers	23	24	1.5	1
Other (including combinations)	7	3		
Don't Know	2	4		
	100%	100%		
N =	(274)	(271)		
Missing Data	(0)	(3)		

1. Respondents were asked to select the procedure which they felt was most satisfactory for financing an operational hail suppression program; and then they were asked to select the least satisfactory procedure.

Table 22

Intercorrelations for Key Variables (Scales)[1]

	WXM	RN2	SO1	KN1	BE1	BE2	BE3	BH1	BH3	AA1	AA2	EV1	EV2	EV3
WXM		-.64	.58	.07	.39	.35	.35	.45	.39	.47	.69	.35	.70	.57
RN2	-.64		-.48	-.15	-.35	-.35	-.30	-.41	-.30	-.49	-.65	-.34	-.62	-.47
SO1	.58	-.48		.08	.27	.25	.23	.33	.31	.42	.53	.24	.51	.44
KN1	.07	-.15	.08		.18	.17	.15	.13	.08	.19	.20	.24	.16	.00
BE1	.39	-.35	.27	.18		.91	.87	.19	.13	.24	.42	.26	.36	.32
BE2	.35	-.35	.25	.17	.91		.60	.17	.14	.20	.38	.26	.32	.26
BE3	.35	-.30	.23	.15	.87	.60		.17	.09	.24	.36	.21	.34	.31
BH1	.45	-.41	.33	.13	.19	.17	.17		.66	.38	.47	.23	.44	.31
BH3	.39	-.30	.31	.08	.13	.14	.09	.66		.29	.40	.20	.35	.23
AA1	.47	-.49	.42	.19	.24	.20	.24	.38	.29		.71	.33	.63	.49
AA2	.69	-.65	.53	.20	.42	.38	.36	.47	.40	.71		.38	.83	.63
EV1	.35	-.34	.24	.24	.26	.26	.21	.23	.20	.33	.38		.33	.20
EV2	.70	-.62	.51	.16	.36	.32	.34	.44	.35	.63	.83	.33		.58
EV3	.57	-.47	.44	.00	.32	.26	.31	.31	.23	.49	.63	.20	.58	

N = 274

[1] See Appendix A for identification of variable symbols, a description of the items comprising the scales, and a presentation of scale statistics.

Table 23

Farm Ownership by Selected Evaluation Items

	Farm Ownership (land)					
	Own All		Own Part/Rent Part		Rent All	
Perceived Economic Benefit or Harm from Hail Suppression	%	(N)	%	(N)	%	(N)
Harm	7	(2)	0	(0)	0	(0)
No Difference	26	(7)	29	(7)	17	(3)
Benefit	67	(18)	71	(17)	83	(15)
Totals	100%	(27)	100%	(24)	100%	(18)
Position Toward Experimental Hail Suppression Program						
Strongly oppose	11	(3)	8	(2)	0	(0)
Oppose	15	(4)	17	(4)	11	(2)
Undecided/Neutral	19	(5)	13	(3)	39	(7)
Favor	44	(12)	62	(15)	44	(8)
Strongly Favor	11	(3)	0	(0)	6	(1)
Totals	100%	(27)	100%	(24)	100%	(18)
Position Toward Operational Hail Suppression Program						
Strongly Oppose	19	(5)	4	(1)	0	(0)
Oppose	22	(6)	33	(8)	33	(6)
Undecided/Neutral	33	(9)	21	(5)	50	(9)
Favor	11	(3)	38	(9)	17	(3)
Strongly Favor	15	(4)	4	(1)	0	(0)
Totals	100%	(27)	100%	(24)	100%	(18)
Willingness to Pay Share of Cost for Operational Program						
Would Pay: Nothing	52	(14)	25	(6)	33	(6)
Up to 15¢/acre	4	(1)	41	(10)	28	(5)
Up to $1.00/acre	29	(8)	17	(4)	33	(6)
Undecided/Don't Know	15	(4)	17	(4)	6	(1)
Totals	100%	(27)	100%	(24)	100%	(18)

Table 24

Farm Size by Selected Evaluation Items

	Farm Size (acreage)					
	Less than 200		200-399		400 or more	
Perceived Economic Benefit or Harm from Hail Suppression	%	(N)	%	(N)	%	(N)
Harm	5	(1)	0	(0)	5	(1)
No Difference	19	(4)	23	(6)	28	(6)
Benefit	76	(16)	77	(20)	67	(14)
Totals	100%	(21)	100%	(26)	100%	(21)
Position Toward Experimental Hail Suppression Program						
Strongly Oppose	10	(2)	0	(0)	14	(3)
Oppose	14	(3)	8	(2)	19	(4)
Undecided/Neutral	24	(5)	23	(6)	19	(4)
Favor	52	(11)	58	(15)	43	(9)
Strongly Favor	0	(0)	11	(3)	5	(1)
Totals	100%	(21)	100%	(26)	100%	(21)
Position Toward Operational Hail Suppression Program						
Strongly Oppose	14	(3)	4	(1)	9.5	(2)
Oppose	33	(7)	19	(5)	33	(7)
Undecided/Neutral	43	(9)	35	(9)	24	(5)
Favor	5	(1)	35	(9)	24	(5)
Strongly Favor	5	(1)	7	(2)	9.5	(2)
Totals	100%	(21)	100%	(26)	100%	(21)
Willingness to Pay Share of Cost for Operational Program						
Would Pay: Nothing	38	(8)	38	(10)	33	(7)
Up to 15¢/acre	5	(1)	27	(7)	38	(8)
Up to $1.00/acre	38	(8)	31	(8)	10	(2)
Undecided/Don't know	19	(4)	4	(1)	19	(4)
Totals	100%	(21)	100%	(26)	100%	(21)

Table 25

Length of Residence As a Farmer By Selected Evaluation Items

	Length of Residence as a Farmer (years)					
	15 or less		16 to 30		more than 30	
	%	(N)	%	(N)	%	(N)
Perceived Economic Benefit or Harm from Hail Suppression						
Harm	5	(1)	4	(1)	0	(0)
No Difference	20	(4)	14	(3)	37	(9)
Benefit	75	(15)	82	(18)	63	(15)
Totals	100%	(20)	100%	(22)	100%	(24)
Position Toward Experimental Hail Suppression Program						
Strongly Oppose	15	(3)	4	(1)	4	(1)
Oppose	15	(3)	9	(2)	21	(5)
Undecided/Neutral	15	(3)	18	(4)	25	(6)
Favor	50	(10)	55	(12)	50	(12)
Strongly Favor	5	(1)	14	(3)	0	(0)
Totals	100%	(20)	100%	(22)	100%	(24)
Position Toward Operational Hail Suppression Program						
Strongly Oppose	15	(3)	4	(1)	4	(1)
Oppose	30	(6)	32	(7)	29	(7)
Undecided/Neutral	30	(6)	27	(6)	38	(9)
Favor	20	(4)	23	(5)	25	(6)
Strongly Favor	5	(1)	14	(3)	4	(1)
Totals	100%	(20)	100%	(22)	100%	(24)
Willingness to Pay Share of Cost for Operational Program						
Would Pay: Nothing	45	(9)	46	(10)	25	(6)
Up to 15¢/acre	20	(4)	27	(6)	25	(6)
Up to $1.00/acre	30	(6)	18	(4)	33	(8)
Undecided/Don't Know	5	(1)	9	(2)	17	(4)
Totals	100%	(20)	100%	(22)	100%	(24)

Table 26

Recent Crop Loss from Hail By Selected Evaluation Items

	Recent Crop Loss From Hail[1]			
	No		Yes	
	%	(N)	%	(N)
Perceived Economic Benefit or Harm from Hail Suppression				
Harm	2	(1)	4	(1)
No Difference	27	(12)	21	(5)
Benefit	71	(32)	75	(18)
Totals	100%	(45)	100%	(24)
Position Toward Experimental Hail Suppression Program				
Strongly Oppose	4	(2)	13	(3)
Oppose	18	(8)	8	(2)
Undecided/Neutral	25	(11)	17	(4)
Favor	49	(22)	54	(13)
Strongly Favor	4	(2)	8	(2)
Totals	100%	(45)	100%	(24)
Position Toward Operational Hail Suppression Program				
Strongly Oppose	7	(3)	12.5	(3)
Oppose	33.5	(15)	21	(5)
Undecided/Neutral	33.5	(15)	33	(8)
Favor	22	(10)	21	(5)
Strongly Favor	4	(2)	12.5	(3)
Totals	100%	(45)	100%	(24)
Willingness to Pay Share of Cost for Operational Program				
Would Pay: Nothing	38	(17)	38	(9)
Up to 15¢/acre	20	(9)	29	(7)
Up to $1.00/acre	27	(12)	25	(6)
Undecided/Don't Know	15	(7)	8	(2)
Totals	100%	(45)	100%	(24)

[1] Question asked of farmers only. "Have you had recent crop losses due to hail, say in the last five years?"

Table 27

Crop Hail Insurance Coverage by Selected Evaluation Items

	Crop Hail Insurance Coverage[1]			
	No/Sometimes		Yes/Always	
	%	(N)	%	(N)
Perceived Economic Benefit or Harm from Hail Suppression				
Harm	0	(0)	4	(2)
No Difference	26	(6)	24	(11)
Benefit	74	(17)	72	(33)
Totals	100%	(23)	100%	(46)
Position Toward Experimental Hail Suppression Program				
Strongly Oppose	9	(2)	7	(3)
Oppose	26	(6)	8	(4)
Undecided/Neutral	9	(2)	28	(13)
Favor	52	(12)	50	(23)
Strongly Favor	4	(1)	7	(3)
Totals	100%	(23)	100%	(46)
Position Toward Operational Hail Suppression Program				
Strongly Oppose	13	(3)	7	(3)
Oppose	35	(8)	26	(12)
Undecided/Neutral	17	(4)	41	(19)
Favor	31	(7)	17	(8)
Strongly Favor	4	(1)	9	(4)
Totals	100%	(23)	100%	(46)
Willingness to Pay Share of Cost for Operational Program				
Would Pay: Nothing	43	(10)	35	(16)
Up to 15¢/acre	17	(4)	26	(12)
Up to $1.00/acre	31	(7)	24	(11)
Undecided/Don't Know	9	(2)	15	(7)
Totals	100%	(23)	100%	(46)

[1] Question asked of farmers only: "Do you normally carry crop hail insurance?"

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APPENDIX C

Statement on Planned Precipitation Modification

North-Central Committee on Weather Information for Agriculture (NC-94)

Introduction

Purposeful alterations of certain local weather conditions in some climatic areas have been accomplished. However, significant wide-scale modification of weather is not established. Research and experimentation are yet very much needed to achieve the information and knowledge for meaningful modification of precipitation (rain, snow, and hail) in the North-Central Region of the United States. This region includes Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin.

This Statement presents 1) a brief review of the status of weather modification, 2) precipitation-related agricultural problems of the region, 3) recommendations for activity, and 4) a discussion of cloud seeding mechanisms.

Status of Weather Modification

There is mounting evidence that cloud seeding using ice nuclei released in or near clouds has produced substantial local changes in clouds and storm systems. Definitive success in cold (supercooled) fog dispersal and in precipitation enhancement in certain climatic areas has been achieved in the past ten years. The mechanisms for cloud seeding are described in the final section of this Statement.

Experimental attempts using silver iodide released from aircraft to increase convective warm season rainfall critical to the growing season of the North-Central Region have provided evidence of local increases (in South Dakota and North Dakota) and local decreases (Missouri). Studies of the effect of large urban areas in the Region (Chicago, Detroit, and St. Louis) on weather have shown warm season rainfall increases of 20 to 30%. Obviously, too little is known about the meteorological processes in Midwestern convective clouds to make the outcome predictable. Evidence also shows that localized precipitation increases and decreases of 20 to 30% in convective rainfall in the Midwest do not result in rain alterations further downwind (> 100 km).

Precipitation from cold orographic (mountain) clouds in winter can be increased from 5 to 30% on a predictable basis. Precipitation increases from non-orographic stratiform systems that are the typical precipitation producers in the Region during winter have not been demonstrated. However, theory indicates it is possible to increase or redistribute precipitation from such systems.

Results from efforts to mitigate hail are encouraging but still indeterminate. On-going operational projects in Canada and Texas, and experimental projects in Canada, North Dakota, and Colorado, have provided recent evidence of 30 to 50% decreases in crop-hail loss. Positive but unsubstantiated claims describe the results to suppress lightning, and there is no evidence to indicate modification of tornadoes is likely in the near future. There has been no research into the mitigation of severe local rainstorms, a major weather problem of the North Central Region, or in severe winter snow and ice storms that also plague the Region.

Problems and Needs

Precipitation-related agricultural problems of the North-Central Region include:

1. too little rainfall during periods of 2 to 12 weeks of crop-critical times during the growing season;
2. extensive droughts persisting for 3 to 36 months across the wide, often multi-state areas in the Region;
3. floods by local short-duration heavy rainstorms or by more widespread multi-day heavy rains;
4. extensive periods (weeks to months) of frequent rainfalls leading to above normal amounts during planting, harvest and other periods critical to crop growth and field operations;
5. hail-produced losses in the growing season; and
6. severe winter storms that can affect winter wheat, orchards, and agricultural activities such as transportation.

Critical to an assessment of the research-experimental needs in precipitation modification (in a region that extends from the Western Great Plains to the Eastern Midwest) is the fact that convective processes and the systems that produce much of the growing season rainfall differ considerably from west-to-east. Basically, the storms that produce the rain in the extreme western portion (western Kansas, Nebraska, North Dakota, and South Dakota) are more isolated and different dynamically than the multi-cellular storm systems that produce the preponderance of the rain in the Midwest, the other part of the North-Central Region. *This difference is particularly critical in assessing convective precipitation (rain and hail) modification potential since all but one of the experimental and operational projects with relevant results have been conducted in the western extremes (Great Plains). Thus, too little is known about modification of the precipitation of the Midwest, the major portion of the Region,* There is little inner regional difference in the precipitation-producing systems of the winter season.

Recommendations

Consideration of the status of precipitation modification, in light of the pressing weather-related agricultural problems of the Region, led to two sets of recommendations for activities, one set of recommendations for the 1970's (1975-79), and one for the 1980's (1980-89).

Recommendations for the 1970's:

1. Two experiments should be launched immediately in the Midwest. One would be to attempt management of warm season rainfall, and the other to attempt hail suppression. These should a) utilize the most advanced yet regionally transferable seeding technologies; b) employ a mixture of statistical and physical evaluations to minimize the experimental period; c) be conducted over areas in a manner to define alterations in area-scale (> 1000 km^2) rain or hail; d) measure precipitation at least 100 km beyond the area; and e) attempt to measure the socio-economic impacts of these activities.
2. Theoretical-climatological feasibility studies should be launched to investigate the possibilities for a) rain increases in broad-scale droughts; b) ameliorations of localized short-duration heavy rainstorms; c) enhancement of precipitation from winter stratiform systems; and d) amelioration of severe winter ice and snow storms.

3. Investigate regional social, legal, and economic impacts from potential precipitation modification.

Recommendations for the 1980's:

1. It seems reasonable to assume that some of the feasibility studies recommended for the 1970's will indicate a potential for modification. Those agriculturally-critical areas showing promise for likely modification should be tested, likely by field experimentation, in the early 1980's.
2. Theoretical studies of the possible modification of other agricultural limiting weather conditions (temperature, sudden fronts and freezes, and non-tornadic damaging winds) should be launched.

Mechanisms for Cloud Seeding

Clouds are composed of minute liquid water droplets or ice crystals. These cloud elements are so small that they essentially float in the air and most eventually evaporate. Precipitation occurs when adequate numbers of the cloud droplets or ice crystals grow large enough to develop a significant fall velocity and reach the surface before evaporating.

The basic problem of precipitation enhancement is to artificially provide mechanisms to stimulate the rapid development of precipitation sized particles in those situations where the natural growth processes are ineffective or inefficient. Prevailing thought provides two practical methods for initiating or enhancing this growth of cloud drops. First, artificial freezing nuclei are placed in the cloud (normally microscopic silver iodide particles are used) which increase the number of ice crystals in the subfreezing portion of the cloud. These ice crystals grow rapidly at the expense of the neighboring supercooled water drops. Second, relatively large hygroscopic nuclei (often NaCl is used) are inserted into the clouds. Large drops (i.e., relative to cloud drops) are formed around these nuclei. These large drops become even larger by "sweeping out" some of the smaller cloud drops as they fall through the cloud. Ultimately the drops become too large and break up into more relatively large drops which join in the process.

Atmospheric conditions favoring "cloud seeding" are specific. Sufficient humidity and environmental instability must exist for initial cloud formation. Since precipitation enhancement occurs through a stimulation of the natural processes, these clouds must extend through several thousand feet of the atmosphere. Seeding clouds with ice forming nuclei releases the heat of fusion which may induce growth of some cumulus clouds. To achieve this growth the seeding must be accomplished at the proper time and sector of the cloud.

APPENDIX D

Summary of Discussions on Hail Suppression with Operational Experts

Interviews were carried out with two owners of commercial weather modification companies. Each operates projects based on one of the two distinct modification approaches eventually selected for the experimental design.

The first was Mr. Thomas J. Henderson, President of Atmospherics, Inc. (AI) of Fresno, California. His company (AI) uses the airborne cloud-base seeding approach to hail prevention. AI has applied this technique under contract in Texas, Kenya, the Republic of South Africa, and as a backup system as part of the early years of the National Hail Research Experiment. He has also done extensive convective weather flying under contract as part of METROMEX in the St. Louis area. The concept which guides AI's operations focuses on the new flanking and merging cells in a multi-cell complex. These new cells or towers are destined to enter the main mass of the complex and lose their identity in 20 minutes or less. The cloud seeding 'target' is a box in the cloud with a temperature range around -15° C where the embryo concentration must be increased to around 10^{s} m^{-3}. This is attempted by cloud-base seeding for several reasons:

1) The clouds and their relationship t6 the main storm are easier to see and identify from below the base. At the level of the tops, one is often flying within obscuring middle and high clouds which accompany the main storm.

2) The silver iodide is introduced low in the storm where it produces less of a dynamic effect. Seeding higher up causes the entire ice nuclei output to be activated locally and rapidly, resulting in a rapid release of heat.

3) Also, in the high level approach the generators of the ice nuclei are released to move at the whim of the airflow and their true trajectories are unknown.

The second interview was with the owner of the company using the upper level (turret) approach to seeding, Dr. L. G. Davis of Colorado International Corporation (CIC). CIC is applying this technique in South Africa. The principal information sought from CIC concerned the operational and logistical factors.

From the conceptual scientific viewpoint (and as reflected in the numerical model used by the project for prediction) this project is viewed by the operators as preventing hail by a process of glaciation of the cloud water alone. This we do not accept as an adequate model of the modification process, as has been explained elsewhere in this report. This is not meant to reflect critically on the project or its scientific components. In particular it does not reflect on the results of the hail prevention operation.

The operation is based on techniques developed for the Alberta hail project. The hailstorm is of the multi-cellular 'feeder cell' type and seeding is carried out in the new rising towers.

The high-speed (500 mi/hr) jet aircraft is a major element in this type of operation. CIC estimates that two such aircraft would be desirable on the basis of our projections on the site and location of the operational area and our radar climatology. The jets can get from the ground to any point at 31,000 feet in a 5000 mi^2 area (2000 mi^2 plus intercept zone) in 9 minutes.

The seeding rate is approximately 600 g AgI per cell each 15 minutes.

The operation is usually described in terms of visual identification of the new turrets. In fact the new turrets are at times not visually identifiable because other clouds are present. In such cases the CIC pilot uses radar-pattern recognition to identify the elements corresponding to the new turrets. The aircraft is equipped with a K-band radar which, at least in theory and at short range, should detect echoes not visible to the ground radar. The aircraft is vectored to the proper quadrant of the main storm (based on the conceptual model) by the ground radar and then seeks the new turrets either by sensing their updrafts or by spotting their echoes on the K-band radar.

APPENDIX E

Distribution of Frontal Passages in East-Central Illinois, 1951-1960

F. A. Huff

Introduction

A study of the distribution of frontal passages in east-central Illinois, the proposed experimental area, was relevant to DESH. Frequency relations by frontal type, year, season, and month, and by diurnal distribution were determined. The association between frontal and rainfall distributions was investigated also. Data for the 10-year period 1951-1960 were used. The time of each frontal passage was determined from analysis of station records of wind, pressure, and temperature, with maximum weight given to wind shift in determining the time of passage.

Distribution of Frontal Passages by Year, Season, and Month

The number of cold, warm, and occluded front passages in each year and the 10-year total are shown in table E-1. Cold front passages were most frequent, warm fronts were second, and occlusions ranked last. The annual number of cold fronts ranged from 59 in 1957 to 81 in 1954, and the 10-year annual average was 71, or an average of approximately one passage every 5 days. The number of warm fronts ranged from 19 in 1958 to 36 in 1954 and the 10-year annual average was 26, an average of one passage every 14 days. The number of occlusions ranged from 2 to 15 with an annual average of 8. The total number of fronts per year ranged from 94 in 1958 to 126 in 1954, and the annual average was 105.

Table E-1. Area Frontal Passages, 1951-1960

	Number of fronts by year			
	Cold	*Warm*	*Occluded*	*Total*
1951	76	28	3	107
1952	76	24	2	102
1953	75	23	2	100
1954	81	36	9	126
1955	65	24	10	99
1956	72	32	8	112
1957	59	23	15	97
1958	63	19	12	94
1959	69	24	7	100
1960*	75	27	12	114
Total	711	260	80	1051

*December 1950, January-November 1960

	Number of fronts by month			
	Cold	*Warm*	*Occluded*	*Total*
January	63	20	8	91
February	43	11	11	65
March	48	24	9	81
April	52	26	12	90
May	72	31	5	108
June	63	27	3	93
July	66	32	0	98
August	57	27	0	84
September	64	18	4	86
October	61	11	3	75
November	58	16	13	87
December	64	17	12	93

A tendency for an inverse relationship between frontal frequency and annual precipitation was indicated. For example, the years which ranked first, second, and third in the number of frontal passages ranked eighth, seventh, and ninth, respectively, in annual precipitation. Conversely, the years which ranked first, second, and third in annual precipitation ranked ninth, fourth, and eighth, respectively, in number of frontal passages. The inverse tendency indicates that the relatively wet years are characterized more by larger, slower moving synoptic systems than are the relatively dry years. With typical drought conditions over the Midwest, there is usually a strong band of westerlies in southern Canada or northern United States which results in the rapid movement of low pressure centers across southern Canada with trailing fronts reaching into Illinois (Huff and Changnon, 1960). The frequent occurrence of the typical drought pattern with its rapidly moving, weak fronts during relatively dry years and the prevalence of larger, stronger, slower moving systems in the relatively wet years appear to be responsible for the tendency for a greater frequency of fronts in the dry years compared with the wet years.

Table E-1 also shows the distribution of fronts by months. During the 10-year sampling period, May was the month with the, greatest number of frontal passages. May ranked first in the number of cold front passages, May and July for warm front passages, and November for occluded front passages. The least number of frontal passages during the 10 years occurred during February. Table E-2 shows the distribution of fronts by seasons. In total number of frontal passages, spring and summer ranked somewhat higher than fall and winter. The greatest frequency of cold front passages occurred in summer and fall, warm fronts were most frequent in summer and spring, and occluded fronts reached their maximum frequency in winter and spring. Table E-3 shows 3-month running totals of frontal passages, and indicates that May through July is the period of most frontal passages, while the least number pass in January through March and February through April.

Table E-4 shows the distribution of quasi-stationary fronts in the area during the 10-year period. Fronts were designated quasi-stationary if they become nearly stationary for a period of 12 hours or longer within 100 miles of Urbana. They were classified as warm or cold front passages depending upon their movement past the station. Table E-4 shows that fronts became stationary in the Urbana region most frequently during the summer months of June through August, the period during which severe rainstorms occur most frequently in central Illinois (Huff and Semonin, 1960). Quasi-stationary fronts were least frequent during winter, December through February.

Table E-5 shows the percentage of the total number of warm and cold front passages which became quasi-stationary in the area. The percentage was highest in summer when approximately 25 percent of the fronts became stationary. The lowest percentages occurred from October through February. A study of the seasonal frequency of storms in which maximum rainfall amounts > 4 inches were recorded in the period 1914-1957 showed that nearly 60 percent of the total number in central Illinois occurred during the summer and only 2 percent during winter (Huff and Semonin, 1960). Approximately 80 percent of the quasi-stationary fronts passed as cold fronts; these represent fronts which decelerated as they approached and/or passed the station.

Diurnal Distribution of Frontal Passages

A study was made of the diurnal distribution of frontal passages on an annual and seasonal basis. First, the diurnal distribution of each type of front and of all fronts combined was determined for the 10-year sampling period. Results are summarized in figure E-1. The ordinate shows the total number of frontal passages for the 3-hour period ending at any hour shown on the abscissa.

Warm fronts show a relatively strong tendency for forenoon passages. Cold fronts show an early morning maximum, but little trend is indicated over the remaining portion of the diurnal curve. Occluded fronts show a forenoon maximum and little trend at other times. When all fronts are combined, a relatively strong forenoon maximum and late afternoon and evening minima are indicated, produced to a large extent by the warm front distribution. The warm front maximum in the morning may result, partially at least, from the intensification of these fronts during the night

Table E-2. Number of Frontal Passages, 1951-1960

Period	*Cold*	*Warm*	*Occluded*	*All fronts*
Dec–Feb	170	48	31	249
Mar–May	172	81	26	279
Jun–Aug	186	86	3	275
Sep–Nov	183	45	20	248
Annual	711	260	80	1051

Table E-3. 3-Month Running Totals of Frontal Passages, 1951-1960

Ending of 3-month period	*Cold*	*Warm*	*Occluded*	*All fronts*
March	154	55	28	237
April	143	61	32	236
May	172	81	26	279
June	187	84	20	291
July	201	90	8	299
August	186	86	3	275
September	187	77	4	268
October	182	56	7	245
November	183	45	20	248
December	183	44	28	255
January	185	53	33	271
February	170	48	31	249

Table E-4. Number of Quasi-Stationary Fronts, 1951-1960

Month	*Number*	*Month*	*Number*
January	8	July	24
February	2	August	22
March	9	September	14
April	13	October	6
May	18	November	7
June	22	December	6

Table E-5. Percent of Warm and Cold Fronts Which Became Stationary in Area

Month	*Percent*	*Month*	*Percent*
January	10	July	24
February	4	August	26
March	11	September	17
April	13	October	8
May	17	November	9
June	24	December	7
Annual	14		

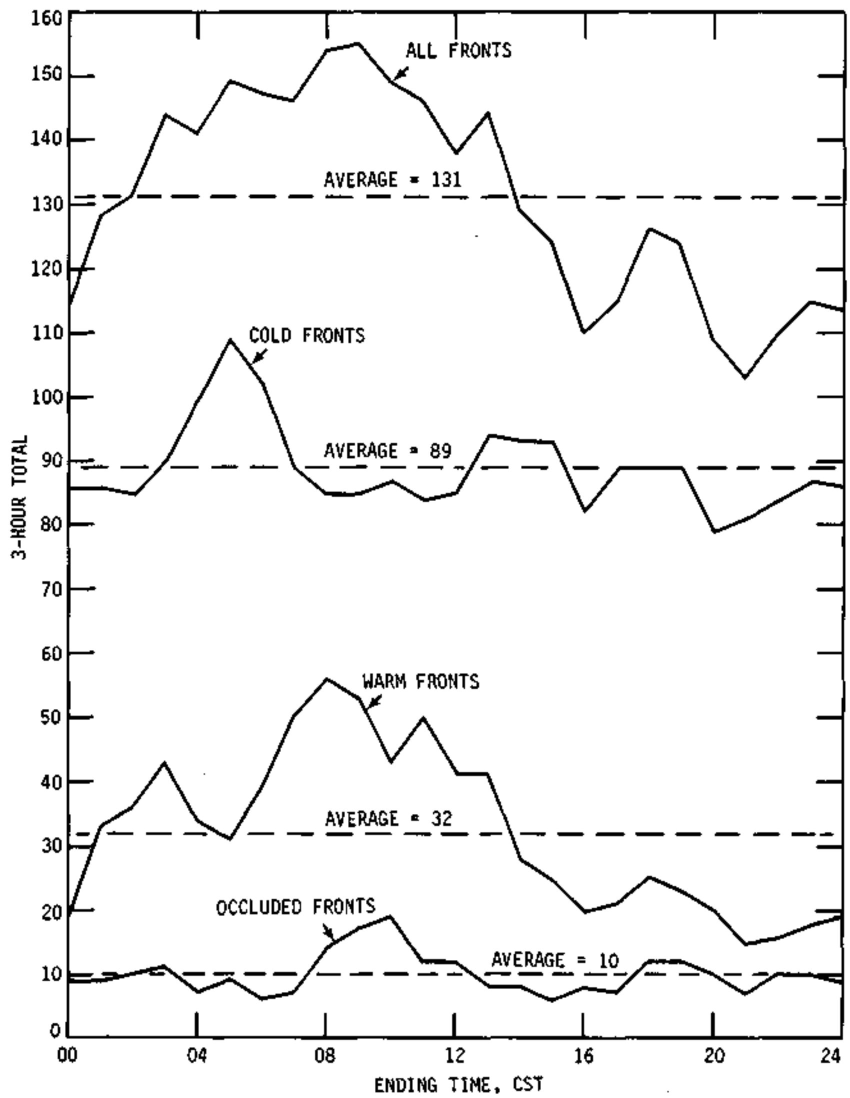

Figure E-1. Diurnal distribution of fronts

and weakening during the daytime, which causes the map analyst to occasionally eliminate them prematurely on the daytime maps. However, occlusions indicate a forenoon maximum and cold fronts an early morning maximum, so that the warm front trend may be real. If this is true, then fronts must have a tendency to approach Illinois at a particular time; otherwise, the diurnal distribution should be random, regardless of the diurnal variation in speed which occurs with fronts due to heating and frictional factors.

Figure E-2 shows the diurnal distribution of all fronts combined by season, based on 3-hour running totals. Spring and summer are similar in several respects. Both show a primary maximum in the forenoon, a minimum in the late afternoon, and a secondary maximum in early evening. Except for an early morning maximum, the fall curve indicates little diurnal trend. Winter shows a diurnal maximum near noon, and minima in the early morning and evening. All four seasons show indications of an evening minimum, but it is more pronounced in summer and winter.

Figure E-3 shows the seasonal distribution of cold fronts. All four seasons indicate an early

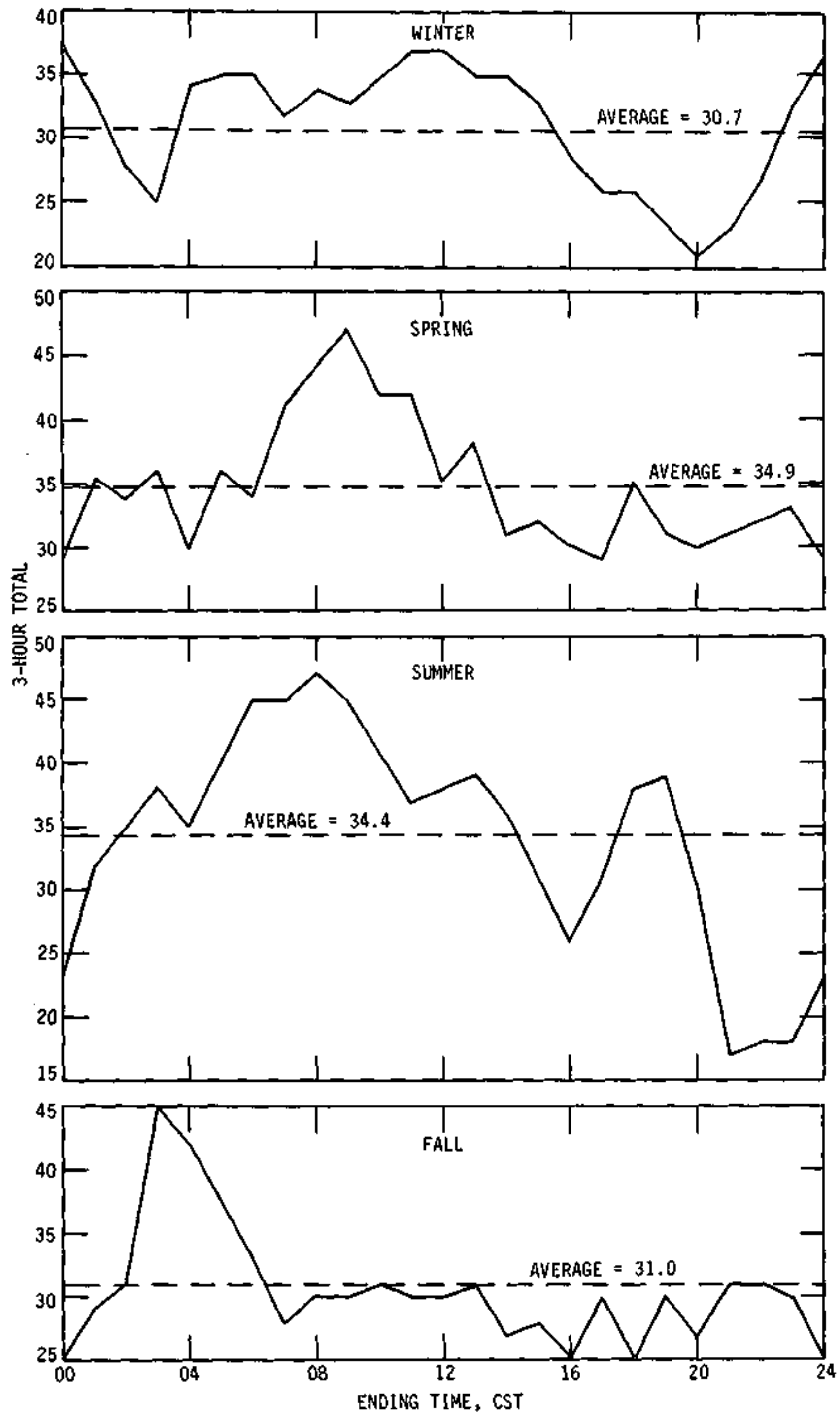

Figure E-2. Diurnal distribution of all fronts by season

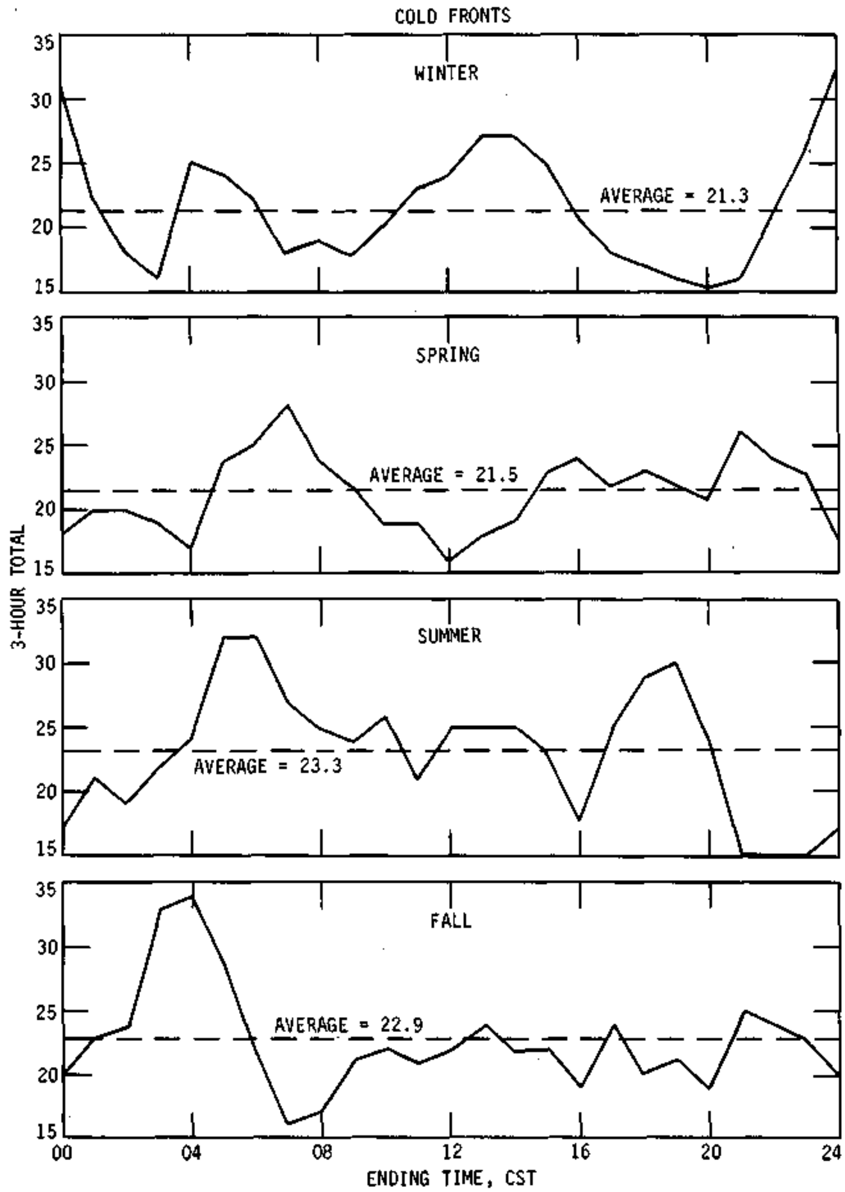

Figure E-3. Seasonal distribution of cold fronts

morning maximum, but elsewhere similarities are few. Spring and summer show a secondary maximum late in the day and winter has a second maximum in the early afternoon.

The diurnal distribution of warm fronts by season showed a pronounced forenoon maximum and a minimum in late afternoon and evening in spring and summer. No outstanding diurnal trends were indicated in the winter and fall, although there was a slight trend for decreasing frequency from the morning to afternoon and evening hours.

Relation between Diurnal Distributions of Fronts and Rainfall

A comparison was made between the diurnal distribution of hourly rainfall in central Illinois

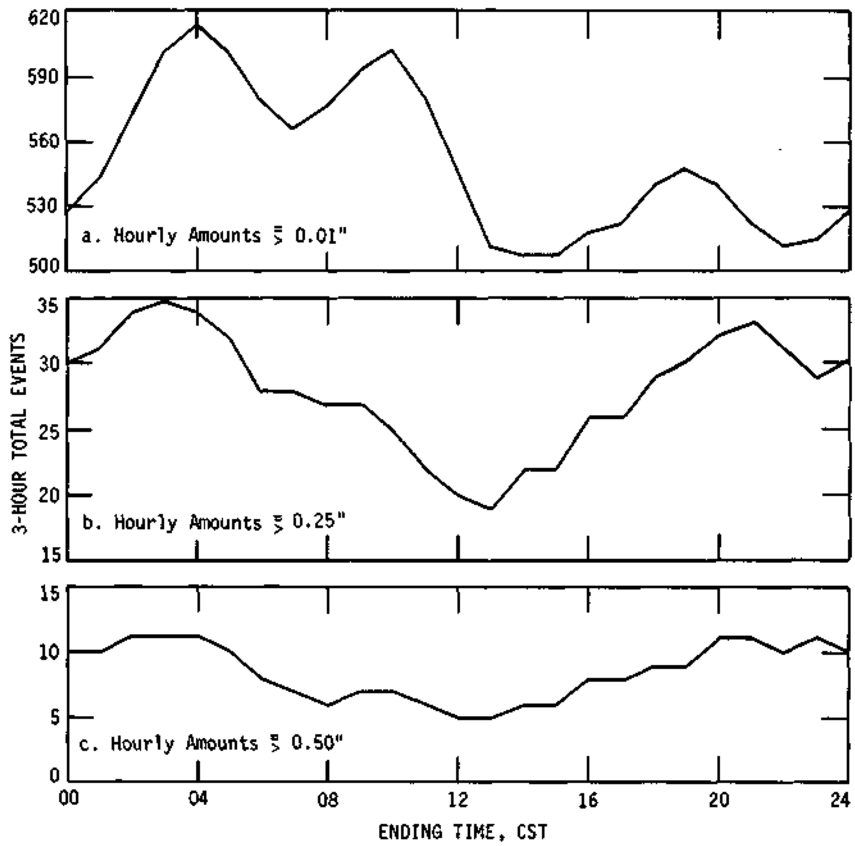

Figure E-4. Diurnal distribution of rainfall

and the frequency of frontal passages. Figure E-4 shows the diurnal distribution of rainfall, based on 3-hour running totals for the 10-year period 1948-1957 (Huff, 1971). Points on the curves represent averages based on nine stations in the north-central section of the state. Curves are presented for hourly amounts equaling or exceeding 0.01 inch, 0.25 inch, and 0.50 inch.

The curve for hourly rainfalls ≥ 0.01 inch (figure E-4a) shows maxima in the early morning mid-forenoon, and early evening, with a major minimum in early afternoon and a secondary minimum in early forenoon. The early morning maximum compares favorably with the early morning maximum of cold fronts shown in figure E-1, and the mid-forenoon maximum corresponds closely with the warm front maximum of figure E-l. The evening maximum of figure E-4a occurs near the time of minor maxima on the curves for warm fronts, cold fronts, and all fronts combined in figure E-l. The primary minimum near 1500 CST in figure E-4a occurs only slightly before minima on the curves of figure E-l. The minimum at 2200 CST in figure E-4a corresponds closely to evening minima on the curves of figure E-l. The early forenoon minimum of figure E-4a corresponds to a slight recession on the curve for all fronts in figure E-l. Summarizing, it appears that the maxima and minima of the frequency distribution of measurable hourly rainfall amounts in central Illinois correlate well with maxima and minima in the diurnal distribution of frontal passages.

The curves for hourly rainfall amounts ≥ 0.25 inch and 0.50 inch in figures E-4b and E-4c were constructed to compare the frequency of frontal passages with the diurnal distribution of moderate to heavy rainfall intensities. Again, comparing Figures E-l and E-4, the early morning maxima for the curves of figures E-4b and E-4c occur slightly earlier than the cold front maximum of figure E-l and near the time of a secondary maximum on the warm front curve. The early afternoon minima of figure E-4 occur about three hours prior to minima on the three frontal curves of figure E-1. The maxima near 2100 CST on figures E-4b and E-4c occur near a minima on the curves of figure E-l and about three hours following a secondary maximum.

Correlation between the curves of moderate to heavy rainfall and frontal passages is not as good as appears to exist between the diurnal distribution of all measurable hourly rainfall and all frontal passages. Part of this difference may be caused by sampling errors due to the much smaller sample for the heavier rainfall intensities. However, other factors may be involved. Since most of the heavier rainfall intensities in central Illinois occur during late spring and summer, the seasonal curves for spring and summer frontal distributions would be expected to correlate • better with the heavier rainfall occurrences. Furthermore, the heavy hourly rates are most likely to occur with cold front situations. Reference to figure E-3 shows an early morning cold front maximum two hours after the early morning maxima on the curves of figures E-4b and E-4c. A spring cold front maximum at 0700 CST corresponds with an area in which the curve of E-4b levels off. The evening maxima of figures E-4b and E-4c correspond with a secondary maximum on the spring cold front curve, while the summer cold front maximum at 1900 CST corresponds with a period of rapidly increasing frequency on figure E-4b. In general, curves on figures E-4b and E-4c correlate better with the spring and summer frontal curves than with the annual frontal curves, as expected.

Summary and Conclusions

Based on data for a 10-year sampling period, the average annual point frequency of frontal passages in central Illinois is 105. Of these 105 passages, 71 are cold fronts, 26 are warm fronts, and 8 are occluded fronts. A tendency exists for inverse correlation between frequency of frontal passages and annual precipitation.

May is normally the month with the maximum number of frontal passages, and February has the least number of passages. May ranks first in the number of cold front passages, May and July for warm fronts, and November for occlusions.

The greatest frequency of cold fronts occurs in summer and fall, warm fronts are most frequent in spring and summer, and occluded fronts pass most often in winter and spring. The 3-month period of most frpntal passages is May through July, whereas the least number pass in January through March and February through April.

Fronts become quasi-stationary in the region most frequently during summer, when an average of 25 percent of the fronts passing the station become quasi-stationary within 100 miles of Urbana. During the colder portion of the year, October through March, less than i0 percent of the fronts become stationary. About 80 percent of the quasi-stationary fronts result from decelerating cold fronts.

Diurnally, a trend was observed for most frequent passages of fronts during the early morning and forenoon and least frequent occurrences during late afternoon and evening when all fronts are combined. Cold fronts appear to have an early morning maximum, whereas forenoon maxima are indicated for warm and occluded fronts. Warm fronts show a pronounced minimum in late afternoon and evening, but cold and occluded fronts do not indicate strong diurnal minima. Similar diurnal distributions should be determined for other stations before the above results are accepted fully, since the possibility exists that the observed trends arise from sampling vagaries.

The frequency distribution of hourly rainfall in central Illinois and the diurnal distribution of fronts appear to correlate well, maxima and minima on the frequency curves corresponding closely.

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APPENDIX F

Summary of Activities Related to DESH

USER RELATIONSHIPS

Interaction with users of the project results was a central thrust of DESH for two basic reasons. First, the project was oriented strongly to provide *information to users of all types.* Second, the project built upon the Water Survey's 15 years of hail research that had been sponsored by commercial insurance interests, the state of Illinois, and the National Science Foundation. This considerable experience and resulting data base had made the Water Survey a recognized national and international leader in hail research and knowledge. One of the weather modification sites in the U.S.A. chosen by the Soviet weather modification visitors in 1974 was the Water Survey, where we devoted one day to discussions of DESH.

The principal users of our results are in two categories: 1) private and commercial users and 2) government users. The major role of user interaction in this project was depicted on figure 1 in the Introduction.

The private and commercial users of results from DESH and prior hail research of the Water Survey fell into six classes. The group reflecting perhaps the greatest interest was the crop-hail insurance industry. We worked closely with this industry in our project, and they supplied us with a variety of data including crop-hail adjusters' worksheets giving detailed data on losses within the hail network study area in 1973-1974. We in turn provided them with results about hail in Illinois, plus general information about hail suppression programs elsewhere. In fact, our competence in hail research, partially displayed by this project, led to the initiation of two research projects (1974 and 1975) suggested by the hail insurance industry.

Two other user classes within the non-governmental category were 1) students performing scientific research related to hail, and 2) scientists, largely meteorologists, performing research and operational duties related to hail. They used our hail data and the closely related meteorological results. Our DESH results relayed to the agricultural community in part led to their weather modification statement (Appendix C). Another user was the general public. Twelve news releases and TV-radio interviews informed the public about hail in general and this project. A fifth user was the hail suppression industry. We have carried out analysis and evaluation of two major commercially performed and public supported hail suppression projects, one in Texas and one in South Africa. Efforts to supply this industry with DESH information of use to them were extensive. The sixth type of non-governmental user included authors of books who sought our material for their use.

The other major category of users was governmental (figure 1), including state, federal, and foreign governments and their scientists. Within the context of state-related users, we include the aeronautical interests in the state of Illinois and at the University of Illinois, who utilized project results and real-time weather data available through our operations for training pilots and for planning aircraft operations. The state of South Dakota utilized our advice in attempts to evaluate their statewide hail seeding project. Certainly a prime user of the results of this research was the State Water Survey. DESH results provided the Water Survey with these elements pertaining to the proper design of a hail suppression experiment for Illinois: *a)* a means to forecast hail, *b)* the means to detect hailstorms with radar, *c)* the means to seed hailstorms, *d)* the instrumentation to measure the surface hail and rain, and *e)* techniques to evaluate the results.

The project results and expertise were utilized in several federal agencies. DESH results were part of the basis of the testimony about weather modification presented in Washington on request of the Subcommittee on Climatic Change of Council on Environmental Quality in May 1975. Another user was the National Center for Atmospheric Research whose researchers sought information and assistance in their NHRE project. We participated in the planning committee activities for NHRE and subsequently served as subcontractors for radar and surface hail projects there. Various hail information also was supplied to representatives of the Environmental Data Service and National Weather Service, both parts of NOAA.

A final set of governmental users comprised foreign nations. Considerable effort was extended to supply extensive hail information, both in published form and through visits, to scientists and representatives of the governments of the Soviet Union, Switzerland, Canada, Italy, France, and the Republic of South Africa. We entertained two major contingents of visiting hail scientists, 5 from the Soviet Union and 3 from Italy in 1974.

Thus, we have provided a vast variety of data and information on hail to a widely ranging audience. Examples of this audience was provided in a partial list of those who requested information during 1973 which appeared in our Annual Report (Changnon et al., 1974).

These user relationships were established *a)* through performing research for and with crop-hail insurance companies, *b)* by exchange of data with insurance companies and other hail projects, and *c)* through long-term consistent efforts to publish hail results in a variety of scientific journals. These relationships were sustained by telephone, routine correspondence, sharing of annual data, and performance of (or assistance in) joint research studies or operational projects. Recognized, time-consuming efforts were involved in sustaining such relationships.

HAIL LIBRARY

The accumulation of bibliographic materials is complete, though it has been a somewhat larger effort than anticipated. It was our good fortune to be able to employ graduate students in Library Science as the principal aids in the inventory.

Virtually all titles and abstracts on the subjects of hail and hail suppression, from the 19th Century to the present, are now in hand. This task was greatly eased by the 1950 publication in the Meteorological and Geoastrophysical Abstracts of an annotated bibliography on hail. An NTIS search on hail and hail prevention was ordered but produced only 50 titles, all subsequent to 1964.

Cards have been prepared for all materials through 1974. Reprints and other materials on hail which were already at the Water Survey have been collected and consolidated with the Hail Library.

All titles have been entered on punched cards so that they can be reproduced, sorted, and manipulated as desired. This will, among other things, facilitate furnishing the bibliography to other potential users. The punched cards contain:

1) an identifying number
2) author name(s)
3) title
4) journal name, if applicable
5) volume
6) number
7) pages
8) year
9) language of article
10) language of summary or abstract (as many as necessary)
11) subject heading (as many as necessary)
12) geographical location when applicable

Over 1400 papers and reports have been inventoried. The Hail Library, now complete, constitutes a very substantial resource for our further research for DESH and other hail studies.

PROJECT PUBLICATIONS AND RELATED PRESENTATIONS

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"Comparison of echo statistics for seeded and non-seeded storms in NHRE 1973," S. A. Changnon, 4th Conference on Weather Modification, Ft. Lauderdale, November 18, 1974.

"A short-term thunderstorm forecast system: step 1, exploitation of the surface data," G. L. Achtemeier, 9th Conference on Severe Local Storms, AMS, Norman, Oklahoma, October 21, 1975.

"Radar studies of severe storms observed on 3 April 1974 in central Illinois," G. M. Morgan, 9th Conference on Severe Local Storms, AMS, Norman, Oklahoma, October 22, 1975.

"On the role of strong winds in the damaging of crops by hail and its estimation with a simple instrument," G. M. Morgan, 9th Conference on Severe Local Storms, AMS, Norman, Oklahoma, October 22, 1975.

"Radar-thermodynamic hail day determination," R. C. Grosh, 9th Conference on Severe Local Storms, AMS, Norman, Oklahoma, October 21, 1975.

"Small-scale variability of hail and its significance for hail prevention experiments," G. M. Morgan, 4th Conference on Weather Modification, Ft. Lauderdale, November 19, 1974

"Design of a hail suppression project for Illinois," G. M. Morgan, Jr., 4th Conference on Weather Modification, Ft. Lauderdale, November 19, 1974.

"Weather modification in Illinois," S. A. Changnon, University Seminar, Southern Illinois University, Carbondale, May 19, 1974.

"State-related research needs for weather modification," S. A. Changnon, States Weather Modification Conference, Sioux Falls, South Dakota, June 10, 1974.

"Hail suppression possibilities," S. A. Changnon, WMAQ-TV, Chicago, July 17, 1974.

"The climate of hail," S. A. Changnon, Illini Radio Network, June 5, 1975.

"Status of hail suppression," S. A. Changnon, at Chicago, Illinois, Executive and Research Committees, CHIAA, February 13, 1975.

"Hail suppression comes of age," S. A. Changnon, talk taped for distribution on Illini Radio Network, March 4, 1975.

"Hail and rain modification," S. A. Changnon, talk on WILL-radio, Urbana, Illinois, May 11, 1975.

"The design of a hail suppression experiment in Illinois," G. M. Morgan, Calgary, Alberta, Canada, September 4, 1975.

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"Development of a mesoscale objective analysis and realtime forecasting capability," G. Achtemeier, talk at Conference on Regional and Mesoscale Modeling, Analysis and Prediction, Las Vegas, Nevada, May 8, 1975.

"Radar observations of hail and tornadic storms on 3 April 1974," R. C. Grosh, talk at Conference on Radar Meteorology, Houston, Texas, 1975.

1973-1974 PROJECT PERSONNEL

Staff	*Prime Activities*
Stanley A. Changnon, Jr.	Project Manager
Griffith M. Morgan, Jr.	Director of Weather Research
Neil G. Towery	Director of Field Operations
Gary L. Achtemeier	Research Meteorologist, Forecasting Task Area
Ronald C. Grosh	Research Meteorologist, Radar Task Area
Herbert Appleman	Research Meteorologist, Seeding Task Area
Paul T. Schickedanz	Statistical Meteorologist
Ronald Alsup	Research Assistant, Radar and Radiosonde Operator and Analyst
Edna Anderson	Director of Data Processing
Oscar Anderson	Field Technician and Analyst
Catherine Jackson	Data Processor and Analyst
Jennie Coppenbarger	Network Technician
Student Analytical Assistants	
Susan Moyer	Hailpad Analyses
Stephanie LaMasters	Hailpad Analyses
Christine Dailey	Hailpad Analyses
Ruth Wilcox	Hailpad Analyses
Shirley Socha	Hailpad Analyses
Beth Marek	Hailpad Analyses
Gale Buehler	Hailpad Analyses
Susan Roth	Literature Search
Mary Cassell	Literature Search
Eugenia Payne	Radar Analyses
Vicka Bell	Radar Analyses
Philip Dortch	Radar Analyses

SUMMARY: ACHIEVEMENTS AND RECOMMENDATIONS

There were several scientific accomplishments during this 30-month project in addition to developing the plan of a hail suppression experiment. The systems engineering approach used successfully involved a carefully interlocked series of data gathering and analysis efforts. These together focused on hailstorm forecasting, hailstorm identification with radar, classification of different storm-producing conditions, and the implications of these on a seeding system that embraces these findings with those of the past 6 years of hail research that centered on evaluation and acquisition of surface hail data. The systems approach allowed us to detect *a)* the failure to collect an adequate sample of 10-cm radar data, and *b)* a potential study of a major tornado day (3 April 1974) sampled extensively by the project and deserving of a special study. However, a proposed extension of the project to perform these two studies has not been funded by NSF.

The research efforts largely involved two general thrusts: *a)* field operations in the spring and fall of 1973 and spring of 1974 and related data analyses, and *b)* analyses of historical hail, radar, and synoptic weather data. Field operations in 1973 resulted in collection of excellent surface data on 4 different types of hail-producing periods on 6 occasions. Operations in 1974 provided excellent data on 3 days with some useable radar data. Analysis of these data gave answers to many questions about the short-term (3 to 6 hour) storm forecasting problems, but did not allow us to answer all questions about our hailstorm identification capability with the 10-cm radar — both key factors in deciding on the optimal delivery system(s) for seeding materials.

An in-depth investigation of all hail-producing conditions of the past eight years in Illinois was performed to learn *a)* how to class these events on a weather-type basis, *b)* how much in advance the hail-producing systems for a specified area can be forecast, and *c)* how all of this scientific information can be integrated to form an operational modification and evaluation system. Results point to a need for high-level airborne seeding delivery systems.

Impacts of the project have been greater than could be expected for a 30-month project because of the extensive background of our hail research. The Illinois hail results are applicable to most areas of the eastern two-thirds of the United States and certain findings on techniques (statistical evaluation and radar detection) are applicable to any hail area. The major impacts or user-related accomplishments of the project are listed below.

1. A key achievement was the extensive advice given by S. A. Changnon to the Alberta (Canada) government, at their request, concerning the design and evaluation of a major 5-year hail suppression project that the government initiated in 1974. The Alberta government asked for advice on the project and its potential design. After a 2-day visit in Calgary during July 1973 to confer with their government officials, the Alberta Weather Modification Board, and the senior project scientists, an extensive design report was developed largely on the basis of the available results from Illinois. Subsequently, the two Canadian project directors, in response to our invitation, visited our staff for 2 days in September 1973 for in-depth discussions on the use and handling of surface hail data and on various statistical evaluation techniques, an area of Survey expertise.

2. G. M. Morgan was invited by the Istituto di Fisica dell' Atmosphera in Italy (a part of the National Research Council) to spend a month at their expense studying and advising its groups engaged in research on hail and fog. He visited and worked in Rome, Bologna, and Verona, and gave several seminars to groups including the full range of researchers, research directors, and politicians in which he described the lines of major effort to be followed in hail prevention projects. More detailed and specific advice on development of field sites and choice of instrumentation (radar and surface hail measurements) was given to the relevant groups in many working sessions and personal interactions.

Following the Italian stay, Morgan accepted an invitation for a brief visit to the hail prevention group in Grenoble, France, directed by Dr. Pierre Admirat, A seminar on surface hail measurements and radar was presented to this group. Advice was solicited and given regarding a future hail prevention experiment. The desire was expressed to involve Morgan directly in this effort. All of this materially aided in the design and evaluation of a 3-nation (France, Italy, and Switzerland) hail suppression experiment launched in 1975 in Switzerland.

3. In a similar vein, we responded with hail information and advice to extensive requests from other governmental groups. For example, the South Dakota Weather Modification Commission and School of Mines and Technology requested data, advice, and information concerning evaluation of the effectiveness of their 1972-1974 statewide hail suppression program. Hail information has been supplied to various individuals with the National Weather Service who wished advice on how to measure hail and information on the climatology of hail.

4. Discussions were held with NHRE leaders and these led to arrangements for joint field interactions in 1974 and 1975 involving our senior staff with their experiment. This effort

was pursued to more directly study the transferability of their system components to a potential Illinois experiment. Advice on design and socio-economic research were furnished to NHRE staff.

5. We have sustained a close communication and a data collection relationship with all crop-hail insurance companies in central Illinois. They supplied us with detailed 1973-1974 hail loss data for central Illinois, and we were able to answer a variety of their requests for specific hail information. In addition, we supplied their national information service (Crop Insurance Research Bureau, Inc.) with information about the Illinois project.

6. Extensive analyses of the hail data for two major commercial projects were performed. Data in and around a 2-county area of Texas where a 4-year locally sponsored hail project has been conducted were evaluated (Changnon, 1974). This evaluation was done for two reasons: *a)* to review the results for their application to the Illinois suppression project design, and *b)* to provide the commercial seeding firms and local (Texas) citizens with information on the results. A second evaluation study concerned a 4-year project in South Africa and a report was written and supplied to the Colorado International Corporation, the South African government, and NHRE (Schickedanz, 1975). In December 1975, G. M. Morgan and S. A. Changnon visited the South African project to inspect the operations and discuss research needs. Suggestions relating to future evaluation and reports were supplied to the staff.

7. Other external accomplishments worthy of note related to supplying hail information to answer requests from a variety of other sources. Authors of 3 books on weather wanted to employ our results; the Soviet hail suppression specialists visited the project for 3 days in 1974; the Illinois Institute of Aviation wanted briefings and instructions on hailstorm forecasting and detection for their pilot trainees; and those organizing scientific conferences desired our participation. The state news media published four project news releases.

There is no doubt that utilization of our recommendations has led and will lead to more definitive hail suppression experiments and projects, both in Illinois and other places (Texas, Canada, Soviet Union, South Africa, Colorado, Italy, Switzerland, and France). Major benefits involve increased public information and scientific knowledge, items difficult to assign dollars to but invaluable in leading to project efficiency and general enhancement of the public image of science. The most apparent direct economic benefits to be realized concern periods of experimentation. The Canadian 5-year project is being designed at a level of $1,000,000 per year, and a 1-year shortening of that experiment, which could be obtained with our design suggestions, would be a savings of $1,000,000.

Obviously, the major savings to be hopefully realized from this project concern the ultimate reduction in crop and property loss due to hail. Our evaluation of results from Texas and South Africa suggest 40 to 50% reductions due to hail suppression efforts. Such a reduction in Illinois could lead to considerable savings but would not equate to the operational costs. Illinois insured crop losses in 1973 and 1975 exceeded $40 million (highest in the nation), and a sizeable (40 to 50%) reduction by hail suppression in those years would have yielded enormous benefits, up to $20 million (not counting costs of seeding). Savings to property in Illinois also could be as much as $1,000,000 per year, on the average. Such reduction in crop-hail losses also would lead to more efficient and stable agricultural operations. This in turn would lead to a more stable economic base both for the individual farmer and for the state of Illinois. However, more inexpensive seeding systems will have to be developed to make hail suppression beneficial in Illinois.