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HAILSTORMS IN THE HIGH PLAINS

by

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and

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I. PURPOSE

The purpose of this report is to provide a written summary of the progress made on a study of hailstorms in the High Plains during the period 1960 through 1964 in northeastern Colorado. Primary support for these studies has been provided by the Atmospheric Sciences program of the National Science Foundation, with supplemental support of the Crop-Hail Insurance Actuarial Association and the Great Western Sugar Company, and this support is hereby gratefully acknowledged.

Initial studies of hailfalls and hail suppression attempts began in 1959 when the principal investigator observed a commerical hail suppression program in northeastern Colorado and conducted an evaluation of it. While the results of that evaluation were mildly favorable (slight indications of less hail and more rain) it was recognized that additional basic research of the hail problem was necessary prior to initiating a large-scale suppression experiment. The hailstorm studies from 1960 through 1963 were to determine the characteristics of hailstorms and to devise appropriate procedures for a scientific hail suppression experiment.

This report is a summary of these background studies, and includes information on hailstorms and hailfalls, and studies which have been made in the design of the hail suppression experiment which was begun in 1964.

This report is intended as a written record of these studies, with the hope that they provide the background data on which future hail suppression research can be continued.

Acknowledgement is due to the many cooperative observers in northeastern Colorado who have provided information on rainfalls and hailfalls, data from which many of the results reported herein have been derived.

II. ABSTRACT

The instrumentation and data collection system used in hailstorm studies in northeastern Colorado for the period 1960 through 1964 is described. Basic data were derived from cooperative observers and passive hailfall indicators to obtain information on rainfall and hailfall to supplement the existing stations. Systematic efforts were made through newsletters to inform people in the area of the research work being conducted. In 1964, assistance was given by the Colorado State Highway Patrol in reporting rainfalls and hailfalls, which proved to be particularly valuable in establishing negative reports of hailfalls.

A variety of radar equipment was used to establish radar characteristics of hailstorms. Cloud seeding on selected thunderstorms was done with silver iodide generators in 1962 and 1963 in limited cases. These results are reported separately.*

The main body of the report gives a summary of project reports in abbreviated form, and detailed results are given in separate appendices. The reported results are those of a background nature on the characteristics of hailstorms and rainstorms, and the associated physical studies that have been made in the period 1960 through 1963 for the purpose of establishing the necessary background information for a scientific hail suppression experiment to be conducted in northeastern Colorado.

The data obtained indicate that such an experiment cannot be conducted on the basis of target and control areas, but must be conducted by studies of the changes in hailstorms as a function of time during their lifetime.

Additional physical studies are continuing, as well as continuation of the hail suppression experiment, which was begun in 1964.

A detailed report of the results of seeding of individual thunderstorms is being prepared as a separate report.

*Schleusener, R. A., and Sand, W. Summary of Data From Test Cases of Seeding Thunderstorms with Silver Iodide in Northeastern Colorado, 1962-63-64. Progress Report, NSF GP-2594. December 1964. CER64RAS35.

III. SUMMARY OF PROJECT

SUMMARY OF SPONSORSHIP

	Identification		
Sponsor	Sponsor	CSU	Period
National Science Foundation	G-12139	2445	4/8/60---4/8/62
National Science Foundation	G-17964	2486	5/23/61---10/23/62
National Science Foundation	G-23706	2515	5/4/62---11/4/63
Crop-Hail Insurance Actuarial Association	-------	310-109	6/1/62---7/31/62
National Bureau of Standards	CST-7419	2560	4/1/63---12/31/63
Crop-Hail Insurance Actuarial Association	-------	310-109	6/1/63---7/31/63
U. S. Navy Ordnance Test Station	N60530-9691	2237	2/1/64---1/31/65
National Science Foundation	GP-2594	2805	3/1/64---2/28/66
National Bureau of Standards	CST-7503	1517	5/1/64---9/30/64
Crop-Hail Insurance Actuarial Association	-------	2064	6/1/64---7/31/64

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IV. INSTRUMENTATION AND DATA COLLECTION

In 1960 Colorado State University conceived the idea of a cooperator network composed of the ranchers and farmers residing in northeastern Colorado. The cooperator network has expanded from 300 volunteers in 1960 to 500 volunteer reporters by 1964. Observers were requested to give information on date, time, and location of hail occurrence. Other information of crop damage, frequency of lightning, color and shape of hail was also requested. Newsletters, defining objectives for the upcoming season, were issued twice each year and stress the importance of the observers' rain and hail reports in the Colorado State University network.

In 1964, the observing network was expanded by utilizing the mobility of Colorado State Patrol. State patrolmen assisted by completing a reporting form each day, giving details of rain and hail encountered during their patrols. These reports were particularly valuable in establishing negative reports of hail occurrence.

As an aid in the evaluation of the hail suppression project, a hail-indicating device, yielding hail energy input per unit area was developed in 1959 at Colorado State University. This statistic of energy was considered to be a better measure of hail intensity than crop damage. Detailed information on hailfall has been obtained in northeastern Colorado by establishing a network of these hail-indicating devices.

Supporting observations of daily rainfall data for northeastern Colorado have been collected for the 1960-64 seasons through networks of U.S. Weather Bureau raingages, standard eight inch raingages operated by Great Western Sugar Co., and standard and recording eight inch raingages installed and operated by the Colorado State University hail research project.

In conjunction with the weather modification studies carried on by Colorado State University five separate radar systems have been utilized. These systems were an Atmospherics Incorporated 3-cm surveillance radar, M-33 acquisition radar, M-33 tracking radar, a modified SO-12 radar, and an Air Force CPS-9 surveillance system. In order to establish a quantitative means of determining storm intensities from radar data, all radars systems, except the M-33, were calibrated for the 1960-64 seasons.

Several aircraft were utilized for the weather modification attempts in 1962-64. During the pilot studies conducted in 1962 and 1963, airborne seeding was accomplished using a Cessna 180 aircraft. In 1964, a decision was made to utilize North American AT-6's for the aircraft seeding and corrollary aircraft operations of weather reconnaissance and photographic documentation.

All cloud seeding activity during the 1962-64 seasons was conducted by means of airborne silver iodide generators. The seeding equipment used in 1962 was an airborne non-combustion type silver iodide generator; the release rate of this ammonia silver iodide generator was approximately 3.1 grams of silver iodide per minute. The rapid evaporation of ammonia droplets releases silver iodide crystals into the air from the aircraft. Production of artificial ice nuclei effective at -20°C was at a disappointing low rate of 5.0×10^{12} nuclei per gram of silver iodide.

The equipment used for seeding in 1963 was an airborne silver iodide generator patterned after the Fuquay model, consuming approximately 8.3 grams of silver iodide per minute, using (appropriately) a 6% solution. This generator produced 1.7×10^{14} artificial nuclei per gram of silver iodide, effective at -20°C.

In 1964 a Lohse generator was used as the primary seeding equipment. The two generators used in 1964 burned 7.7 and 6.3 grams of silver iodide per minute, again using (approximately) a 6% solution. This generator is unique in that it contains no mechanical moving parts necessary for combustion of the acetone and silver iodide solution, but rather utilizes the flow of air through the generator to supply solution for steady combustion. The Lohse generator is considered highly efficient, yielding approximately 10^{15} artificial nuclei per gram of silver iodide, effective at -20°C.

V. PROJECT RESULTS

A. CHARACTERISTICS OF HAILSTORMS IN THE COLORADO STATE UNIVERSITY NETWORK, 1960-64

Hail occurrences during 1960-64 were analyzed to show the characteristics of hailstorms as observed over the Colorado State University hail network in northeastern Colorado. Volunteer observers and hail indicators were the primary source of information from the network. This abstract summarizes some of the information obtained from this data collection system.

Investigations of the times of onset and duration of hailfall reveal that for the 1960-64 period nearly 20 per cent of all reports of hail occurrence lie between the hours of 1600 and 1800 MST; in May and June most hailfall occurs between 1600 and 1700 MST, and by July the times of onset moves to 1700 to 1800 MST. Most reports indicate that 25 per cent of the hailfalls have a duration of 10-15 minutes, and approximately 80 per cent of the hail reports have a duration less than 20 minutes.

Information on percentage of ground covered and hailfall depth was also obtained. Data were biased by observer preference for reporting common percentages, i.e., 50, 75 per cent. Approximately 20 percent of the reports indicated that the ground was totally covered with hail, and when this occurred, the depth of hail was two inches or less 70 per cent of the time.

Nearly 85 per cent of the cooperator hail showed the most common stone size equal to or less than 1/2" in diameter. However, 60 per cent of the maximum stone size observed was between 1/2" and 3/4" diameter. If the stone size is compared by months for the five year period, it appears that the most common stone size for June and July is 1/4" larger in diameter than the 1/2" diameter stones in May. In considering the maximum stone size, both May and June show a frequency of 65 per cent for maximum stone sizes between 1/2" and 3/4" diameter, while in June the frequency drops off to 25 per cent in this size range.

Values of impact energy were computed on the basis of observed size distribution of dents on hail indicators in the Colorado State University network. For the five year period, nearly 40 per cent of all reports indicated impact energies equal to or less than 10 ft-lb per sq ft. Greater values (up to 2800 ft-lb per sq ft) also occurred, but at small frequencies.

Radar tracks and speed of movement of echoes known to produce hail were compared to the environmental field. Generally all movements of hailstorms in May, June, and July was from the southwest, but with a decreasing frequency later in the season. The change to movement from the northwest later in the season is only slight. This difference, though slight, is believed caused by the changing synoptic patterns, i.e., a change from cold-frontal passages and unstable waves in May to surface heating and cooling aloft in June and July. Most hail tracks moved in a direction clockwise from the upper-level wind direction. June shows the greatest clockwise movement of hail tracks with respect to wind direction. Speed of the hail tracks was usually faster than that of the 14,000 ft wind. Speed of hail tracks were less than the wind speeds at 18,000 feet and only slightly negative above.

B. RADAR CLIMATOLOGY OF HAILSTORMS

This study is directed toward the determination of hailstorm genesis areas, subsequent tracks of these hailstorms, and knowledge beneficial to possible modification attempts of these hailstorms.

Colorado State University began this study in 1961 using a 3.2 cm-wavelength radar system furnished by Atmospherics Incorporated of Fresno, California. Radar surveillance was expanded during the 1962-64 seasons with the addition of a vertical scanning system operated by CSU and a CPS-9 system located at Lowry Air Force Base, Denver. Both the Atmospherics and the CSU radar systems were located near the center of the CSU hail network at New Raymer, Colorado. Sixteen-millimeter time lapse motion pictures of the PPI scope provided a permanent record of the 80 nautical mile radar range of the Atmospherics surveillance system.

Echoes that passed through the Colorado State University hail recording network were classified as hail producers if hail reports were received from the CSU hail reporting network. Echoes outside the network were classified by comparing a plot of precipitation echoes with similar plots of insurance claims, local newspaper reports, and word-of-mouth reports that were obtained from CSU field personnel in the area.

The radar data from the period 1961-64 tend to confirm the following observations in the High Plains hailstorm in northeastern Colorado.

In 1962 there were more echoes which produced hail and these echoes developed closer to the Rocky Mountains. In 1961, 1963, and 1964 the genesis of hailstorms was more widely dispersed with the least number of hail echoes forming in 1964.

The frequency of initial location of radar echoes which later produced hail is greater in areas of rapid change of elevation of terrain than in flat terrain.

Individual radar echo plots indicate a general change in direction of storm movements during the season;in May and June echoes move from the west or southwest, while in July they travel from the west or northwest. From the 1962 hail damage reports, it appears that movement from the southwest is characteristic of high hail frequency.

The percentage of total number of echoes that are hailers is seen to vary only slightly from year to year.

The periods of late June and early July have the greatest percentage of hailers when compared to the total number of echoes cataloged.

These results provide a substantial beginning of developing factural knowledge concerning the climatology of hailstorms and information on their physical characteristics. With the continuation of data collection, it is hoped that these results may be further strengthened.

C. POSITION OF HAILFALL WITH RESPECT TO RADAR ECHOES

Radar PPI data available for northeastern Colorado for 1961-64 were analyzed with concurrent information on hail from cooperator-observers of the Colorado State University hail network. The positions of the hailfalls were classified into one of the four sectors of a radar echo: left front, left rear, right front, and right rear. For each of the hailfalls that occurred in these four sectors, the following data were obtained from the surface network:

1. Maximum stone size
2. Most common stone size
3. Hail impact energy

The mean and maximum values of these parameters for each of the four sectors and the number of cases within each sector were then determined. Since the frequency of occurrence of the maxima of the above parameters gives a measure of the relative frequency of hail within each sector, it also was determined.

The results indicate that there is a favored tendency for hail on the right-hand side of the radar precipitation echo. While the most common and maximum stone sizes show little variation between sectors, hail impact energy number is considerably greater in the right-hand sectors, both in the mean and maxima. During June and July the frequency of occurrence of maxima of the hail parameters lies in the right-hand sector, while for May the frequency is nearly equal for both the left and right-hand sectors.

It thus appears that the right-hand side with respect to cell movement is favored for the occurrence of hailfall as characterized by the most common stone size, the maximum stone size, and the hail impact energy.

D. PHYSICAL CHARACTERISTICS OF HAILSTONES

Eight hailstone parameters were determined from samples of hail collected in Colorado during the summer of 1962. The mean and variance of each hailstone parameter was determined by various groupings of geographical area and time of year. Correlation coefficients between the hailstone parameters were determined. An analysis of variance using the "F" test was applied to determine significant difference of hailstone parameters between months and geographic areas.

The average hailstone for the summer of 1962 had the following mean parameters:

Size (diameter)	= 1.83 centimeters
Shape hailstone	= Spheroid or ellipsoid
Density	= .888
Ice crystal volume ratio	= 1
Number of dry growth rings	= 1
Number of wet growth rings	= 1
Diameter of embryo	= 0.8 centimeters
Shape of embryo	= Spheroid or ellipsoid

On a seasonal basis, May had the smallest mean hailstone diameter and July had the largest. June had the least dense hailstones and July had the most dense hailstones. The other hailstone parameters (ice crystal volume ratio, embryo diameter, and the number of wet and dry growth rings) varied little during the summer.

An analysis of variance using the F test and students "t" tests showed that there were significant seasonal differences in hailstone diameter and density.

E. DROPLET CONCENTRATIONS IN A FEW YOUNG CUMULI

The continuous formvar sampling technique of Meteorology Research, Inc., Altadena, California, was used to obtain cloud droplet samples from regions less than 600 meters above the base of newly developed cumulus clouds near Fort Collins, Colorado. Simultaneous recordings of the rate of climb, temperature, turbulence, liquid water content, and altitude were made with a special eight channel Brush recorder. Only data from the non-freezing portions of the clouds were analyzed.

Analyses were made of the droplet concentration variations and the liquid water content variations as the clouds were transversed. Relationships between all of the above measured quantities were also presented.

These clouds that were sampled did not appear to be capable of producing rain by coalescence and diffusion in the non-freezing portion (less than 1000 meters thick) of the clouds according to presently accepted theories.

Samples of droplets concentrations were taken near the base of young cumulus clouds. The position of the samples and the age of these clouds influenced the results that were obtained.

The study of the liquid droplet concentration variation revealed the following:

a. Small scale variation of droplet concentration in the main part of the cloud was indicated to be between 6 to 20 meters. Changes in droplet growth conditions seemed to occur at regions greater than 6 meters apart but less than 20 meters apart. Variations between regions more than 20 meters apart were always present. At the edges of the clouds, turbulence and mixing caused variations on a scale that was less than 6 meters.

b. Decrease of droplet concentration was observed over distanced of 10 to 400 meters at the edges of clouds. These regions were referred to as transition regions and were caused by the mixing of drier air surrounding the cloud with the saturated air causing droplets to evaporate. This type of observation was not possible with a "single shot" cloud droplet sampler.

c. Transition regions of some of the clouds sampled contained a larger per cent of the smaller diameter class of droplets than the main body of the cloud and a smaller per cent of the larger classes than in the main body of the cloud. This indicated that droplet growth was decreased in the transition regions due to mixing of unsaturated air with the cloud region.

d. Cloud passes that terminated with the high droplet counts were observed to have a high per cent of smaller droplets than the main body of the cloud. These smaller droplets evaporated faster leaving a more distinct termininating point of the cloud than would have occurred if more larger droplets were present.

e. The larger, more developed clouds generally have a higher per cent of the total concentration in the larger two classes of droplets.

f. There was an indication of a decrease in the mean droplet radius as the average concentration increased which indicated a decreasing droplet growth rate.

g. An increase in cloud width gave a general increase in droplet concentration which possibly corresponded to an increase in cloud activity. Greater droplet growth (higher per cent of larger droplets) was also associated with greater cloud width.

h. Some of the cumulus clouds had peak concentrations of 600 to over 1000 droplets per cubic centimeter while smaller clouds had concentrations of only 400 (or less) droplets per cubic centimeter. Concentrations as high as this have been found only rarely by other investigators. Average maritime cloud droplet concentrations have been given as 100 droplets per cubic centimeter or less. Two of the sampled clouds did not have any apparent peaks. Larger clouds generally had larger average concentrations.

i. An increase in updraft velocity indicated an increase in droplet concentration. This would correspond to a higher maximum supersaturation which resulted in a larger number of activated nuclei.

j. The droplet diameters ranged from 4 microns to 20 microns with a mean diameter of 8 microns.

k. The average liquid water content of the larger clouds that were sampled was 0.5 to 0.6 g/m^3 (measured directly and computed from the droplet distribution) while the smaller clouds gave 0.1 to 0.3 g/m^3.

F. THE EFFECT OF TERRAIN AND LOW-LEVEL WIND ON HAIL GENESIS

In 1961 and 1962 a study was made in an effort to determine what effect the topography of northeastern Colorado had on the genesis locations of storms that later became identified as hailers. During the first two hours of operation each day, the location of new radar echoes genesis areas was recorded. The genesis point for the convective cell was arbitrarily determined ten miles upstream from the first radar echo. At this genesis point, and at four additional points located in the cardinal directions, a measure of the amount of low-level lift produced by topographic effects was computed. The topographic lift equals the elevation difference in feet per mile times the wind velocity in miles per hour. For topographic lift to be a significant factor in cloud formation, the lift difference between the genesis point and the four surrounding points must be positive. For both 1961 and 1962, a comparison was then made of this lift parameter at the genesis point and with the average of the four surrounding points. The results of the study indicate that it is not possible to use the topographic lift factor for the prediction of areas of first development of hail-bearing thunderstorms.

G. METEOROLOGICAL PARAMETERS AND HAIL

An investigation was made of certain meteorological parameters and the occurrence of hail in northeastern Colorado, including a comparison in the intensity of hail fall during the 1960-64 period and the mean flow patterns at 700-mb; the presence of a jet maximum overhead and the occurrence of hail; relationship of the 500-mb west wind and the occurrence of hail in the lee of the Rockies; and the development of a hail forecast equation utilizing computer techniques.

The years of the study were classified according to the hail intensity observed and the following ranking resulted: 1962, 1960, 1963, 1964 and 1961. The difference in intensity of hail among 1963, 1964, and 1961 is very small. The most severe hail year occurred in 1962.

The mean 700-mb charts for the hail season during the 1960-64 period were examined. During 1962, the long wave trough position lay approximately 400 nautical miles west of northeastern Colorado; no other year in the 1960-64 period has had such a favorable mean position of the long wave trough.

In 1960, the year which ranked second in hail occurrence, the 700-mb mean long wave was displaced east of northeastern Colorado, allowing northwesterly flow to dominate. It is thought that thunderstorm formation during this period was the result of surface airmass heating with cooling aloft; also thunderstorm activity occurs in the center and slightly west of the mean trough line.

The year 1963 gave marked changes in the upper flow patterns. Hail intensity decreased during the years of 1963, 1964, and 1961. The predominating feature on the mean 700-mb charts was the westward intrusion of the subtropical high pressure into regions southeast of Colorado. The effect of subsiding air due to the subtropical anticyclone overcame any tendency for large areas of upward vertical motion. A slightly stronger intrusion of the subtropical high remained during the 1964 season. Thunderstorm activity in both 1963 and 1964 was limited to short wave passages over northeastern Colorado. Consequently, the entire Plains area of Colorado was subjected to severe drought conditions during 1963 and 1964.

A third synoptic pattern developed during the hail season of 1961. The mean 700-mb charts indicated one long-wave position 1,000 nautical miles east and another 1,500 nautical miles west of Colorado. The subtropical high pressure zone was not as influential as in previous dry years; still 1961 ranks as a low hail occurrence year.

No direct reference is made to the existence of low level moisture needed for thunderstorm genesis; however, the supply of available moisture is governed by the stability and flow patterns mentioned above. For example, the presence of troughing to the west usually results in weak cyclogenesis in southeastern Colorado or southwestern Kansas, thereby feeding Gulf moisture into the Plains of Colorado.

An analysis of vertical wind profiles was made for days of severe, moderate, and no hail occurrence for the period 15 May - 31 July, 1960-63. Subjective analysis was used to classify the daily hailfall intensities.

It was found that the presence of a jet maximum overhead of 50 knots during May and June coincided with the occurrence of severe hail damage. In July this maximum speed fell to 40 knots. Values of the wind speed aloft for days with moderate hail exhibited slightly slower winds between 40 and 50 knots. A primary difficulty in this study was the inability to find a wind profile which distinquished days of moderate and no hail occurrence. In summary, there does appear to be a slight tendency for the occurrence of hail to favor the wind profiles with faster winds at all altitudes to 60,000 feet MSL.

An additional study was concerned with the relation of the occurrence of hail during May, June, and July in the lee of the Rocky Mountains and the latitudinal distribution and strength of the 500-mb west wind component along 110 degrees west longitude. The latitudinal position of relative maxima and minima offers some encouragement for possible use of a time-section of zonal wind speed as a forecasting aid, provided some relationship can be found between the zonal westerly wind and the weather phenomenon for which forecasts are desired.

Time sections of the zonal wind speeds at five degree latitude intervals along 110 degrees west longitude were prepared for the seasons of 1959 through 1964. The data were examined for a qualitative relationship between the zonal winds and weather phenomena, such as the number of hail reports or the number of hail-producing thunderstorms.

For the purposes of this study, a hail day within the Colorado State University observing network was defined, prior to 1962, as a day on which there were three or more reports of hail occurrences in northeastern Colorado; for the years 1962 and after, a hail day was defined as a day on which two or more radar echoes were classified as hailers.

Data for the 0000Z 500-mb west wind calculations was obtained from the U. S. Weather Bureau Daily Weather Map. These west wind components were compared with the normal values obtained from the U. S. Weather Bureau Technical Paper No. 21. Since 14-fold variations and departures ranging from 13 percent of normal to 176 percent of normal were found, it is evident that a method of comparison is necessary which is not influenced by the year-to-year variation in the strength of the zonal wind component.

The following procedure was used to define a difference in departures from normal in the westerly wind component along 110 degrees west longitude:

$$\Delta = \frac{\Sigma\,(x-x')_H}{n_H} - \frac{\Sigma\,(x-x')_{NH}}{n_{NH}}$$

where

Δ = difference in departures from normal of the geostrophic 500-mb west wind components along 110 degrees W.

x = 500-mb west wind component for a particular day.

x' = mean 500-mb west wind component determined from U. S. Weather Bureau Technical Paper No. 21.

n = number of days.

The subscripts of H and NH refer to days of hail and no hail, respectively. This parameter Δ was used in studies of hail occurrences in the Colorado State University network.

In order to determine the changes that took place before a hail event, the values of Δ were computed for the day of hail occurrence (D), for the first day prior to hail (D-1), and for the second day prior to hail (D-2).

For the months of May and June, a gradual increase of the west wind component is found in the latitudes south of the hail occurrence areas, namely 40 to 30 degrees north. At D-2, there is a distinct minimum, increasing to near normal for D-1, and finally progressing to a most obvious maximum value Δ for the day of hail, D.

This variation of Δ with time suggests a wind regime in which above normal westerly winds appear in lower latitudes without exhibiting continuity from higher latitudes. Such an explanation could be that of the passage of a 500-mb trough over the 110 degrees west longitude. Wind distributions around a trough would account for the latitudinal fluctuations of Δ. Another possible explanation is the progression of the northern edge of the subtropical jet to latitudes of 30 to 35 degrees north (May and June).

In July the values of Δ do not deviate more than four knots from the normal, suggesting either a decrease in westerly wind component or an increase in northerly wind component for days with hail in July.

The tendency for an increased Gradient_{40} (change of Δ at 40 degrees north) is evident in each month.

The foregoing discussion illustrates specific features that appear to be favorable for hail occurrences:

1. Passage of a relative velocity maximum in Colorado in May and June.

2. An increase in the positive anomaly south of the latitude of hail occurrence.

Neither of these features is found to hold true for hail occurrences in July.

These results indicate the importance of including the broad-scale circulation in connection with studies of local phenomena such as hail.

In efforts to produce a hail forecast equation, a stepwise screening regression technique was utilized to find meteorological parameters associated with hailfall in northeastern Colorado. The stepwise equation is of the form:

$$Y = K + C_1X_1 + C_2X_2 + \ldots + C_nX_n$$

where $Y = \log_{10} E_{max}$, E_{max} being the maximum hail impact energy (ft-lb/ft^2) expected; and X_n is the appropriate meteorological parameter. A complete listing of the constants and meteorological parameters is found in Appendix G. The meteorological parameters were divided into groups representing hailfall during 15 May - 30 June, and during 1-31 July. The equations were derived from data gathered in 1960-1962. Hail forecasts were then made using independent data from the 1963-64 seasons. These forecasts were then compared to the actual maximum hail impact energy observed over the Colorado State University hail reporting network.

A paired t test was used to examine the hypothesis that no difference existed between the forecast and observed hail impact energies. When considering either the forecast for all days (155 samples) or only those in which the forecast hail impact energy exceeded 10 ft-lb/ft^2 (80 samples), it was found that a difference, significant at the 5 percent level, did exist; hence, it was concluded that use of the stepwise regression equation did not result in a satisfactory hail forecasting equation.

H. HAILFALL DATA FROM A FIXED NETWORK FOR THE EVALUATION OF A HAIL MODIFICATION EXPERIMENT

Hailfall data collected from a fixed network in northeastern Colorado during three seasons (1960-62) included the estimated impact energy, duration of hailfall, most common stone size, maximum stone size, and number of stones per square inch. These basic data, X, along with the transformations, lnX, $\sqrt{X}$, and $1/X$, were analyzed by computer methods to determine which parameters could be used in a statistical analysis of a hail suppression experiment. The gamma distribution function was fitted to the hailfall data by the method of maximum likelihood. A chi-square goodness of fit was applied to the data, and one transformation was tested using a sequential analysis technique.

The conclusions were as follows:

1. From the 9 hailfall parameters derived from data on hailfalls collected by the Colorado State University hail network, 6 were eliminated for use in any statistical analysis of hail modification because of bias, nonhomogenity between years, or sparcity of samples. The remaining parameters were impact energy and number of hailstones per square inch.

2. The transformations which produce the minimum mean coefficient of variation are logarithm of impact energy and the square root of the number of stones per square inch.

3. The hypothesis of dependence between adjacent indicators spaced 2 to 4 miles apart cannot be rejected, even though the correlation coefficients are less than 0.50.

4. A period of 3 to 5 years is estimated to be required to detect scale changes of 10 to 25 percent in the hail parameters that might be accomplished by modification attempts. However, there are practical difficulties involved in attaining the conditions assumed in the analysis, one of the most difficult being the problem of handling zero values if complete hail suppression were to be attained.

5. Lack of significant correlation between adjacent areas indicates that a target-control analysis is not feasible for attempting to detect significant changes that might result from a hail modification experiment.

6. Of the data collected and the transformations studied, only the data of square root of number of hailstones per square inch can be fitted by a gamma distribution function and it provides only a marginal fit.

7. The sequential analysis test alone could not adequately evaluate the effectiveness of this hail modification experiment.

I. AUTOCORRELATION AND REGIONAL CORRELATION OF SUMMER RAINFALL

Autocorrelation coefficients were computed for point rainfall and mean rainfall on a north-south line containing one to seven stations (line rainfall) for summer rainfall in northeastern Colorado. This line was approximately 50 miles in length. The rainfall was for non-overlapping periods of length (1-day, 2-day, 3-day, 5-day, 10-day, and 15-day).

Transects at known times were made across the tracks of five thunderstorms to determine the path rainfall.

The following conclusions were drawn:

1. Point summer rainfall is an independent time series for non-overlapping periods of length 1-day to 15-day.

2. Daily line rainfall is not significantly correlated at lag one for a 50 mile line containing less than six stations.

3. The regional correlation coefficients of point and line rainfall increases as days are combined, especially below five days.

4. Four years of July point rainfall data are not sufficient to estimate the regional correlation coefficients between two points.

5. The correlation coefficient between two gages a small distance apart is between 0.40 and 1.00 for summer convective daily rainfall.

6. The relationship of regional correlation coefficient of summer line rainfall (three stations per line) versus distance between lines has a negative second derivative between zero and 100 miles for 1-day through 15-day precipitation. The relationship approaches linearity for 10-day precipitation.

7. The time to maximum rainfall of path rainfall from an individual thunderstorm increases as the season progresses from 15 May to 15 July.

From the above conclusions one can draw the following inferences concerning the possible techniques of evaluation of a thunderstorm modification experiment or operation:

1. Point summer rainfall is not suitable for a target-control analysis because of conclusions 1 and 4.

2. Line rainfall is more suitable for control analysis because of conclusions 2, 3, and 6. If several north-south lines of stations were in operation during an experiment, then the last line which the thunderstorm passes prior to being seeded could act as the control and the first line crossed after seeding had had time to take effect could act as the target. With several lines, one could pick a target line and control line each day according to the location of the thunderstorms. The possibility of combining different lines on different days for 3-day to 5-day precipitation has not been explored but could be of significant benefit.

3. If conclusion 7 is true, then it would appear that if one had several north-south high density raingage lines then he could compute the path rainfall along each raingage line for each individual seeded thunderstorm. One would then be taking advantage of all benefits in inference 2 above plus gaining the mobility required to observe thunderstorms relative to their state of development.

J. THE VERTICAL DISTRIBUTION OF AITKEN NUCLEI IN THE VICINITY OF FORT COLLINS, COLORADO

A small particle counter, type CN, manufactured by the Gardner Associates, Inc, Instrument Company, was used for counting Aitken nuclei. These nuclei counts were obtained by aircraft measurement from the surface (5,000 feet MSL) to 12,000 feet MSL for the dates July 25, July 29, July 30, and July 31, 1964 in the vicinity of Fort Collins, Colorado.

Since the Gardner counter is calibrated only for sealevel conditions and for full vacuum expansions, a correction factor for varying sampling altitudes was computed and applied to the instrument's readout to more accurately estimate the nuclei concentrations. It was found that at 5,000 feet MSL with Aitken nuclei concentrations of less than 500 nuclei/cm^3, the Gardner counter indicates concentrations too high. For all other altitudes and nuclei concentrations, a positive correction must be added to the observed Gardner counter concentrations to obtain a more reasonable estimate of the nuclei concentrations.

All flights were made at 1000 MDT; during all flights, the only clouds observed were small cumulus over the mountains and occasionally a small weak cumulus developing overhead. From our limited sample, there appears a tendency for increasing the local Aitken nuclei concentration when the accompanying environmental winds aloft are from the southwest. The presence of northwesterly flow seems to decrease the counts slightly. More positive conclusions can result only from continuing climatology.

Also, this limited sample suggests that the air in the vicinity of Fort Collins may be slightly "cleaner" below 8,500 feet MSL with regard to the total number of Aitken nuclei than other areas of continental air mentioned in the literature. Above 8,500 feet MSL, the total number of Aitken nuclei is still slightly less than the other average values quoted in the literature.

K. RADAR STUDIES IN NORTHEASTERN COLORADO, 1961-64

Severe storm surveillance for northeastern Colorado was provided by Atmospherics Incorporated's 3-cm radar, an Air Force CPS-9 radar, and a vertically scanning SO-12 radar. A description of these radar systems is found in Appendix A, Table 1.

A study using the Atmospherics Inc., radar system was undertaken to determine the average heights, both uncorrected and corrected for beam width, of hailers and non-hailers in northeastern Colorado. It was found that the average height of an echo identified as a hailer is higher than the mean height of the family of all echoes and also for the echoes identified as non-hailers. A statistical test was applied to the difference between the average heights of hailers and the average heights of non-hailers (corrected for beam width) to determine the existence of any significant difference between hailers and non-hailers. A significant difference does exist between radar tops of echoes identified as hailers and those identified as non-hailers for both June and July between the ranges of 40 to 79 nautical miles. Other significant differences exist for ranges less than 40 nautical miles in July and for ranges of 80 to 119 nautical miles during June.

Cooperative effort between the United States Air Force and Colorado State University made possible the use of the CPS-9 weather radar system located at Lowry Air Force Base, Denver, Colorado. Earlier studies have shown that it is possible to estimate thunderstorms intensity from radar measurements taken with the CPS-9 "step-gain" system. It is now possible to estimate the intensity of the storm at the time of the radar observation by determining the echo top at "O" step gain and the appropriate radar reflectivity factor, Z, at 30,000 feet MSL. Given the reflectivity and echo height criteria, a probably weather forecast with regard to hail and damaging winds may be issued. In order to forecast the occurrence of severe weather at some time in the future, a pilot study was undertaken to determine the probability that a given echo would persist in time. Measured values of RHI tops and 10 log Z_{30} (reflectivity factor Z at 30,000 feet MSL) from the CPS-9 were plotted as a function of time for each cell identified as hailer or non-hailer at some time during their life cycle. From these time plots the values of the RHI tops and 10 log Z_{30} were computed by linear interpolation between the time that tops first exceeded 30,000 feet MSL and the time echo heights last exceeded 20,000 feet MSL. The results of the 1962 pilot study can be summarized as follows:

1. Radar echoes remained higher than 30,000 feet MSL for approximately 1.5 to 2.0 hours.

2. Radar tops for the hail cases remained above 30,000 feet MSL for an average of about 1.75 hours, and the non-hailers about 1.25 hours.

3. The average value of 10 log Z_{30} remained above 30 for about 1.4 hours for echoes averaged for the 1962 season.

4. The average changes in RHI tops for various time intervals (15, 30, 45, and 60 minutes) were determined as a function of time after the radar tops were first observed to exceed 30,000 feet MSL.

5. When the echoes first exceeded 30,000 feet MSL, the change in height was positive for all of the time increments except 60 minutes; for 30 minutes lapsed time or longer, all increments gave negative changes in RHI tops.

The results of this study indicates a strong degree of persistence of echo tops higher than 30,000 feet MSL, and the value of 10 log Z_{30} greater than 30 for time periods of from one to two hours. Both of these criteria are indicative of probably severe weather. From the viewpoint of forecasting severe weather, this study indicates that if a thunderstorm echo exceeds 30,000 feet MSL at step gain "O", the best forecast is for it to persist for at least one hour and possibly for 1.5 hours, with some likelihood of hail.

The CPS-9 radar system at Lowry Air Force Base was used to get measurements of echo tops, maximum reflectivity factor Z, elevation of the maximum reflectivity factor, and the reflectivity factor at 20,000, 30,000, and 40,000 feet MSL. A statistical analysis, similar to the one mentioned earlier, was performed to determine whether significant differences at the 5 percent confidence level occurred in the above mentioned parameters between echoes identified as hailers and those identified as non-hailers. A comparison of the CPS-9 data with that from the Atmospherics Inc. radar system indicates that in most cases the CPS-9 tops are slightly less than the echo tops obtained at New Raymer for the respective classes of storms. This lower value of echo heights at the CPS-9 may be explained by the fact that the CPS-9 possess a smaller vertical beam width (1°) than does the Atmospherics Incorporated system (2°).

A significant difference exists between radar tops of echoes identified as hailers and those identified as non-hailers for both June and July.

The value of reflectivity at 20,000 feet MSL shows significant differences between hailers and non-hailers for the months of May and July only.

Values of maximum reflectivity and the reflectivity at 30,000 feet MSL are significantly different for hailers and non-hailers for all three months.

In summary, it can be said that both the maximum reflectivity and the reflectivity at 30,000 feet MSL offer the best method for determining the existence of hail or no hail in an echo. In July five of the six parameters obtained from the CPS-9 indicate significant differences between hailer and non-hailer at the 5 percent confidence level.

In order to study the vertical structure of thunderstorms, a Navy SO-12 horizontal scanning radar was modified to give vertical scanning capability. A study was made in 1963 to determine what difference exists between the values of the radar reflectivity factor, Z, as measured with the RHI capabilities of the CPS-9 3-cm weather radar and the modified vertically scanning SO-12 3-cm system. The SO-12 was operated by Colorado State University at New Raymer, Colorado. A similar comparison was made between the observed radar echo tops using the same radar sets. Comparisons were between two radar systems looking at the same identical cell; the identification of the observed cell as a hailer or non-hailer did not enter into the comparison. The most difficult problem in such a study is the assurance that both the CPS-9 and SO-12 radars are monitoring the same cell. However, the resolution of the SO-12 horizontal scan is of such increment (1°-2°) that the position of a cell that both radars are nearly simultaneously observing can be accomplished with sufficient accuracy. A paired t test was used to test for significance, at the 5 percent confidence level, the hypothesis that the mean difference of the radar parameters observed on the two radar systems was not different from zero. For our data, the only significant differences existing between the two radar systems occurs when observations are made of the maximum reflectivity factor and the reflectivity factor at 20,000 feet MSL. The fact that there is no significant difference in observations of echo tops between the two radar systems is encouraging. The difference in observations of the elevation of the maximum reflectivity and the value of the reflectivity at 30,000 feet MSL are likewise found not to be significantly different.

L. DESIGN OF THE SEEDING EXPERIMENT, 1964

This abstract summarizes the techniques utilized in the Colorado State University hail suppression project during the 1964 hail season in northeastern Colorado.

The experimental procedures for the 1964 season were designed to provide comparisons of physical parameters of the hailstorms at successive times for an interval before, an interval during, and an interval after the seeding of storms selected at random and for other control storms left unseeded (also selected randomly) for corresponding periods. After an accumulation of a significant number of cases, the differences between seeded and unseeded storms are to be evaluated.

At the time of development of individual thunderstorms, the seeding aircraft was advised to proceed to a possible seeding location. When the radar echo was observed to exceed 30,000 feet MSL, and at the same time to have updrafts in the vicinity of the cloud exceeding 500 feet per minute, an order was given by the radar controller for the pilot to open an envelope containing a random decision to "seed" or "not seed." If the decision was made to seed the storm, the pilot attempted to place the silver iodide in the strongest updraft of the storm. This continued until either (1) the storm dissipated, (2) passed beyond the radar range, or (3) the aircraft and/or generator ran low of fuel. For a "no seed" decision, a similar flight plan was carried out as though seeding were actually taking place. In either situation, the test cases were carried on for approximately one hour. The pilot and the observer on board the seeding aircraft were the only personnel that knew at the time whether or not the thunderstorm was being seeded.

During the test case operation, extensive radar surveillance was maintained. Photographic records in the form of 16 mm time lapse movies and 35 mm slides were also taken; this enabled any change in the cloud appearance to be detected. Field surveys determined the extent and intensity of hail, maximum stone size, estimated impact energy numbers, and precipitation. The observers in both the seeding and observation aircraft took numerous 35 mm slides and 8 mm movies to document the test case. Following the termination of seeding or equivalent time for the "no seed" cases, the seeding aircraft was used for aerial reconnaissance of areas of rain and hail on the ground.

VI. CONCLUSIONS AND RECOMMENDATIONS

The project results to date (see Section V above) have given sufficient information on the observed characteristics of hailstorms in the High Plains, their physical properties, and climatology to serve as the basis for a design for a hail suppression experiment involving randomization. This experiment was initiated in 1964 and is being continued into 1965.

Concurrently with the development of the randomized cloud seeding experiment, there has been increased attention to the physical processes involved in severe thunderstorms and in hailstone formation. Such cloud physics studies are necessary for continuing to improve the prospects for success in hailstorm modification.

In addition to the randomized cloud seeding experiment design and the cloud physics studies, there was an opportunity in 1963 to seed one thunderstorm with large qualities of silver iodide from a pyrotechnic device (Navy "Alecto" unit), which gave an indication of stimulation of convection. Continued exploration of the effects from such treatments are desirable in future hailstorm research.

The recommended course of action for future studies includes the following:

1. Continuation of the randomized cloud seeding experiment until the accumulation of an adequate number of cases (probably 50 or 60) to permit comparisons of the appropriate parameters between the seeded and the non-seeded catagories. It is estimated that this would require approximately two additional seeding seasons.

2. Continuation and expansion of the appropriate cloud physics and associated studies to increase the understanding of the mechanisms of hailstorm processes.

3. Designation of a portion of the summer season to a non-randomized treatment of thunderstorms with various cloud seeding devices and techniques that are different than those employed in the randomized experiment for the purpose of detecting obvious changes that might occur.

VII. CONTINUING STUDIES

Certain lines of investigation are felt to be necessary for an increased comprehension of the problem at hand. Following are some of these studies which have been initiated and will continue in the future.

PROXIMITY FLIGHTS

During the 1964 test case flights, an investigation consisting of cloud proximity flights was initiated by the Colorado State University hail suppression project. The objective of this investigation was to describe the characteristics (strength, location relative to cloud, duration) of updrafts, downdrafts, turbulence, and temperature fields in the vicinity of cumulus clouds and thunderstorms, ranging in intensity from no rainfall to heavy precipitation.

An inertial lead vertical speed indicator (IVSI) was installed in the rear cockpit of an SNJ-4 aircraft. The IVSI is a rate of climb meter; however it lacks the characteristic lag of an ordinary rate of climb instrument. Also included in the rear seat instrumentation is an altimeter, magnetic compass, air speed indicator, G-meter, temperature readout from the thermistor located on the mid-section of the wing, and a stopwatch.

Two sampling procedures are used for the cloud proximity flights. First, small cumulus clouds, in the early growing stages and/or those showing evidence of virga, were sampled. Here the specific mission of the aircraft is updraft sampling. For small, non-precipitating cumulus the aircraft can fly beneath cloud base without endangering the occupants. Secondly, during full operation cases the test case in question was sampled during stages of light, moderate, and heavy precipitation by the seeding aircraft while the operational flight plan is followed. Obviously while seeding is in progress the aircraft would seek and attempt to maintain position over areas of strong, steady updrafts. On all cloud proximity samples taken while seeding, the airplane would attempt to keep a position slightly below and ahead of the cloud base. This does not imply that turbulence samples can not be validly obtained on the flank and trailing edge of the cloud; but rather that samples are generally taken from beneath the cloud's base, to be compatible with the seeding flight plan.

For the 1964 season, a total of 55 observations, sampling 27 clouds, was made. The spectra of sampling ranged over 12 non-precipitating cumulus clouds, 8 cases of virga, 9 cases of light precipitation, 17 samples of moderate rain, and 9 cases of heavy precipitation. In most instances, after each run a 35 mm color slide was taken to show the relative position of the aircraft to the cloud and general cloud characteristics.

The 1965 program of cloud turbulence and updraft sampling is expected to follow the above outlined procedure. Additional instrumentation in the rear compartment will include a manifold pressure gage for determining the aircraft power setting without consultation with the pilot. Also the use of a magnetic tape recorder is expected to eliminate the confusion in writing down numbers while the sampling is in progress. Some penetrations of small cumulus clouds will be attempted to investigate local in-cloud changes.

It is felt that the continuing study of updraft positions and their relative location to the cumulus cloud is necessary for revealing where the strongest updrafts may be expected during the modification attempts in order that the seeding material can be dispersed in this area and drawn directly into the cloud.

WIND FLOW STUDIES

A M-33 radar system has been used to track rawin balloons and superpressure balloons. These balloons, released at the radar, are used to determine the winds aloft and the characteristics of lee waves, respectively. Continuing balloon launches on the regular schedule using the M-33 system are planned during 1965.

Several thunderstorm environmental studies have been made in northeastern Colorado with only limited success. It is planned to establish a network of pilot balloon (pibal) stations in northeastern Colorado during the 1965 season in order to describe the wind environmental structure leading to the genesis of the High Plains thunderstorm. A U.S. Weather Bureau loan to Colorado State University has provided thirteen pibal theodolites plus corollary equipment for use during July 1965. A total of fifteen pibal stations will be located on an approximate rectangular grid measuring 60 miles by 110 miles north and east of Denver, Colorado. It is expected that pibal observations will be taken on a daily basis, and on selected days at three hour intervals.

A computer analysis of the data will be made to determine the mesoscale vorticity, vertical velocity field, amount and diurnal variation of horizontal divergence, depth and diurnal variation of moisture-carrying southerly wind layers, and the interaction and characteristics of Rocky Mountain lee waves with the above mentioned synoptic observations.

CONDENSATION NUCLEI

During the 1964 season, measurements of condensation nuclei were made in the vicinity of Fort Collins, Colorado. Observations were taken both on the ground and by an airborne counter. A small particle dectector, type CN, manufactured by the Gardner Associates, Inc., Instrument Company was used for the measurements. While the number of observations is still somewhat limited for a thorough investigation, preliminary results are being compiled for 1964. Joint observations are planned for the 1965 season in cooperation with Dr. Patrick Squires of the National Center for Atmospheric Research. Samples of air collected in thunderstorm updrafts will be gathered in mylar bags and returned to the surface for analysis of both Aitken and cloud nuclei. An established pattern of nuclei observations in the vicinity of cumulus and cumulonimbus will also be undertaken by the seeding aircraft on all test cases, using the portable Gardner nuclei counter.

These nuclei measurements may reveal an answer to the question of whether or not cloud characteristics are any different over this region of maximum hail occurrence than the cloud characteristics over other continental regions.

APPENDIX A

INSTRUMENTATION AND DATA COLLECTION

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COOPERATORS

In 1960 Colorado State University conceived the idea of a cooperator network composed of the ranchers and farmers residing in northeastern Colorado. Some 300 volunteers were recruited at that time and were requested to report hail occurrences to Colorado State University. By 1964, the cooperator network has expanded to 500 volunteer reporters. Figure 1 shows the reporting form used by the cooperators. The cooperators were asked to complete the reporting forms immediately after each hail occurrence and mail to Colorado State University. Though the number of cooperators in northeastern Colorado (north and east of Denver) is significant, as illustrated in Figure 2, there are areas of lacking coverage. These areas are generally in extreme northern Colorado where irrigation is not available for agriculture. Most cooperator-observers live along and south of the Platte River Valley.

Twice a year, in the spring and autumn, newsletters are mailed to the cooperators. The newsletters define objectives for the upcoming season, stress the importance of the observers' rain and hail reports in the Colorado State University study, and reveal any findings since the last newsletter.

Figure 1 shows the reporting form used by the cooperator. The observer was requested to give the exact location of the hailfall, date and day of the week, time of beginning and duration of hail, and the accuracy of his time of observation. In addition the cooperator was asked to give a size distribution of the hailfall. Using the reporter's comments concerning percent of ground coverage by hail and wind velocity, a hailfall energy number can be calculated. Other information of crop damage, frequency of lightning, color and shape of hail was also requested. Hailfall data from the cooperators is used in the evaluation of hailfall characteristics.

COLORADO STATE PATROL

In 1964, the observing network was expanded by obtaining reports from the Colorado State Highway Patrol. State patrolmen from the district offices of Fort Collins, Greeley, Fort Morgan, and Sterling assisted greatly by completing a reporting form (Figure 3) each day, giving details of rain and hail encountered during their patrols. From examining Figure 3, it can be seen that the patrolman records time and location when encountering any evidence of hail or rain, occurring either at the present time or earlier in the day. He was asked to make an estimate of the intensity (light, moderate, or heavy) as found on the back of the form. If no evidence of precipitation was encountered along his route, the officer would simply circle "no precipitation" in the space provided for remarks. Each officer carried the Colorado State University hail reporting sheet on a clip board found in all patrol cars.

Information for each day from the Colorado State Patrol was plotted on maps showing the routes of each patrol car with its respective observation times. This data complements that of the cooperator network and the Colorado State University hail indicator network in evaluating hailfall characteristics.

In return for this information, Colorado State University attempted to advise the patrol of severe thunderstorms with possible high winds and/or hail in northeastern Colorado.

INDICATORS

As an aid in the evaluation of a hail-suppression project, a hail-indicating device consisting of two types of aluminum foil over styrofoam was developed in 1959 at Colorado State University. After calibration in the laboratory, dents in the indicator were interpreted in terms of hail energy input per unit area. This statistic was considered to be a better measure of intensity of hail than crop damage.

Detailed information on hailfall has been obtained in the region shown in Figure 4 in northeastern Colorado by Colorado State University from 1959 through 1962. The locations of the hail indicators are shown on the map in Figure 4. In 1963 it was shown that the east half of the network can be abandoned without significantly affecting the statistical properties of the indicator data. Hence, for logistic and economic reasons, the eastern half of the network was abandoned; this procedure was continued through 1964. Figure 5 reveals the location of the indicators, including some additional samplers, utilized in the 1963 and 1964 seasons.

ADDITIONAL SOURCES

In addition to the method of gathering rainfall and hailfall mentioned above, supporting observations of daily rainfall data from northeastern Colorado have been collected for the 1960-64 seasons. These additional data were provided by:

a. U. S. Weather Bureau raingages.

b. Standard 8" raingages operated by Great Western Sugar Co.

c. U. S. Forest Service 8" raingages installed and operated by the Colorado State University hail research project in 1963-64.

d. Ferguson 8" recording raingages installed and operated by the Colorado State University hail research project in 1963-64.

e. One-inch diameter plastic bottles installed near the hail indicators on the two north-south lines of the Colorado State University hail research project for 1963-64.

In 1961 a number of mechanically cooled boxes were added to the existing network for collection of hailstones. Timing devices accurate to

REPORT OF HAIL OCCURRENCE

(PLEASE FILL OUT COMPLETE REPORT)

INSTRUCTIONS

1. Please fill out one of these forms for each hail occurrence at your home, no matter how small the hailstones.

2. Mail completed form immediately to the Atmospheric Science Department, Colorado State University, Fort Collins, Colorado; using the attached self-addressed envelopes.

3. If you cannot give all the information requested, please send us as much information as possible Any information is helpful to us.

4. Please give TIME and DURATION of hail as accurately as possible (to the nearest minute, when possible).

NAME__________ Mailing Address__________

LOCATION of hail occurrence: 1/4_____, Sec._____T_____N, R_____W.

DATE of storm:__________ Day of week:__________

TIME hail began__________ a.m. p.m. DURATION of hail__________minutes.

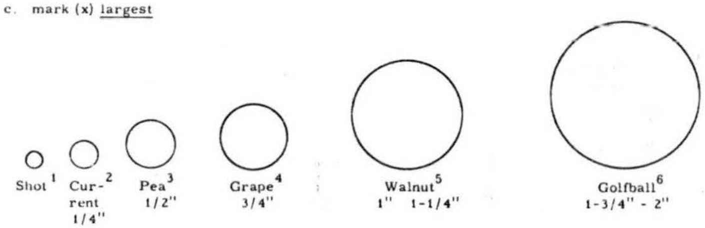
ACCURACY OF TIME is to nearest (1, 5, 10, 30, more than 30) minutes (circle one).

SIZE distribution of hail

a. check ( ) smallest

b. circle (0) most common

c. mark (x) largest



If larger than golfball, estimate diameter in inches__________

PRECIPITATION (total including hail)__________inches.

(PLEASE FILL OUT THE BACK OF THIS REPORT)

PERCENT OF COVERAGE

Ground covered 1, 5, 10, 25, 50, 75, 100 percent and ____ inches deep.

HARDNESS OF HAILSTONES

What percent of stones splashed, broke, bounced, or did not break on striking ground?
splashed_____%, broke_____%, bounced_____%, did not break_____%

WIND VELOCITY accompanying hail

- □ 0 No wind
- □ 3 Gentle breeze (Leaves and small twigs in constant motion)
- □ 5 Fresh breeze (Small trees begin to sway)
- □ 8 Fresh gale (Breaks twigs off trees)
- □ 10 Strong wind (Trees uprooted or broken, some structural damage)
- □ 12 Severe wind (Widespread wind damages to trees and buildings)

CROP DAMAGE estimates

Wheat 1	Percent damage__________
Corn 2	Percent damage__________
Sugar Beets 3	Percent damage__________
Other 4	Percent damage__________

LIGHTNING

	None	About 1 stroke/min	2-10 strokes/min	Greater than 10 strokes/min
Before hail				
During hail				
After hail				

SHAPE of hail - round, flat, conic, conglomerate, other (circle one).

COLOR of hail clear, milky, all white (circle one).

REMARKS

Check here if you have no more reporting forms □

Figure 1. Cooperator report form used by volunteer hail observers in the Colorado State University hail network, 1960-64.

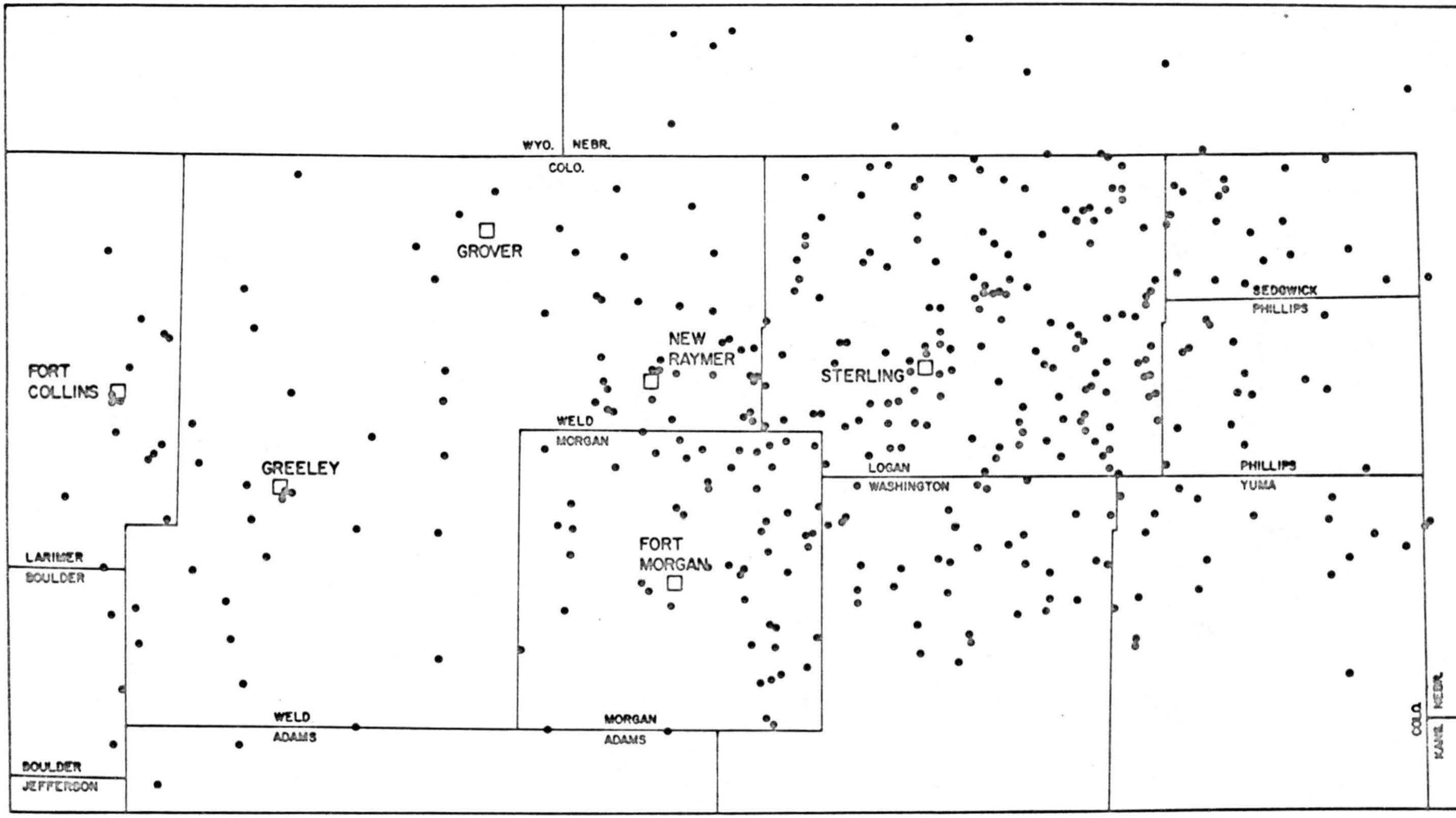


Figure 2. Location of Colorado State University Hail Reporting Cooperators in Northeastern Colorado, 1964.

DAILY REPORT OF HAIL AND RAIN
Colorado State University

Name__________ Date__________ Car No.__________

		Occurred Earlier Today			Occurring Now		
Time________	HAIL	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Location________	RAIN	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Remarks No Precip							
Time________	HAIL	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Location________	RAIN	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Remarks No Precip							
Time________	HAIL	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Location________	RAIN	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Remarks No Precip							
Time________	HAIL	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Location________	RAIN	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Remarks No Precip							
Time________	HAIL	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Location________	RAIN	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Remarks No Precip							
Time________	HAIL	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Location________	RAIN	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Remarks No Precip							
Time________	HAIL	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Location________	RAIN	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Remarks No Precip							
Time________	HAIL	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Location________	RAIN	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Remarks No Precip							
Time________	HAIL	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Location________	RAIN	Lgt	Mod	Hvy	Lgt	Mod	Hvy
Remarks No Precip							

INSTRUCTIONS

Please report occurrence and intensity of hail (and rain) by filling in blanks and circling correct entries, as follows:

1. Give time and location for each entry.
2. If no precipitation occurred earlier today and there is no precipitation now, circle "No Precip".
3. If precipitation occurred earlier today but none is occurring now, indicate intensity as follows:

   HAIL

   Lgt: any evidence of hail, not enough to cover the ground or cause significant crop damage.
   Mod: Moderate hail, ground covered, some damage to crops.
   Hvy: Heavy hail, accumulating in drifts, severe crop damage.

   RAIN

   Lgt: Any evidence of rain today, but not enought to leave roads or fields muddy.
   Mod: Moderate rain, fields muddy, but no flooding.
   Hvy: Heavy rain, water running off fields, flooding.

4. If precipitation is occurring now, indicate intensity, and in remarks describe the location where it was first encountered and where last encountered.

   HAIL (Give most common stone size in remarks)

   Lgt: A few stones, not enough to cover the ground.
   Mod: Moderate hail, enough to cover the ground.
   Hvy: Heavy hail, more than enought to cover the ground.

   RAIN

   Lgt: Ground wet, but fields not muddy.
   Mod: Fields muddy, but no flooding.
   Hvy: Heavy rain, water running off fields, flooding.

5. If precipitation is occurring now and there is evidence of heavier precipitation occurring earlier today, fill out both (3) and (4) above.

Return of forms: Return forms to Atmospheric Science Department, Colorado State University, Foothills Campus, Fort Collins, Colorado, Attn: R. A. Schleusener. Mail in envelopes provided once each week.

Figure 3. Hail and rain report form used by the Colorado State Patrol in the Colorado State University hail network, 1964.

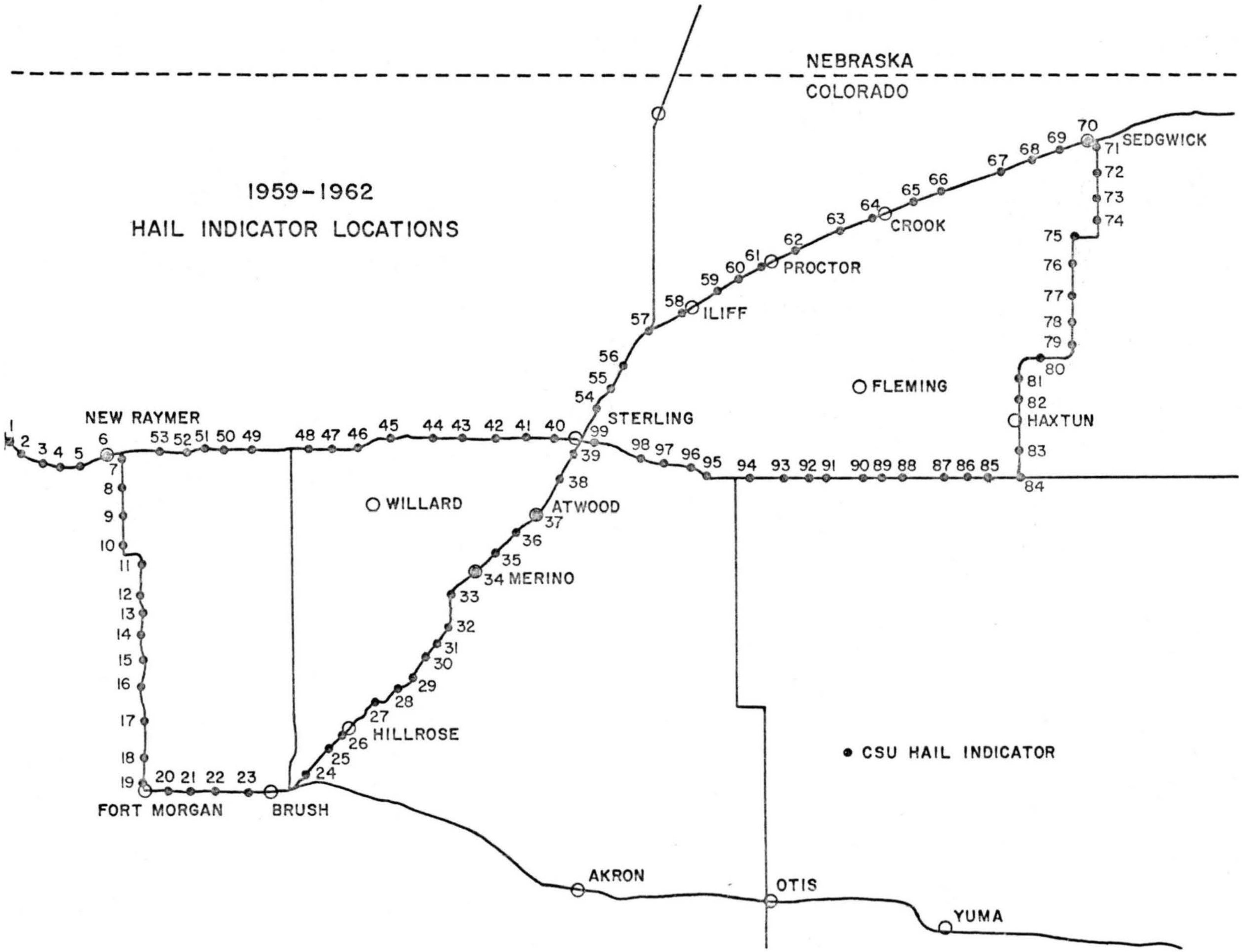


Figure 4. Location of Colorado State University Hail Indicators in Northeastern Colorado During the 1959-62 Hail Seasons

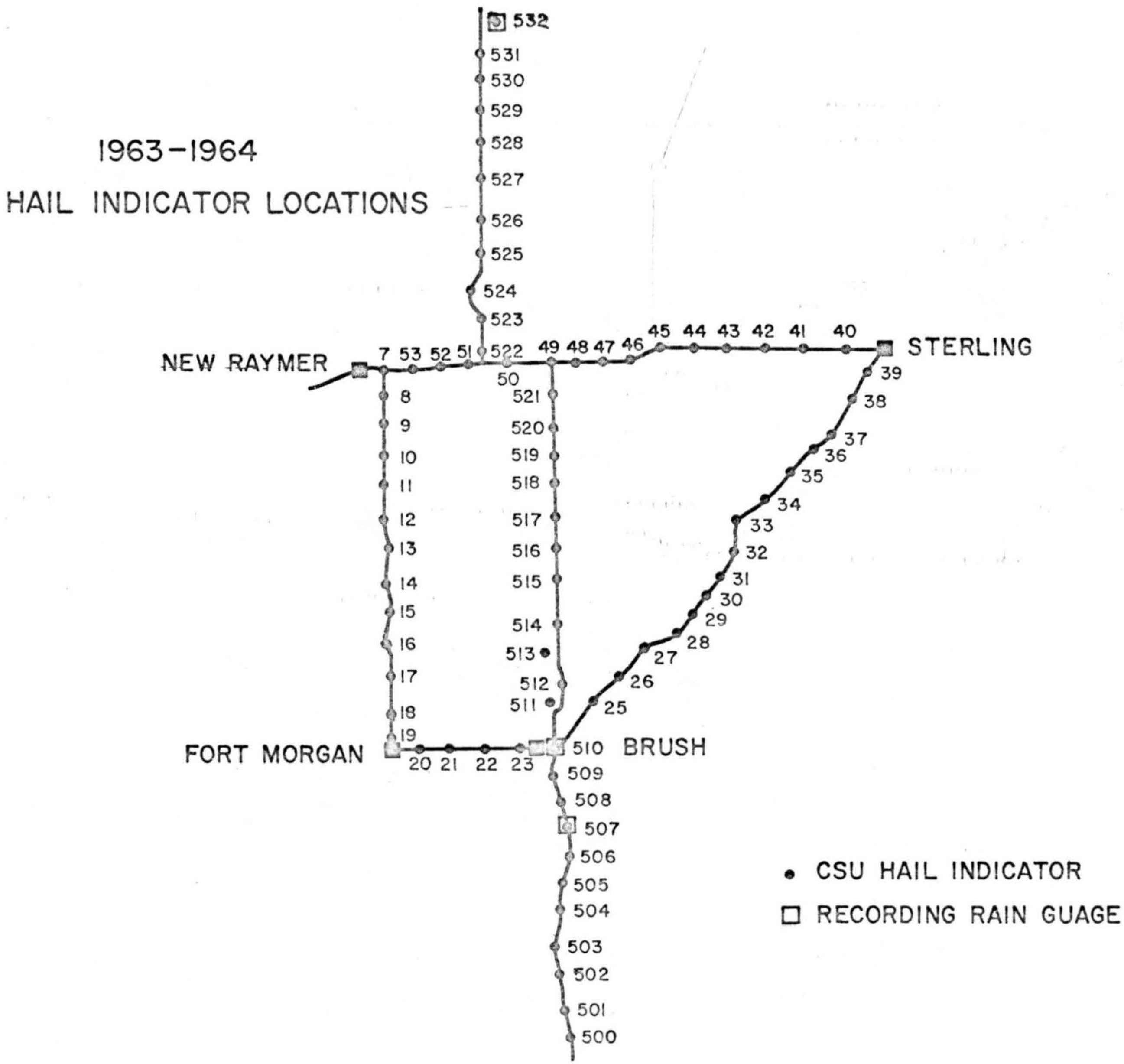


Figure 5. Location of Colorado State University Hail Indicators and Recording Rain Gauges in Northeastern Colorado During the 1963-64 Hail Seasons.

about one-minute were also added at approximately 100 points to get the time of beginning of first hail-fall. However, due to mechanical failures and frequent non-malicious vandalism, the use of the boxes and timing devices was abandoned.

RADARS

In conjunction with the weather modification studies carried on by Colorado State University five radar systems have been utilized. These systems were: Atmospherics Incorporated surveillance radar, M-33 acquisition radar, M-33 tracking radar, a modified SO-12 radar, and a CPS-9 surveillance system. A description of these radars follows, and a list of each radar system's characteristics is found in Table 1.

The primary radar system of the project was furnished and operated by Atmospherics Incorporated, Fresno, California. This was 3-cm equipment operating on a frequency of 9375 megacycles with peak power output of about 40 kilowatts. A maximum range of 200 nautical miles was available with a choice of ranges of 4-10-20-80-200 nautical miles. This radar system employed a tilt indicator which gives the vertical angle of the antenna. The antenna was kept on an angle of about $+1^0$ for most of the general scanning but was occasionally elevated through a maximum of $+35^0$ during measurements of the elevations of precipitation echo tops and studies of growth rates. The system was located about one mile southeast of New Raymer at an elevation of about 4800 feet above sea level. The Atmospherics Incorporated radar was modified slightly in 1964; however, the operating characteristics did not significantly change.

The M-33 radar system, modified from a M-33 Fire Control System, consists of two systems: an acquisition radar (9. 6 cm) and a tracking radar (3. 2 cm). Both the track and acquisition radars of the M-33 system have tuneable magnetrons which were set at 3. 2- and 9. 6-cm wavelengths, respectively, to correspond as closely as possible to 3. 2- and 10. 0-cm wavelengths. The acquisition radar operates with a peak power output of about 1000 kilowatts, while the output of the track system lies near 300 kilowatts. Maximum ranges of the acquisition and track radars are 60 nautical miles and 50 nautical miles, respectively. The tracking radar antenna can be employed to point vertically upward through the full range of 90^0. Attempts to track the hail or rain spikes were not possible because thunderstorms were too homogeneous in structure; generally the radar would track downward and look into the ground. Occasionally, when a thunderstorm came overhead, the tracking antenna was pointed upward; bases and tops were then recorded from an expanded A scope.

In addition, a technique has been developed with which to place a no-lift or constant volume balloon assembly at any desired altitude for the purpose of measuring lee-wave characteristics. The M-33 radar was found to be capable of tracking the balloon assemblies to ranges in excess of 20 nautical miles.

The M-33 was found to be a very sophisticated and intricate system which requires a substantial effort for maintenance.

During the summer of 1963, the M-33 was located on a knoll about three and one-half miles west of Fort Collins, Colorado. In 1964 the radar system was moved to a more suitable surveillance point approximately ten miles east of Fort Collins; this position provided the M-33 with observations of the west side of thunderstorms, while the Atmospherics Incorporated system provided radar coverage of the storms from the east side.

In order to study the vertical structure of hail-bearing thunderstorms, a Navy SO-12 horizontal scanning radar was modified to give vertical scanning capability. The peak output of the SO-12 is 50 kilowatts, and the operating wavelength is 3. 0 cm. The operating range of this RHI system was normally 80 nautical miles. When a decision was made to scan a particular azimuth (based on examination of the PPI), the SO-12 was employed to make vertical scans along azimuth lines which encompassed the cell of interest. A typical sampling program included one series of vertical scans through a particular cell. A step-gain system was incorporated into the radar set for making reflectivity measurements. After each vertical scan, an automatic tripper would change the increment of attenuation through five 10 db steps, 10 through 50 db, plus the normal gain (no attenuation) position. The conversion to reflectivity Z was accomplished by reference to a suitable calibration graph of gain-step vs. Z. This vertical scanning radar was also located about one mile southeast of New Raymer, Colorado, near the Atmospherics Incorporated radar system.

The United States Air Force permitted access by Colorado State University to the CPS-9 weather radar system located at Lowry Air Force Base, Denver, Colorado from 1962-64. Operating with a peak power output of 250 kilowatts, this 3. 2 cm wavelength radar provides detailed storm surveillance over most of northeastern Colorado. The Lowry CPS-9 was modified in the spring of 1961 with the addition of a step-gain device to reduce the receiver gain automatically through a series of eight steps calibrated from step 0 (95 db.) to step 7 (42 db.). Principle radar information obtained from this system was elevation of the echo top, elevation of the maximum radar reflectivity, and reflectivity of 20, 000 feet, 30, 000 feet, and 40, 000 feet msl.

In order to establish a quantitative means of determining storm intensities from radar data, the radar systems used by Colorado State University during the 1960-64 seasons were calibrated. With the exception of the CPS-9 and the M-33 radar systems, the method of calibration was that recommended by Atlas and Mossop (1960). The results contain inaccuracies inherent in the calibration method, but are considered satisfactory for determining approximate reflectivity values.

TABLE 1. Characteristics of Radar Systems Used by the Colorado State University Hail Project.

Parameter	Units	Atm. Inc. 1961-63	Atm. Inc. 1964	M-33 Acq.	M-33 Track	SO-12	CPS-9
P_t : Peak Transmitted Power	kilowatts	30	40	1000	300	50	250
P_m : Minimum Detectable Signal	watts	10^{-12}	10^{-12}	10^{-13}	10^{-13}	$1.1x10^{-13}$	$1.6x10^{-13}$
θ : Horizontal Beam Width	degree	2.0	2.0	1.4	1.1	2.0	1.0
ϕ : Vertical Beam Width	degree	2.0	2.0	4.1	1.1	1.5	1.0
τ : Pulse Length	μ sec	2.35	2.35	1.3	0.25	1.0	0.5
λ : Wavelength	centimeter	3.2	3.2	9.6	3.2	3.0	3.2
F : Pulse Repetition Rate	sec^{-1}	600	400	1000	1000	465	931
S : Antenna Shape		Circular	Circular	Rect.	Circular	Rect.	Circular

The Lowry CPS-9 radar system, 1962-64, and the Atmospherics Incorporated system. 1964, were calibrated with a signal generator (TS-147). This calibration apparatus is capable of measuring the outgoing and incoming power within $\pm$ 2 db. The M-33 radar has yet to be calibrated against a known reflectivity value; for that reason, all thunderstorm intensity measurements with this radar have thus far been relative estimates only.

AIRCRAFT

Several aircraft were utilized for the weather modification attempts in 1962-64.

During the pilot studies conducted in 1962 and 1963, airborne seeding was accomplished using a Cessna 180 aircraft. While aircraft performance was satisfactory and reliable, it was felt that a more sturdy aircraft should be used to withstand thunderstorm turbulence for the further modification attempts anticipated. In 1964, the decision was made to use North American AT-6's as the seeding aircraft and weather reconnaissance aircraft, and an observational aircraft used for photographic documentation of the modification test cases. All aircraft performed satisfactorily with only minor maintenance problems.

GENERATORS

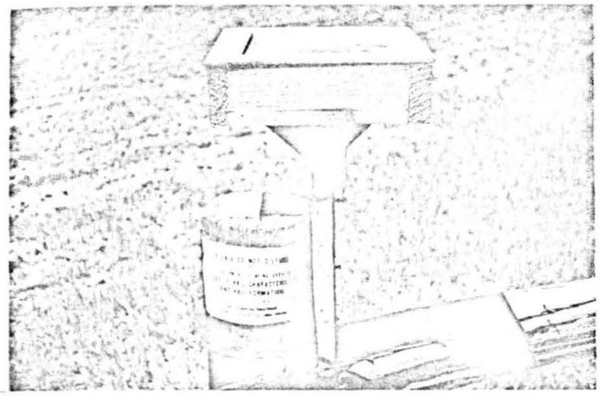
All cloud seeding activity during the 1962-64 seasons was conducted by means of airborne silver iodide generators.

The seeding equipment used in 1962 was an airborne non-combustion type silver iodide generator. The release rate of this non-combustion type generator was approximately 3.1 grams of silver iodide per minute. The practibility of using artificial ice nuclei formed by the residue left after the evaporation of small carrier droplets was explored as the basis of a usable silver iodide generator for the 1962 pilot study. Silver iodide is placed in a container into which liquid anhydrous ammonia is added (approximately two grams of silver iodide per gram of anhydrous ammonia). The solution is stored under medium pressure at ambient temperatures in the liquid state. The ammonia-silver iodide liquid complex is allowed to expand through a nozzle to ambient pressure which results in rapid evaporation of the ammonia. This rapid evaporation process releases silver iodide crystals into the air from the aircraft. Production of artificial ice nuclei effective at -20° C was at a disappointing low rate of 5.0×10^{12} nuclei per gram of silver iodide.

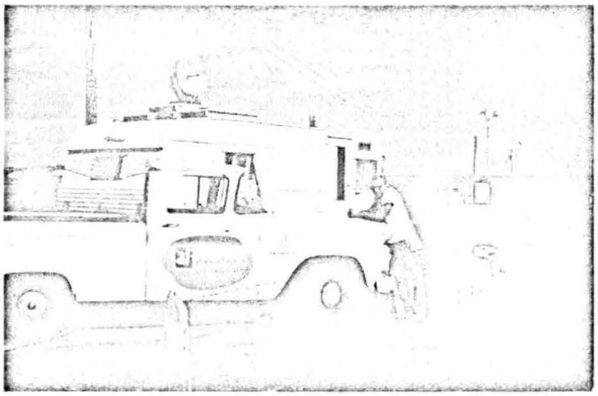
The equipment used for seeding in 1963 was an airborne silver iodide generator patterned after the Fuguay model, consuming approximately 8.3 grams of silver iodide per minute, using a 6 percent solution. In use, silver iodide is dissolved in a solution of acetone and sodium iodide and pumped by ram pressure and a mechanical pump. This pressurized mixture of acetone solution is then directed into a flame chamber and ignited initially by a momentary electric spark. Once ignited, the atomized acetone solution burns freely. The volatilized silver iodide condenses into crystals as the smoke passes from the flame around a quench chamber mounted beyond the flame chamber. This generator produced 1.7×10^{14} artificial nuclei per gram of silver iodide, effective at -20°C.

The seeding equipment used in the 1964 cloud seeding attempts was a Lohse generator (manufactured by and leased from Ora Lohse, Valier, Montana). The two generators used in 1964 had burning rates of 7.7 and 6.3 grams of silver iodide per minute, using a 6 percent solution. This generator is unique in that it contains no mechanical moving parts necessary for the combustion of the acetone and silver iodide solution. Air enters the front of the generator and does a three-fold duty. First, it pressurizes the acetone solution in the supply tank. In addition, the movement of air through appropriate ducting creates a venturi effect in the vicinity of the fuel nozzle, thus drawing the acetone solution out through the nozzle. Third, by means of a series of fins, the air moving through the vicinity of the nozzle atomizes the acetone solution into minute droplets suitable for steady combustion. This dissolved solution of silver iodide in acetone is then initially ignited by a momentary electric spark; once ignited the atomized acetone solution burns freely. This Lohse generator is considered highly efficient, yielding approximately 10^{15} artificial nuclei per gram of silver iodide, effective at -20°C.

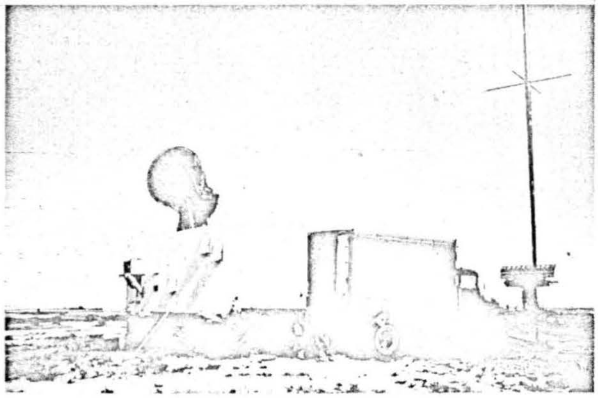
Some of the Equipment Used on the Project



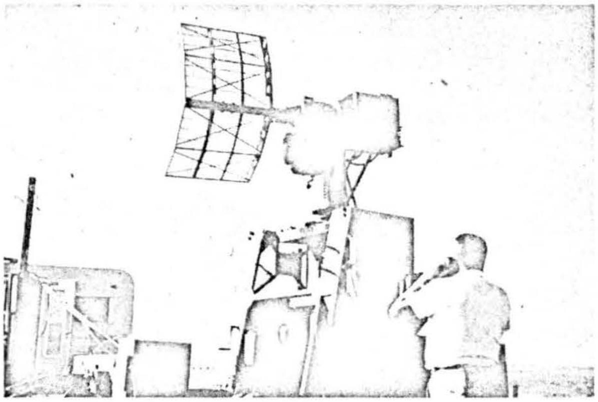
A hail energy indicator. These were scattered throughout the northeastern Colorado area during 1959 through 1964.



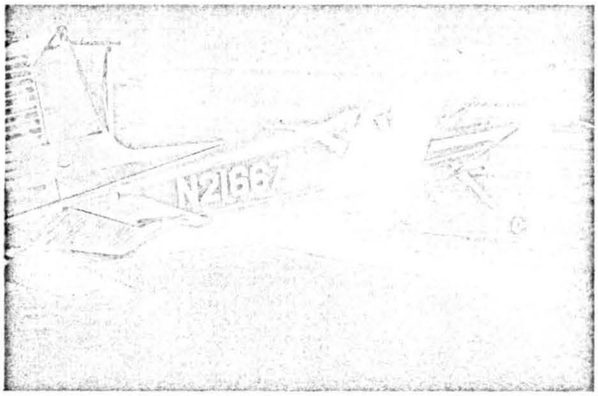
Radar system, approximately one mile southeast of New Raymer, Colorado. This equipment was used during the 1961-64 seasons.



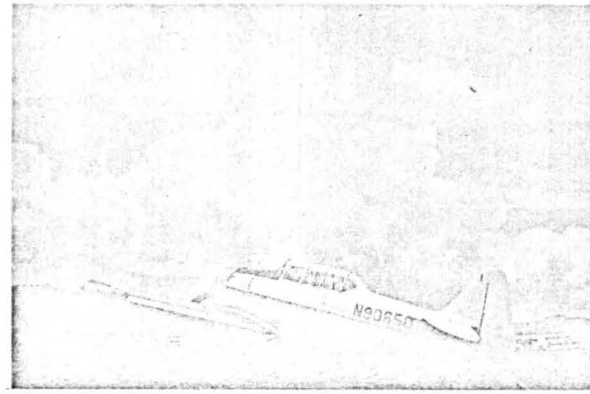
M-33 radar system, ten miles east of Fort Collins, Colorado. This site was used during the 1964 seasons.



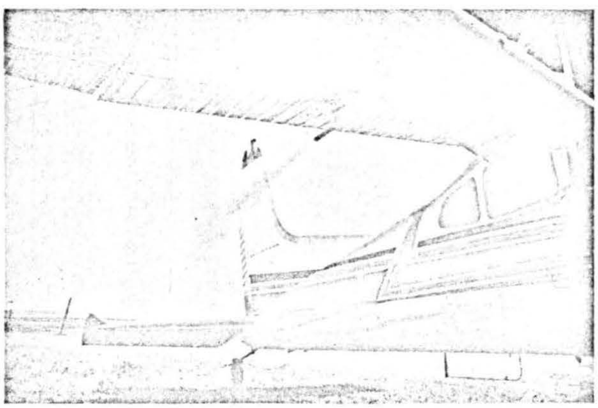
SO-12 vertically scanning radar system, approximately one mile southeast of New Raymer, Colorado. This equipment was used during the 1962-64 seasons.



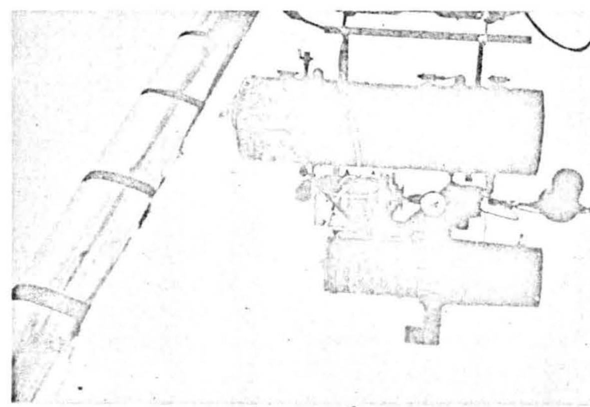
Cessna 180. This aircraft was used during the pilot seeding studies conducted in 1962 and 1963.



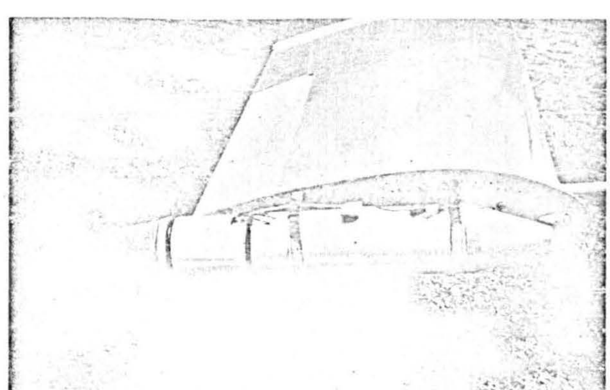
North American AT-6. This sturdy aircraft was used for seeding operations during 1964.



Non-combustion type silver iodide generator. This generator was used for the pilot seeding studies conducted in 1962.



Fuquay generator in flight. This unit was used for seeding operations during 1963.



Lohse generator on AT-6 wingtip.
Two of these generators were used for cloud seeding research conducted in 1964.

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Battan, L. J., 1959: Radar Meteorology, University of Chicago Press, Chicago, Illinois.

Atlas, D. and S. C. Mossop, 1960: Calibration of a Weather Radar by Using a Standard Target. Bull. American Meteor. Soc., 14(7), 377-382.

APPENDIX B

CHARACTERISTICS OF HAILSTORMS IN THE COLORADO STATE UNIVERSITY NETWORK, 1960-64

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INTRODUCTION

This appendix is a summary of Civil Engineering Report CER61RAS59, "Characteristics of Hailstorms in the Colorado State University Network, 1960-61", by Richard A. Schleusener and Lewis O. Grant, Colorado State University, expanded to include the period 1960-64.

METHODS

Detailed information on hailfall and rainfall has been obtained in northeastern Colorado by Colorado State University from 1960 through 1964; volunteer observers were the primary source of information from the network (see appendix A). This appendix summarizes some of the information obtained from this data collection system.

RESULTS

The times of onset of hailfall as reported by cooperative observers is shown in Figure 1. Examination of Figure 1 reveals that the most common time of hail onset is in the middle of the afternoon; the average onset time, based on the five years of data, indicates that nearly 20 percent of all reports of hail occurence lie between the hours of 1600 and 1800 MST. There is an increased tendency for hail to occur between the hours of 1600-1700 MST for the months of May and June, while in July more hail falls between 1700 and 1800 MST. The months of June and July give a peaked distribution of onset times, owing to the fact that many storms are the result of summertime afternoon instability; in May some small percentage of storms occur in early morning hours, providing the clue that many of the early season storms are still the result of transitional air mass changes and large scale synoptic disturbances. Figure 1 is based on a total of 1,425 cooperator reports.

The duration of hailfall, in minutes, is presented in Figure 2. This curve, Figure 2, reveals that 25 percent of the hailfall reports shows a hail duration of 10-15 minutes. Approximately 80 percent of the hail reports yield a duration time of less than 20 minutes. The minimum percentage that occurs between 25 and 30 minutes can be attributed to observational procedure, since not many volunteer observers will record a 25 minute hailfall, but rather would round the time off to an even 30 minutes. Figure 2 is based on a total of 1,390 cooperator reports.

From cooperator data, a histogram was plotted showing the fraction of ground covered by the hailfalls; in addition to indicating complete ground coverage by hail, observers were also requested to give the depth of hailfall for those cases when the ground was completely covered. These histograms are shown for five-year period in Figures 3a and 3b, respectively. A strong bias towards reporting "favored or familiar" fractional coverage by the observers can be seen; for example, note the preference for fractional coverages of 50 percent and 75 percent, while definite subjectivity in observations prohibits reports of, say, 40 percent. Also notable from Figure 3a is that approximately 20 percent of the reports reveals that 100 percent of the ground was covered with hail. Turning to Figure 3b, we see that when hail has accumulated with 100 percent covering the ground, nearly 70 percent of the volunteer reports indicate a depth of 2" or less. Figure 3a and 3b are based on a total of 1,385 cooperator reports.

A survey based on cooperator reports of hailstone size yields Figures 4a and 4b showing monthly distribution of the most common stone size and the maximum stone size observed in the hailstorms of that month. The histogram plot of most common size versus percent reports approximates a positively skewed normal distribution for each month; similarly the plot of maximum stone size versus percent reports yields a close estimation of a normal frequency curve for each month. From Figure 4a, it can be seen that for May nearly 90 percent of hail reports show that the most common stone size is equal to or less than 1/2" in diameter; in June the 1/2" diameter or less stone size accounts for nearly 80 percent, while in July the percentage reports indicating 1/2" diameter or less recovers to 85 percent. Further comparison reveals from Figure 4a that the most common stone size for June and July is 1/2" in diameter as compared to 1/4" diameter stones of May. In considering the maximum stone size, both May and July show a frequency of 65 percent for maximum stone size of the 1/2" and 3/4" diameter range, while for June the frequency drops off to 52 percent in these size ranges. Both Figures 4a and 4b are computed using 1,289 cooperator reports.

Impact energy of hailfall has been suggested as a measure of the severity of the hailfall, including the effect of wind. A histogram showing the frequency of occurrence of impact energy values E is shown in Figure 5 for 1960-64. Values of E were computed on the basis of the most common stone size observed, attendant wind, and the percentage of the ground covered by hail. Nearly 70 percent of the cooperator reports reveal the hail impact energy to be equal to or less than 60 ft-lb per square feet. There appears to be an increase in the percent of reports for E values of 100 to 200 ft-lb per sq ft; this is believed to be due to the grouping of a number of reports owing to the change in scale of the abscissa at those values. Figure 5 is based on 1,347 observations.

Tables 1 through 4 give some information concerning the direction cells moved that produced hail and their relation to the environmental wind field. Table 1 shows that most movement of hail paths in May, June, and July was from the southwest, but with a decreasing percentage later in the season. The change to movement from the northwest later in the season is only slight. The decrease in movement from the southwest is probably associated with differences prevalent in synoptic patterns. In May it is common for cold fronts and unstable waves to affect eastern Colorado. Late in the season frontal passages become less common and hail is received frequently with dynamically-induced airmass lifting

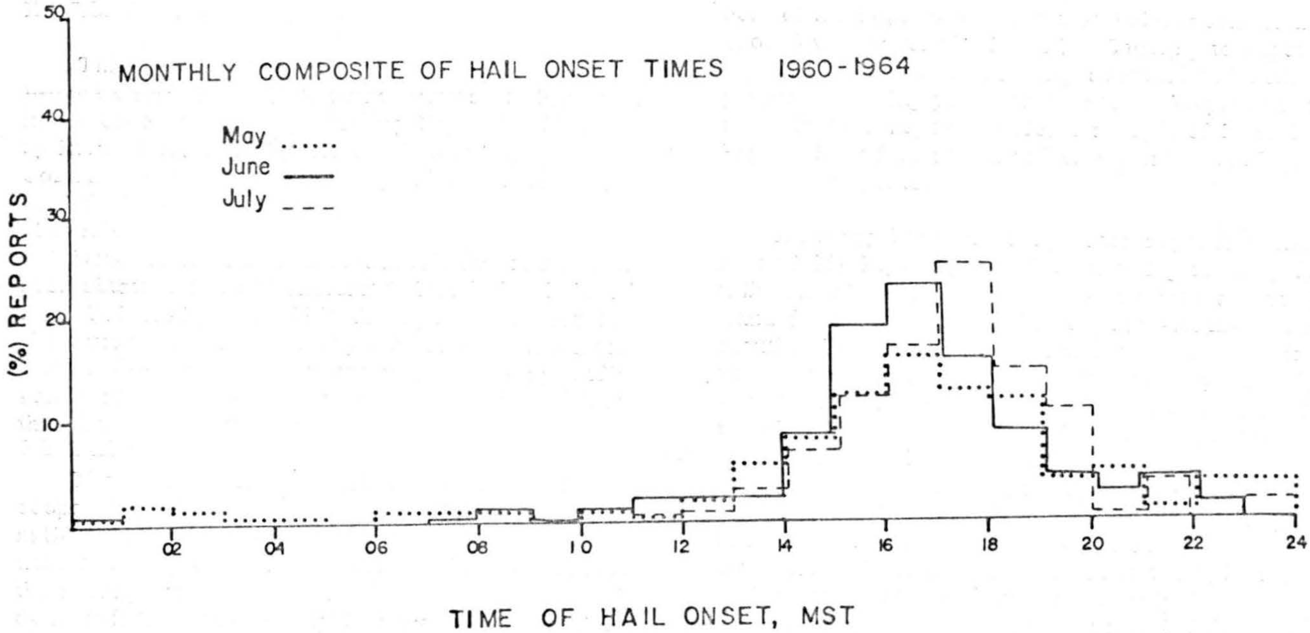


Figure 1. Percentage of cooperator reports versus monthly composite of hail onset times (MST), 1960-64.

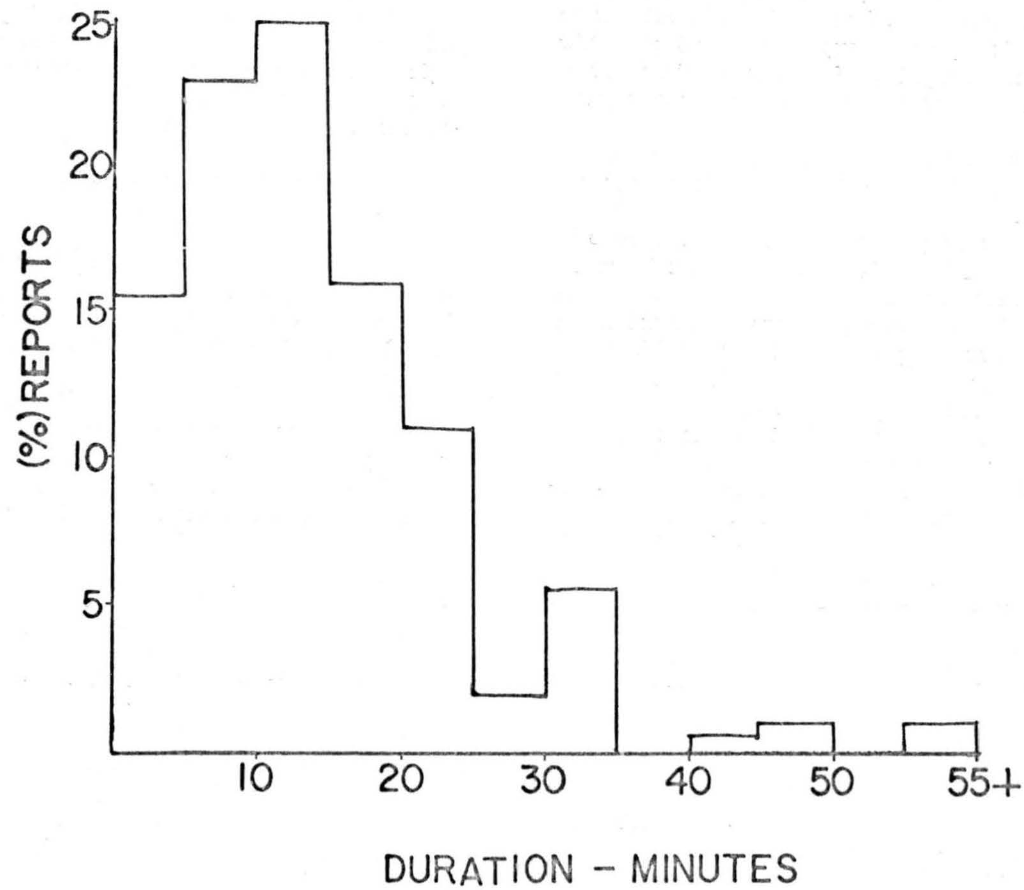


Figure 2. Percentage of cooperator reports versus duration of hail (minutes).

and surface heating and concurrent cooling aloft from northwesterly currents.

Tables 2, 3, and 4 show the relation of the speed and direction of precipitation echoes that produced hail to the environmental wind field. The environmental wind field was established from Denver, Goodland, and North Platte wind observations. Most hail tracks moved in a direction clockwise from the upper-level wind direction; June shows the greatest clockwise movement of hail tracks with respect to wind direction. Speed of the hail tracks was usually faster than that of the 14,000 ft. wind; speed of hail tracks was less than the wind speeds at 18,000 feet and higher only for May and June. In July the difference in speeds is positive at 18,000 feet and only slightly negative above.

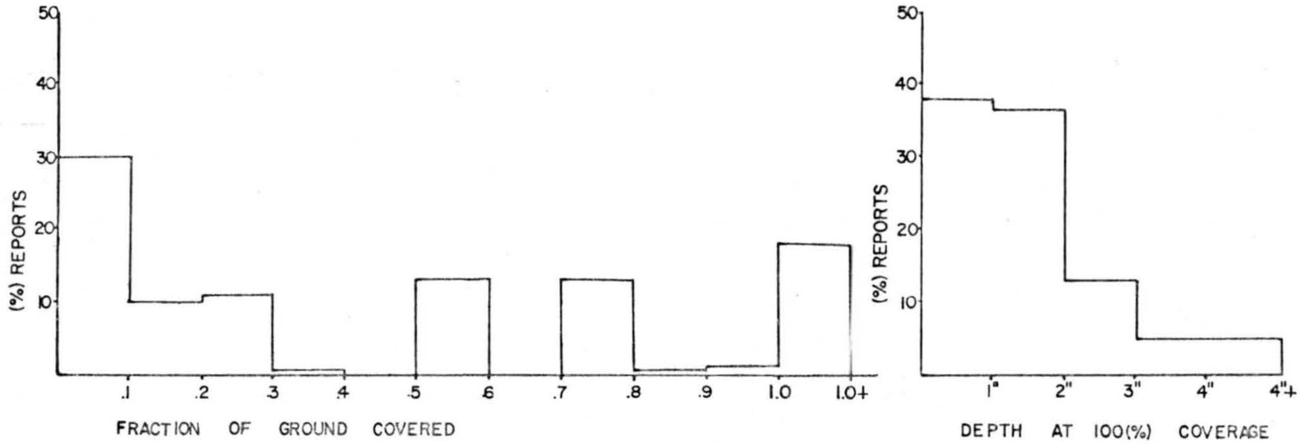
The data presented herein characterize hailfalls in the Colorado State University hail reporting network for 1960-64. These data are being combined with physical studies of the hail clouds and their environment to gain a better understanding of the hail formation process and procedures for eventual modification attempts.

Table 1. Direction From Which Precipitation Cells Moved That Produced Hail

PERIOD	NUMBER OF CASES	PERCENT OF CASES 0-90°	90-180°	180-270°	270-360°	MOVEMENT UNCERTAIN
1961-2-3-4 Monthly Total						
15-31 May	96	0	5	67	21	7
June	216	0	5	55	28	12
July	200	3	6	43	36	12

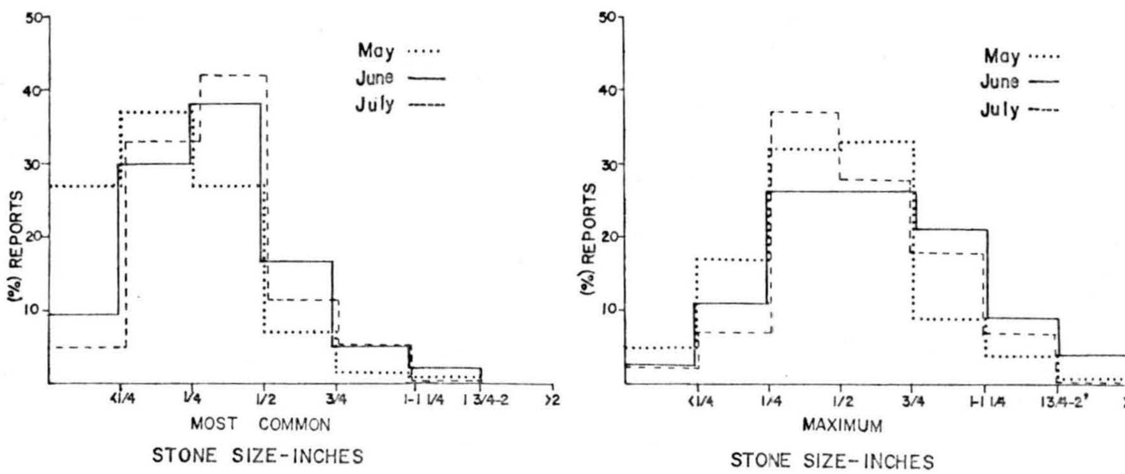
Table 2. Relation of the Environmental Wind Field to Speed and Direction of Precipitation Echoes That Produced Hail May 1961-64

NUMBER OF CASES WITH	KFT MSL 14	18	25	30
Hail Track Same as Wind Direction	6	2	1	11
Hail Track CW from Wind Direction	40	56	45	52
Hail Track CCW from Wind Direction	37	25	37	20
Speed of Hail Track = Wind Speed	3	6	6	2
Speed of Hail Track > Wind Speed	5[illegible]	21	14	10
Speed of Hail Track < Wind Speed	33	64	61	79
Deviation of Hail Track from Wind Direction, Degrees	-3.1	11.1	7.4	40.8
Average (CW)	-3.1	11.1	7.4	40.8
Standard Deviation	23.8	25.6	27.0	28.5
Speed, Knots				
Average	4.7	-2.1	-12.4	-17.9
Standard Deviation	32.6	16.1	18.0	13.2



(a) (b)

Figure 3. Percentage of cooperator reports versus (a) fraction of ground covered and (b) depth (in.) at 100 percent coverage.



(a) (b)

Figure 4. Percentage of cooperator reports versus (a) most common stone size diameter (in.) and (b) maxmum stone size diameter (in.).

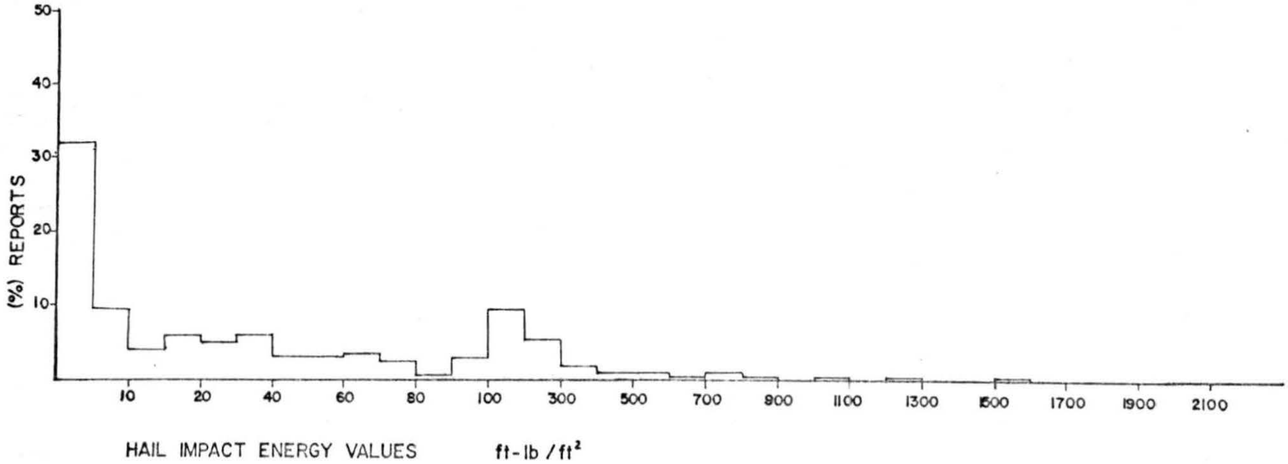


Figure 5. Percentage of cooperator reports versus hail impact energy (ft-lb/ft^2)

Table 3. Relation of the Environmental Wind Field to Speed and Direction of Precipitation Echoes that Produced Hail June 1961-64

	KFT MSL			
NUMBER OF CASES WITH	14	18	25	30
Hail Track Same as Wind Direction	23	2	7	1
Hail Track CW from Wind Direction	119	91	84	96
Hail Track CCW from Wind Direction	44	93	95	89
Speed of Hail Track = Wind Speed	6	9	9	7
Speed of Hail Track > Wind Speed	147	70	49	41
Speed of Hail Track < Wind Speed	55	129	150	160
Deviation of Hail Track from Wind Direction, Degrees				
Average (CW)	40.4	40.9	54.8	33.6
Standard Deviation	42.4	47.1	46.0	37.8
Speed, knots				
Average	10.0	-6.1	-8.2	-8.6
Standard Deviation	10.9	7.1	8.4	19.2

Table 4. Relation of the Environmental Wind Field to Speed and Direction of Precipitation Echoes that Produced Hail July 1961-64

	KFT MSL			
NUMBER OF CASES WITH	14	18	25	30
Hail Track Same as Wind Direction	0	3	3	2
Hail Track CW from Wind Direction	71	79	92	80
Hail Track CCW from Wind Direction	87	78	67	68
Speed of Hail Track = Wind Speed	4	8	3	13
Speed of Hail Track > Wind Speed	98	109	63	55
Speed of Hail Track < Wind Speed	48	76	127	125
Deviation of Hail Track From Wind Direction, Degrees				
Average (CW)	28.3	.5	8.6	26.6
Standard Deviation	54.9	53.6	49.2	52.6
Speed, Knots				
Average	18.4	13.0	-2.0	-6.4
Standard Deviation	35.7	34.9	78.2	49.1

APPENDIX C

RADAR CLIMATOLOGY OF HAILSTORMS IN AND NEAR

NORTHEASTERN COLORADO, 15 MAY - 31 JULY 1961-64

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INTRODUCTION

This appendix is a compilation of the Civil Engineering Reports CER61RAS58, "Hail Genesis Areas in and Near Northeastern Colorado," by R. A. Schleusener and T. J. Henderson, Colorado State University; CER62RAS79, "Radar Climatology of Hailstorms In and Near Northeastern Colorado, 15 May-31 July 1962, with Comparative Data for 1961," by R. A. Schleusener and T. J. Henderson, Colorado State University; CER63RAS69, "Radar Climatology of Hailstorms In and Near Northeastern Colorado, 15 May-31 July 1963, With Comments on the Relation of Radar Climatology to Selected Synoptic Parameters," by R. A. Schleusener, T. J. Henderson, and H. Hodges, Colorado State University; and CER65JDM19, "Radar Climatology of Hailstorms In and Near Northeastern Colorado, 15 May-31 July 1964," by J. D. Marwitz, T. J. Henderson, and R. A. Schleusener, Colorado State University.

The High Plains region of Eastern Colorado and Wyoming, and Western Nebraska, suffers from frequent damaging hailstorms. Because of the frequent occurrence of hailstorms, this is an excellent area for studying the origin, genesis, and motion of such storms. Hailstorms originating in this region frequently move further to the east and produce damaging storms in Nebraska and Kansas. Since there is little information available on the climatology of hailstorms, a study of the radar climatology of hailstorms was undertaken by Colorado State University in 1961 and was continued through 1964.

The objectives of this study were as follows:

1. To determine hailstorms genesis areas.

2. To determine the subsequent track of hailstorms following their formation.

3. To gather some insight towards the ultimate beneficial modification of hailstorms.

METHODS

In 1961, radar equipment for the project was furnished by Atmospherics Incorporated of Fresno, California. The system was mobile and employed a 3.2 cm radar wave length. Three radar systems were available on the project during the 1962-64 seasons. The additional systems were the CPS-9 system at Lowry Air Force Base near Denver, and a vertical scanning system modified by Colorado State University. Both the weather radar system of Atmospherics Incorporated and the vertical scanning set of CSU were located near New Raymer, Colorado. At an elevation of approximately 4800 feet above sea level, this site provided excellent view of the project study area, allowing precipitation echoes and hail paths to be determined as far west as the Continental Divide to as far east as the maximum 200-nautical-mile radar range. The first of two 7" PPI indicators of the Atmospherics Incorporated system was used for general story tracking, while the second indicator was utilized for gathering of 16 mm black and white time-lapse motion pictures.

Operation of the equipment was very reliable for the 1961-64 period, with only about eight hours of "off the air" time due to lightning strikes near the radar.

Echoes that passed through the Colorado State University hail recording network were classified as hail producers if hail reports were received from the CSU hail reporting network. To determine whether an echo was a "hailer" when it was outside the network, a plot of precipitation echoes was compared with a similar plot of insurance claims, local newspaper reports, and word-of-mouth reports that were obtained from CSU field personnel in the area.

RESULTS

Figures 1-4 show the initial locations of radar echoes which later produced hail for the period 15 May to 31 July 1961-63 and 18 May to 31 July 1964. Several facts may be noted from comparison of these figures: (1) in 1962 there were more echoes which produced hail; (2) a larger fraction of the echoes developed closer (5500' msl) to the Rocky Mountains in 1962; (3) a larger fraction of the echoes developed approximately 50 miles east (5000'msl) of the Rocky Mountains in 1963; (4) the initial location of hailers is more widely dispersed over the region in 1961 and 1964; and (5) in 1964 there were less echoes that produced hail.

The frequency of occurrence, within grid squares of 200,000 feet on a side, of first echoes that later produced hail is shown in Figure 5. From this figure a general tendency can be noted for a greater number of first echoes to form west of the radar site than east of the radar site. The area 80 miles east of the north-south line between Denver, Colorado, and Cheyenne, Wyoming, is found to have the highest frequency of occurrence of first echoes that become hailers; in particular, the 1600 sq. mile area just east of Fort Collins is outstanding in being a region of hailer genesis with almost twice as many hail echoes forming in this area as in other grid squares. Thus, the frequency of occurrence of initial locations of radar echoes which later produced hail is higher in the areas of rapid change of elevation of terrain than in flat terrain.

Table 1 gives a summary of the radar climatology of hailstorms within range of the radar at New Raymer, Colorado, for 1961-64. A comparison of the data from Table 1 shows that both the total number of echoes and the number of echoes which were known to have produced hail on the ground in 1964 were considerably less than for the three previous years. This comparison is a reflection of the general drought conditions prevalent in northeastern

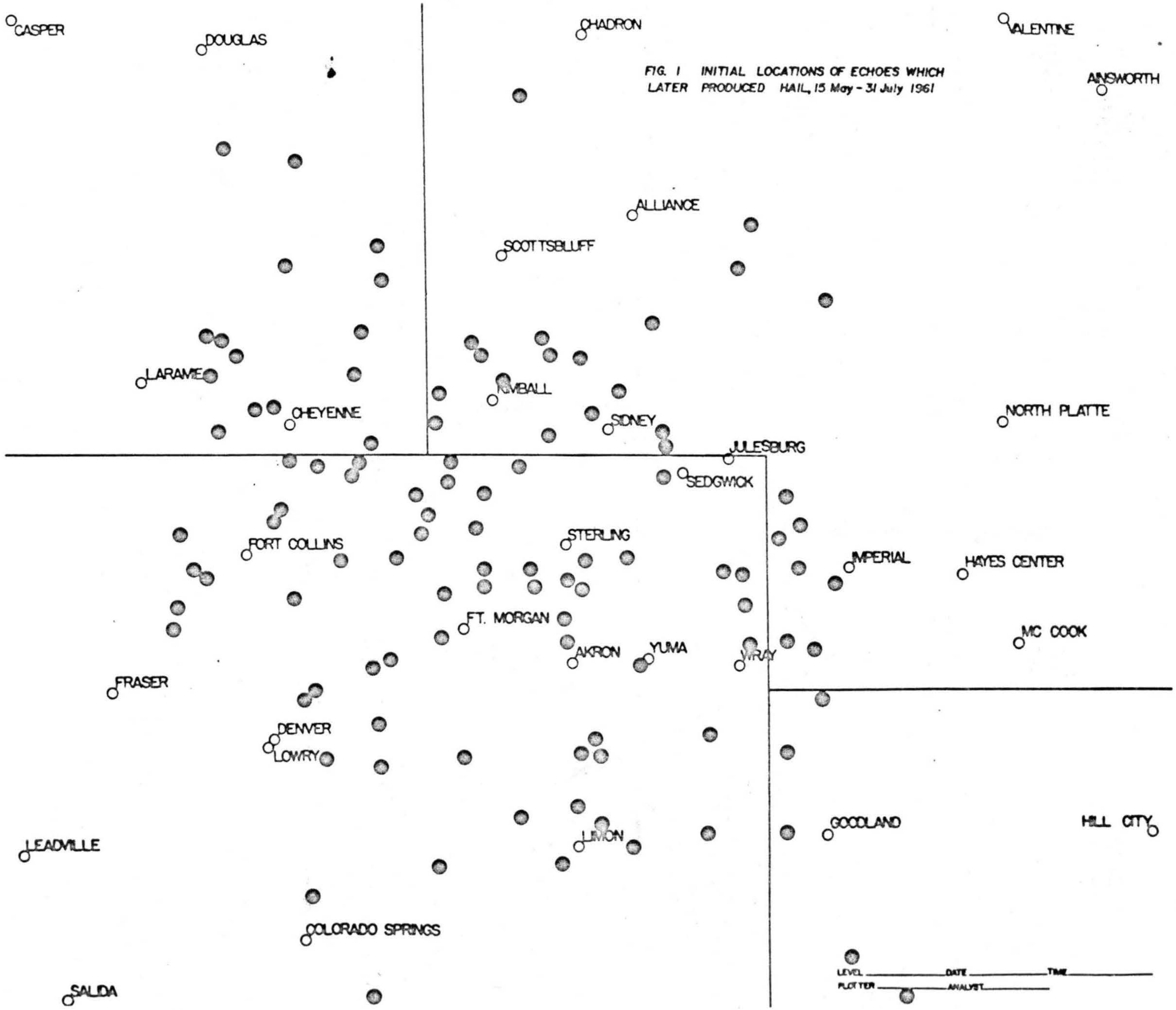

FIG. I INITIAL LOCATIONS OF ECHOES WHICH LATER PRODUCED HAIL, 15 May - 31 July 1961

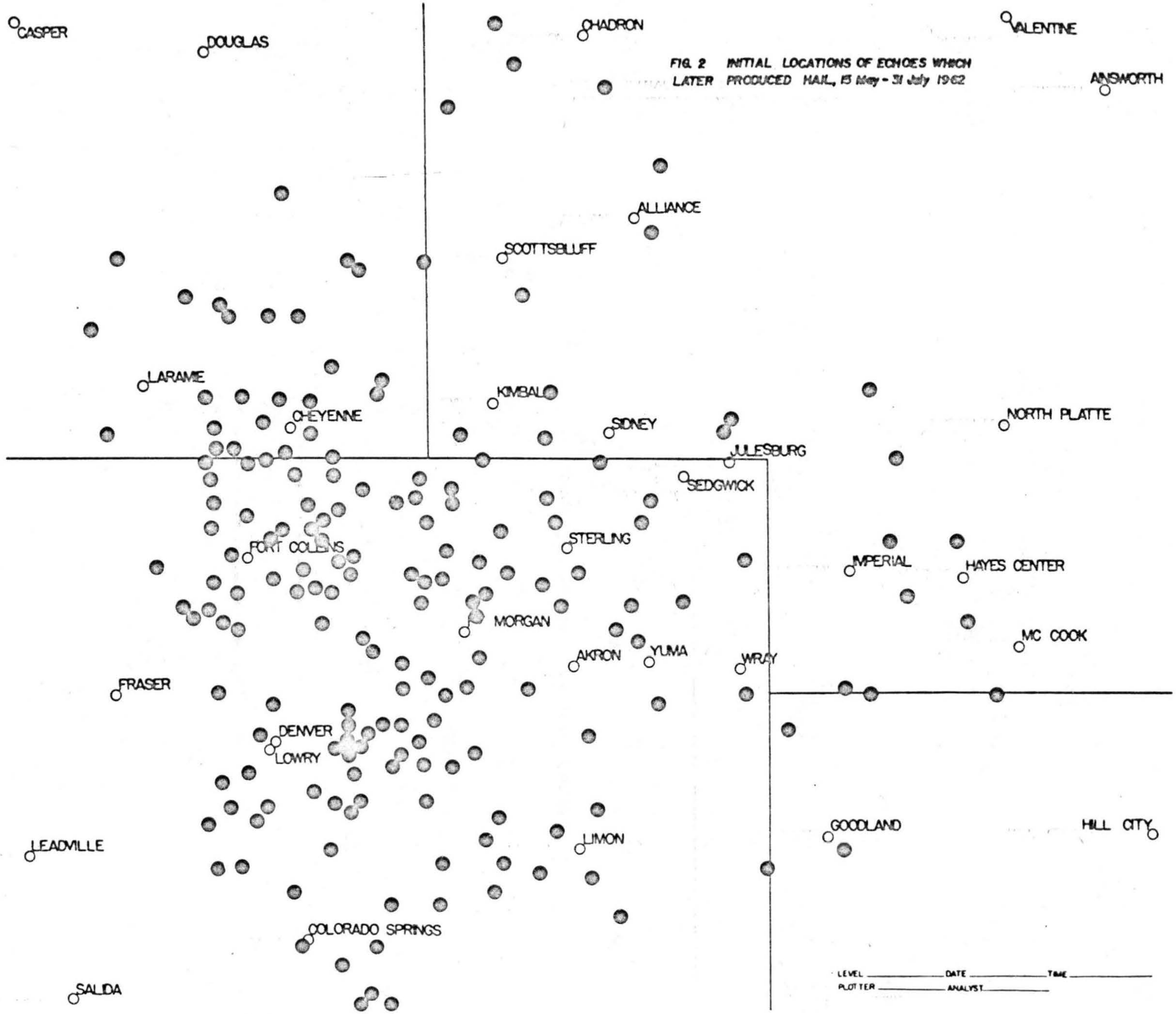

FIG. 2 INITIAL LOCATIONS OF ECHOES WHICH LATER PRODUCED HAIL, 15 May - 31 July 1962

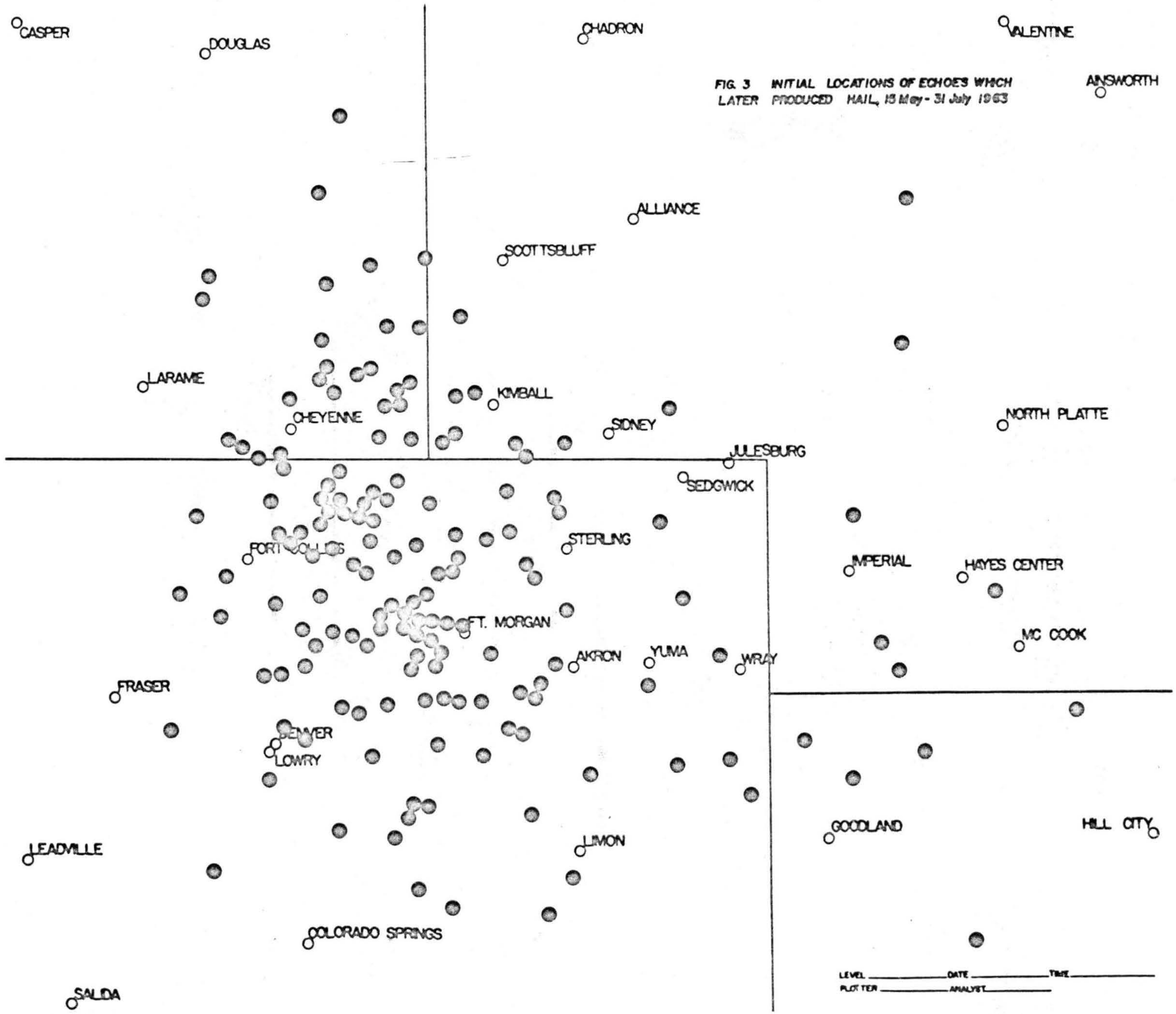

FIG. 3 INITIAL LOCATIONS OF ECHOES WHICH LATER PRODUCED HAIL, 15 May - 31 July 1963

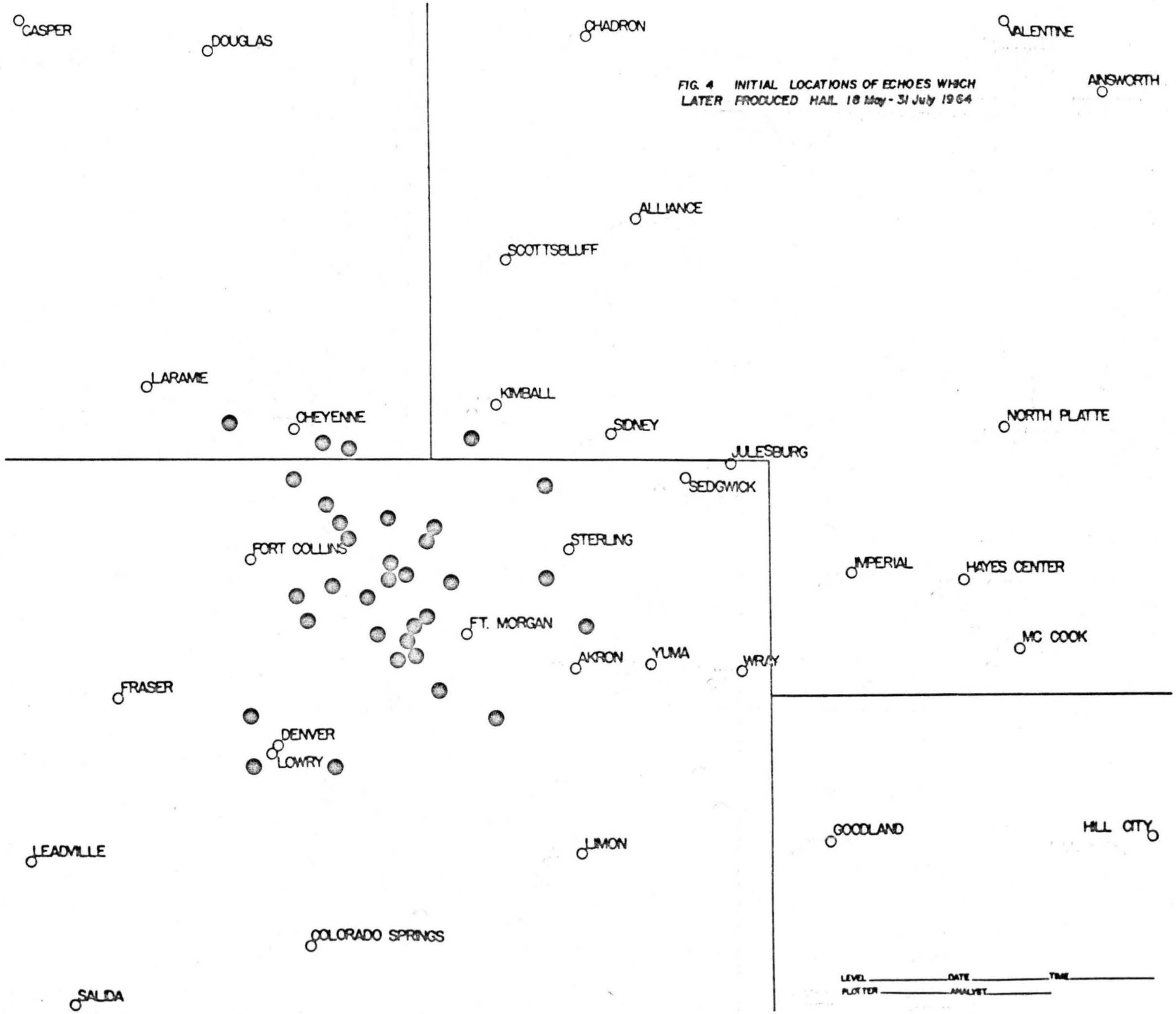

FIG. 4 INITIAL LOCATIONS OF ECHOES WHICH LATER PRODUCED HAIL 18 May - 31 July 1964

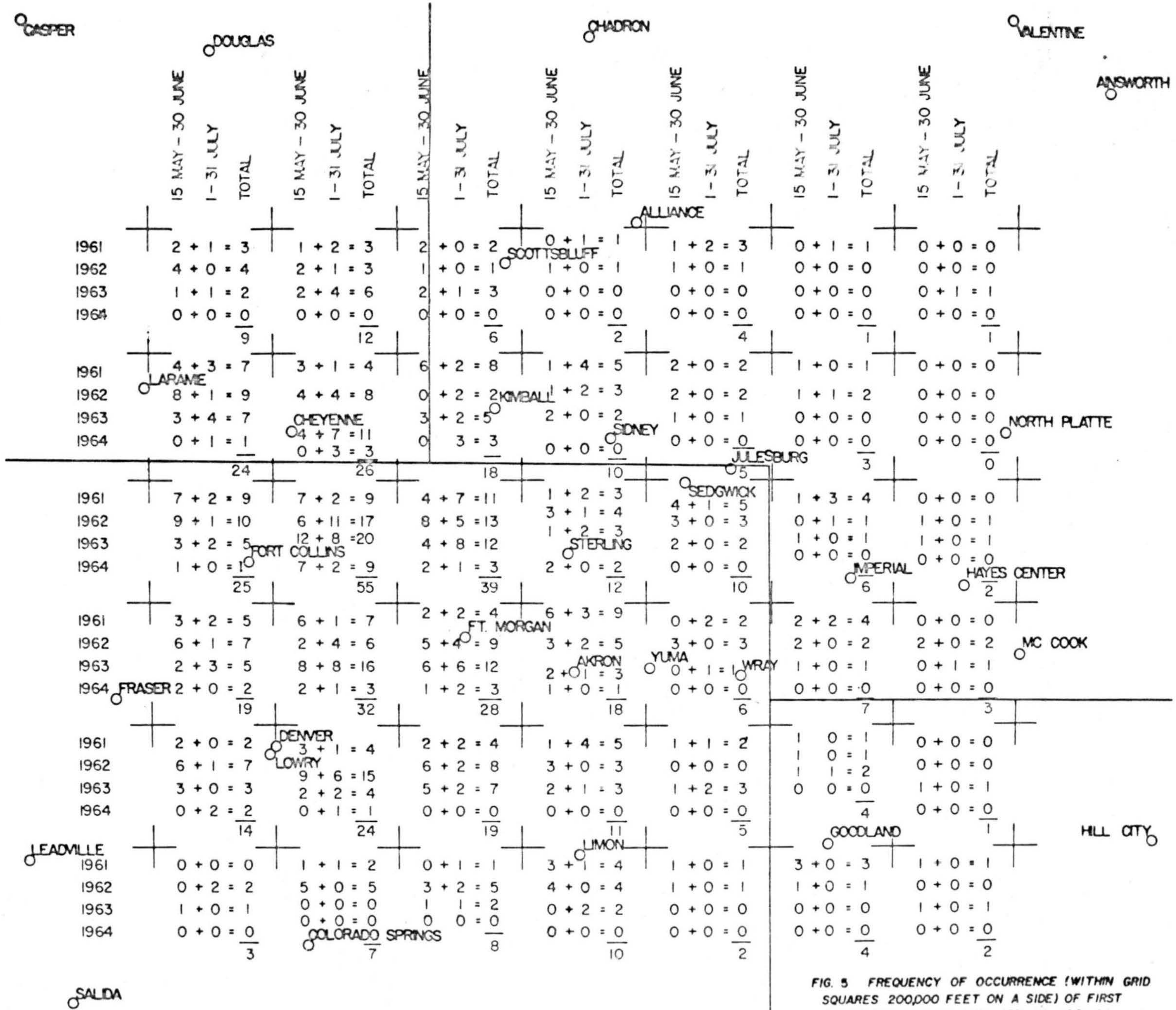

FIG. 5 FREQUENCY OF OCCURRENCE (WITHIN GRID SQUARES 200,000 FEET ON A SIDE) OF FIRST ECHOES THAT LATER PRODUCED HAIL, 1961-64

Table 1. Thunderstorm Hail Days and the Number of Echoes with Hail Within Range of the PPI Radar System at New Raymer, Colorado.

Period	Storm Days With Hail	Storm Days Without Hail	Total	Total Echoes Catalogued	Number of Echoes Which Were Known To Have Produced Hail on Ground
			1964		
18-31 May	3	5	8	4	4
1-15 June	6	2	8	57	10
16-30 June	3	4	7	13	5
1-15 July	5	4	9	28	7
16-31 July	5	8	13	36	7
Total	22	23	45	138	33
			1963		
15-31 May	9	1	10	117	32
1-15 June	8	0	8	81	42
16-30 June	3	3	6	25	8
1-15 July	6	3	9	110	30
16-31 July	11	2	13	165	43
Total	37	9	46	498	155
			1962		
15-31 May	11	6	17	140	34
1-15 June	9	6	15	186	37
16-30 June	10	4	14	194	55
1-15 July	11	4	15	106	28
16-31 July	11	3	14	126	29
Total	52	23	75	752	183
			1961		
15-31 May	10	2	12	98	26
1-15 June	13	0	13	124	42
16-30 June	7	2	9	79	21
1-15 July	8	4	12	104	43
16-31 July	9	2	11	99	17
Total	47	10	57	504	149

Colorado during 1964. Table 1 also reveals that the number of storm days with hail in 1963 was less than for the preceding years 1961 and 1962, while the number of echoes which were known to have produced hail in 1963 were not greatly different from 1961 and 1962. This apparent discrepancy is probably due to an improved verification system for determining hail occurrences for the years 1962 and 1963. The 1962 season was one of more severe weather, both in terms of a greater number of total echoes, and a greater number of echoes which were known to have produced hail at the ground.

Table 2 summarizes the origin and movement of echoes identified as producing hail on the ground. The greatest anomaly appears to be the number of echoes originating in Colorado and moving to Nebraska in 1962. By comparing the data for echoes originating in Nebraska and Wyoming and moving to Colorado and Kansas with the data for echoes originating in Colorado and Kansas and moving to Nebraska and Wyoming, it may be noted that in 1962 more storms traveled from south to north and fewer from north to south than in 1961, 1963, or 1964. The individual radar echo plots indicate that a general change of direction of storm movement exists since in May and June echoes move from the west or southwest, while in July they travel from the west or northwest; this is particularly true in 1962, an exceptionally strong hail year. It can be noted that, in 1964, 82 percent of the hail-bearing echoes originating in Colorado and failed to move to neighboring states.

Table 2. Origin and Movement of Echoes Identified as Producing Hail on the Ground

Echoes Originated In	Year	- Echoes Moved to -			
		Colorado	Kansas	Nebraska	Wyoming
Colorado	1961	56	12	21	3
	1962	67	5	52	8
	1963	84	5	22	1
	1964	27	0	1	1
Kansas	1961	0	7	0	0
	1962	0	1	3	0
	1963	0	3	2	0
	1964	0	0	0	0
Nebraska	1961	12	6	11	0
	1962	1	1	19	0
	1963	2	0	12	1
	1964	1	0	0	0
Wyoming	1961	13	0	7	1
	1962	7	0	14	5
	1963	2	0	16	6
	1964	3	0	0	0

Table 3 illustrates the percentage of total echoes that were identified as producing hail on the ground. The classification is for the years studied. The percentage of hailers to total number of echoes is seen to vary slightly from year to year; for example 31.1 percent in 1963 to 23.9 percent in 1964. It is surprising that the year of greatest hail occurrence, 1962, exhibits only 24 percent of the total number of echoes as being hailers. In summary, Table 3 shows that a slightly greater percentage than one out of four echoes tracked produced hail on the ground during the 1961-64 period.

Table 3. Percentage of Total Echoes Identified as Producing Hail on the Ground

Year	Total Echoes Catalogued	Number of Echoes Which were Known to Have Produced Hail on Ground	Percentage
1961	504	149	29.6
1962	752	189	24.3
1963	498	155	31.1
1964	138	38	23.9
Total	1892	520	27.5

Table 4 showns the average semi-monthly percentage during 1961-64 of total echoes that were identified as producing hail on the ground at some stage in their life cycle. The averaging period is divided into the first and last two weeks of each month of the hail-study season. The periods 16-30 June and 1-15 July show the greatest percentage of hailers with 28.6 percent and 31.0 percent, respectively. However, the total number of echoes tracked over these two periods is less than for any other corresponding period in Table 4. The interval 1-15 June, while exhibiting the greatest number of echoes (634), has a percentage of hailers of only 20 percent.

Table 4. Average Semi-Monthly Percentage of Total Echoes Identified as Producing Hail on the Ground During 1961-64

Period	Total Echoes Catalogued	Number of Echoes Which were Known to Have Produced Hail on Ground	Percentage
15-31 May	359	96	26.7
1-15 June	634	131	20.7
16-30 June	311	89	28.6
1-15 July	348	108	31.0
16-31 July	426	96	22.5

SUMMARY

The radar data from the period 1961-64 tend to confirm the following observations concerning the High Plains hailstorms in northeastern Colorado.

First, in 1962, there were more echoes which produced hail and these echoes developed closer to the Rocky Mountains. In 1961, 1963, and 1964 the genesis of hailstorms was more widely dispersed with the least number of hail echoes forming in 1964.

Second, the frequency of initial location of radar echoes which later produced hail is greater in areas of rapid change of elevation of terrain than in flat terrain, with the area of maximum frequency lying just to the east of Fort Collins, Colorado

Third, individual radar echo plots indicate a general change in direction of storm movement exists. In May and June echoes move from the west or southwest, while in July they travel from the west or northwest; this is particularly true in 1962, an exceptionally strong hail year. As would be expected with this type of movement, most echoes identified as producing hail on the ground when leaving Colorado enter Nebraska, and nearly one fourth of this number enter Kansas. Thus, it appears that movement from the southwest is characteristic of high hail frequency.

Fourth, the percentage of total number of echoes that are hailers is seen to vary only slightly from year to year.

Fifth, the periods 16-30 June and 1-15 July have the greatest percentage of hailers (28.6 percent and 31.0 percent, respectively) when compared to the total number of echoes catalogued. The interval 1-15 June showns the least percentage, 20 percent.

These data provide a substantial beginning of developing factural knowledge concerning the climatology of hailstorms and information on their physical characteristics. It may be possible to speculate here that the common features of 1961 and 1962 (years of unusually heavy hail damage) do not apply to 1963 and 1964 (years of less intense hail activity). With the addition of data from other seasons of varied hail intensity, this speculation could be more positively discussed.

The data in this report have been and will continue to be used as background for experiments on beneficial modification of hailstorms.

APPENDIX D

POSITION OF HAILFALL WITH RESPECT TO RADAR ECHOES

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APPENDIX D

POSITION OF HAILFALL WITH RESPECT TO RADAR ECHOES

This appendix is a summary of the Civil Engineering Report CER62RAS1, "Observational Data on the Position of Hailfall with Respect to Precipitation Cells," by R. A. Schleusener and T. J. Henderson, Colorado State University, expanded to include the period 1960-64.

Since the processes by which nature produces hailstones is not as yet clearly understood, it is of interest to examine records of the occurrence of hail to attempt to determine the pattern of hailfalls with respect to radar echoes.

Radar PPI data are available for northeastern Colorado for 1961-64 concurrent with information on hail from cooperative observers of the Colorado State University hail network. The positions of the hailfalls were classified into one of four sectors of a radar echo shown in Figure 1. These sectors were left front (LF), right front (RF), left rear (LR), and right rear (RR) relative to the movement of the radar echo. Projecting time-lapse movies of the radar PPI scope onto a plot of the reports from cooperator-observers, the position of the hailfall with respect to radar echoes could be determined. For each of the hailfalls that occurred in these four sectors, the following data were obtained from the surface network:

1. Maximum stone size (diameter, inches)
2. Most common stone size (diameter, inches)
3. Hail impact energy, ft-lbs/ft^2.

The mean and maximum values of these parameters for each of the four sectors and the number of cases within each sector are shown in Figure 1. For example, for hailfalls which occurred in the LF sector, the mean maximum stone size was 1/2 inch; the mean energy was 18 ft-lbs/ft^2, etc.

Each of the above parameters might be considered as a measure of the intensity of hail occurrence. Hence, the frequency of occurrence of maxima of the above parameters with each sector gives a measure of the relative frequency of hail within each sector. This frequency of occurrence is expressed in terms of the number of days per month that the maximum value of the parameter occurred. Figure 2 gives the frequency of maxima of the parameters of Figure 1 within each sector LF, LR, RF, and RR. No significance is attached to a comparison between front (F) and rear (R) sectors, since any error in the timing of reports from the network observers would cause an error in the sector classification.

Figures 1 and 2 show a favored tendency for hail on the right-hand side of the radar precipitation echo. This observation is consistent with the work of Newton (1960), Ludlam (1961), Fujita (1963), and Browning (1964) who have shown theoretical models of a thunderstorm with the maximum hail frequency on the right-hand side of the storm path. While the most common and maximum stone sizes show little variation between sectors (though larger in the right-hand sectors) it is the hail impact energy number that is considerably greater in the right-hand sectors, both in the mean and maxima. Figure 2 reveals that the number of days on which the maximum of the hail parameters did occur during 15-31 May 1961-64 is nearly equal for both the left and right-hand sectors. However, during June and July, the emphasis on frequency of occurrence of maxima of the hail parameters shifts strongly to the right-hand sector.

Thus, on the basis of the 1961-64 radar and cooperator data for northeastern Colorado, it appears that the right-hand side with respect to cell movement is favored for the occurrence of hailfall as characterized by the most common stone size, the maximum stone size, and the hail impact energy.

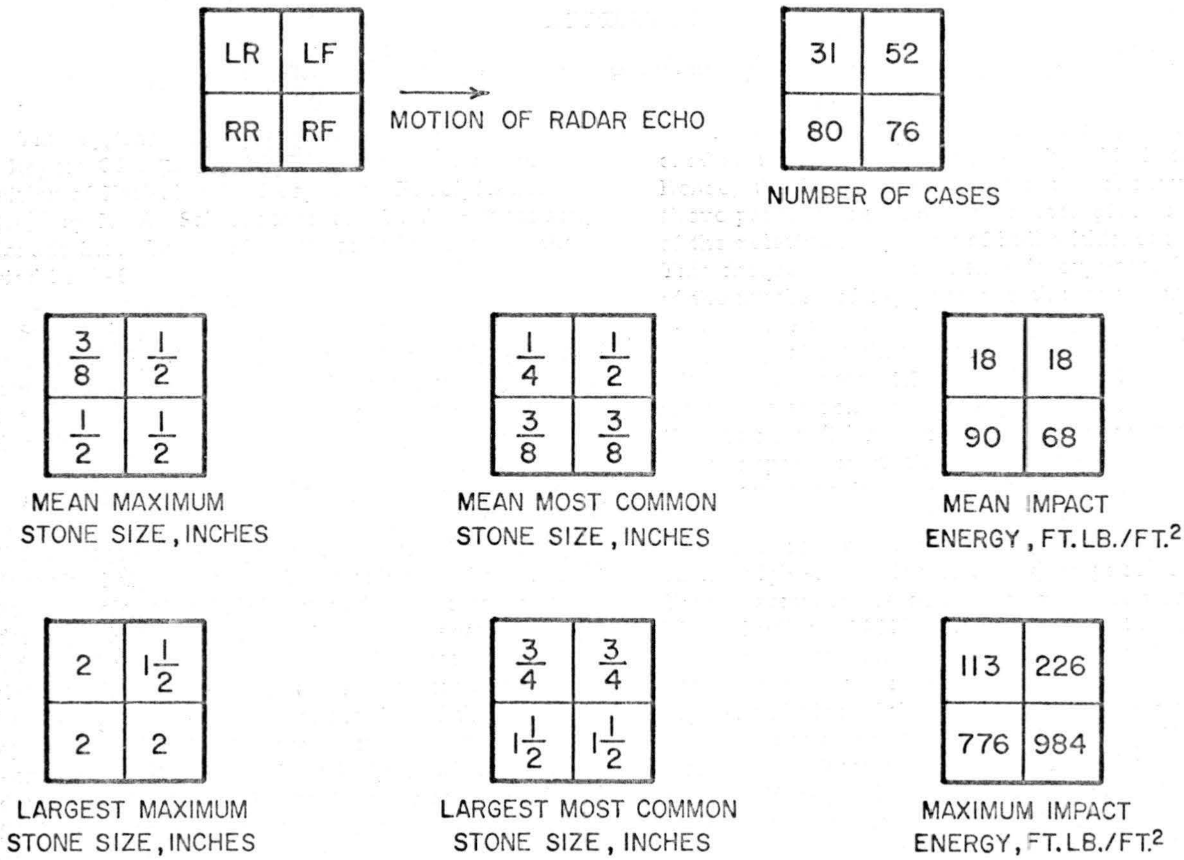

Figure 1. Characteristics of hailfalls falling within each of the four sectors (LR, LF, RR, and RF) of precipitation cells. CSU network, period 15 May-31 July, 1961-64.

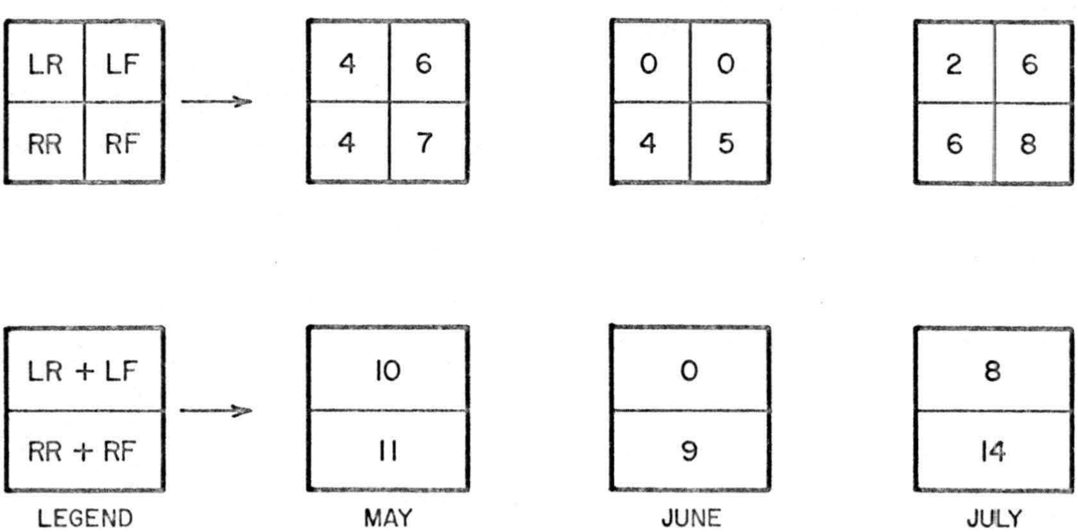

Figure 2. Frequency of occurrence (number of days) of maxima of the parameters (maximum stone size, most common stone size, and maximum impact energy) observed in each sector.

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APPENDIX E

PHYSICAL CHARACTERISTICS OF HAILSTONES

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DEFINITIONS

Term	Definition
Density	Mass per unit volume, gm cm^{-3}
Hailstone size	Hailstone diameter, cm
Large hailstones	Hailstones $>$ 3 cm diameter
Medium hailstones	Hailstones $\leq$ 1.5 $\leq$ hailstone diameter $\leq$ 3 cm
Small hailstones	Hailstone diameter $<$ 1.5 cm
Small ice crystals	Length dimension $\leq$ 0.3 cm
Large ice crystals	Length dimension $>$ .3 cm
Dry growth	Ice made up of small ice crystals
Wet growth	Ice made up of large ice crystals
Ice crystal volume ratio	Ratio of the volume of small ice crystals in a hailstone divided by the volume of large ice crystals in the hailstone
Embryo	Ice particle serving as the initial growth center of the hailstone
Embryo size	Embryo diameter for spheroidal embryos, and greatest length dimension for non-spheroidal embryos, cm.

INTRODUCTION

This appendix is a summary of the Civil Engineering Report CER63RRR38, "Analysis of Hailstones from Northeastern Colorado, 1962, " by Ron R. Robinson and Richard A. Schleusener, Colorado State University.

A large number of hailstones were collected in Northeastern Colorado during the summer of 1962, and certain measurements were made on these stones for the purpose of determining their physical characteristics. Measurements were made of the following: density, ice crystal volume ratio, number of wet and dry growth rings, hailstone size, shape of the hailstone, size of the embryo, and shape of the embryo.

PROCEDURES

A. Laboratory Procedures

While the slicing of hailstones for photographing is a tedious and exacting operation, with some practice, it is possible to slice and photograph four stones per hour.

For slicing a hailstone an apparatus was used which contained two hot wires attached to an inclined plane. These two wires could be adjusted to cut any thickness desired. The hailstone was frozen to a brass cart, which was rolled down the inclined plane. The hot wires made contact with the hailstone, and were adjusted to cut a hail slice three millimeters thick. The hailstone slice was then polished on a damp chamois to a final thickness of one millimeter. The slice was then ready to be photographed for air bubble structure.

Photographing a hailstone slice must be done at $0^{\circ}C$ or colder. To accomplish this, a photobox was mounted in a refrigerator. The photobox contains its own light source, cross-polarized lenses, and a Roleflex camera mounted in the top. For black and white pictures the film used was Pan-X-125. In taking the picture of the air bubble structure, only one polarized lens was used. The hail slice (one millimeter thick) was placed in the photobox, and a time exposure of five seconds was taken. The hail slice was then removed and further polished to a thickness of one tenth of a millimeter. Again the hailstone was placed in the photobox with two polarized lenses crossed. For a picture of the crystal structure of the hail slice, the time exposure was eighteen seconds.

The cross polarized lens let only the refracted light from the crystals pass through the camera, thus giving a picture of the crystal structure of the hail slice.

For taking color photographs of the crystal structure of hailstone slices, a 35 mm single lens reflex camera was used which contained a bellows attachment with magnification of 2.7. The bellows attachment made it possible to take detailed pictures of small hailstone slices. The photobox used for taking colored photographs was made of plexiglass, and had the dimensions of 6" x 6" x 12". For a light source, 700 watt photoflood light bulb was mounted in the base of the photobox. The hailstone slice was placed eight inches above the base of the photobox on a glass slide for photographing. One polarized lens was placed one inch above the glass slide which held the hailstone slice. The second polarized lens was placed 0.25 inch above the first. These lenses were crossed to allow only light refracted from the crystals to enter the camera. The top of the photobox was left open to allow the 35 mm reflex camera, which was mounted on a tripod, to be focused on the hailstone slice. The lens setting and lens speeds were variable, and depended on the magnification, thickness of the hailstone slice, and the power of the photoflood light in the photobox. The settings we used were: Lens opening f/16, lens speed 1/4 second, type of film Kodachrome II. The photoflood light could only be left burning for a few seconds, because the heat produced tended to melt the hailstone slice. This prohibited time exposures of any length.

Several methods may be used for measuring the densities of hailstones. The method that we used was introduced to us by the late Dr. Lyle V. Andrews of Nebraska State Teachers College. The materials needed were one gallon can, a gallon mixture of alcohol and water with the ratio of 25 percent alcohol to 75 percent water, ice, 250 milliliter flask, a bracket for holding the 250 milliliter flask, carbon tetrachloride (CCl_4) and paint thinner. The gallon can was used to hold the mixture of alcohol, water and ice. The 250 milliliter flask containing CCl_4 and paint thinner with a density of .885 was lowered into the solution of alcohol, water and ice. It was held in position by a four-pronged bracket (see Fig. 2). The mixture of alcohol and ice hold the 250 milliliter flask of CCl_4 and paint thinner just below $0^{\circ}C$; this allowed the hailstone to be placed into the solution of CCl_4 and paint thinner without melting. When a hailstone was placed into the 250 milliliter flask containing CCl_4 and paint thinner, it would either sink or float. If the hailstone floats, the density of the solution was decreased by adding paint thinner to the solution until the hailstone was suspended midway in the solution. If the hailstone sinks to the bottom of the solution of CCl_4 and paint thinner, then the density of the solution was increased by adding CCl_4 until the hailstone was suspended midway in the solution. Once the hailstone was suspended in the solution CCl_4 and paint thinner, the density of the solution (and thus that of the stone) was measured with a hydrometer. Once the density kit was in operation, it took very little time to measure densities of hailstones.

Density measurements were always made after all other physical operations were completed, since it is possible that the soaking of the hailstone in a solution of CCl_4 and paint thinner may change the inner structure of the stone.

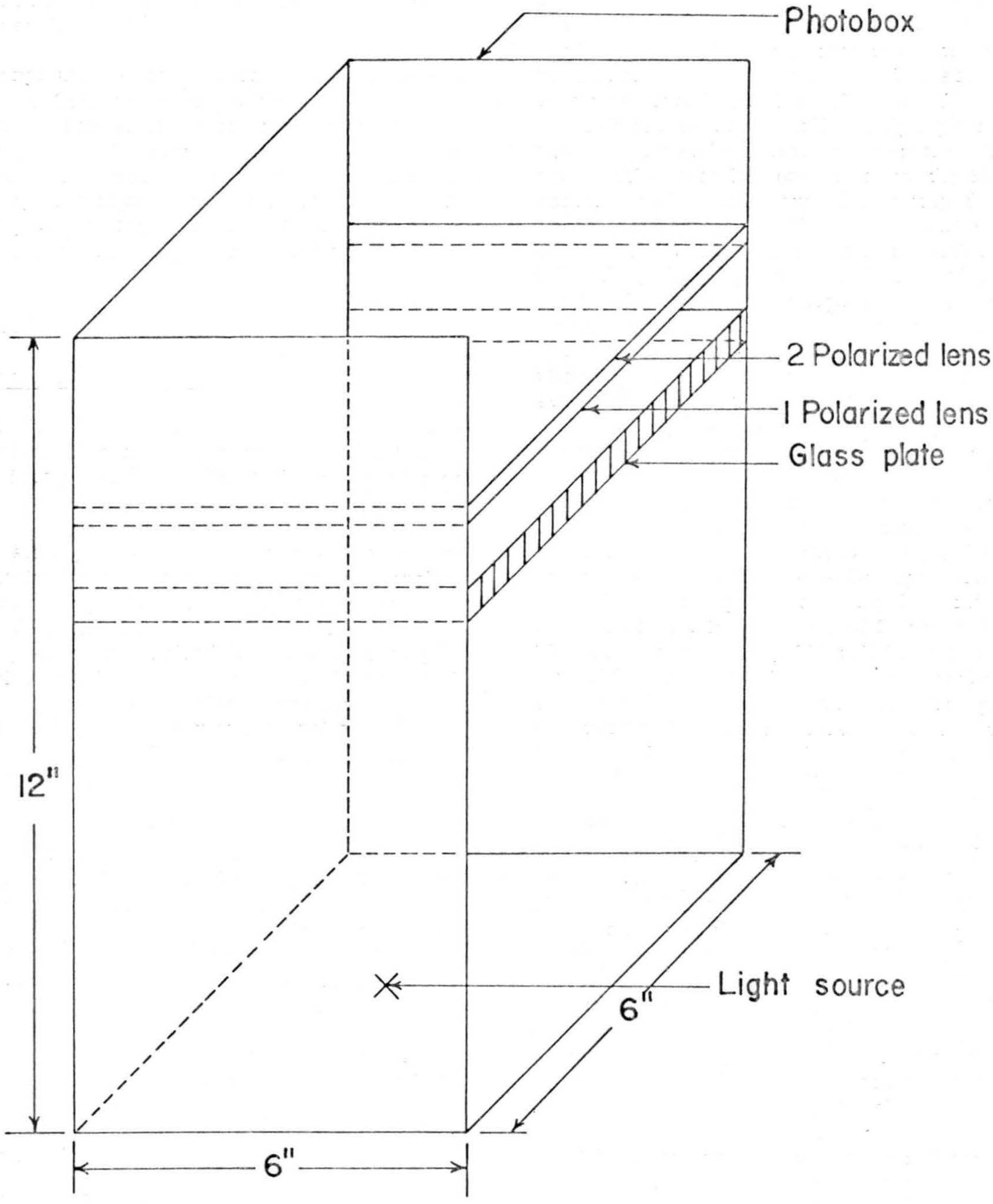

Figure 1. Photobox used for photographing hailstone slices. The photobox contains its own light source and cross-polarized lens.

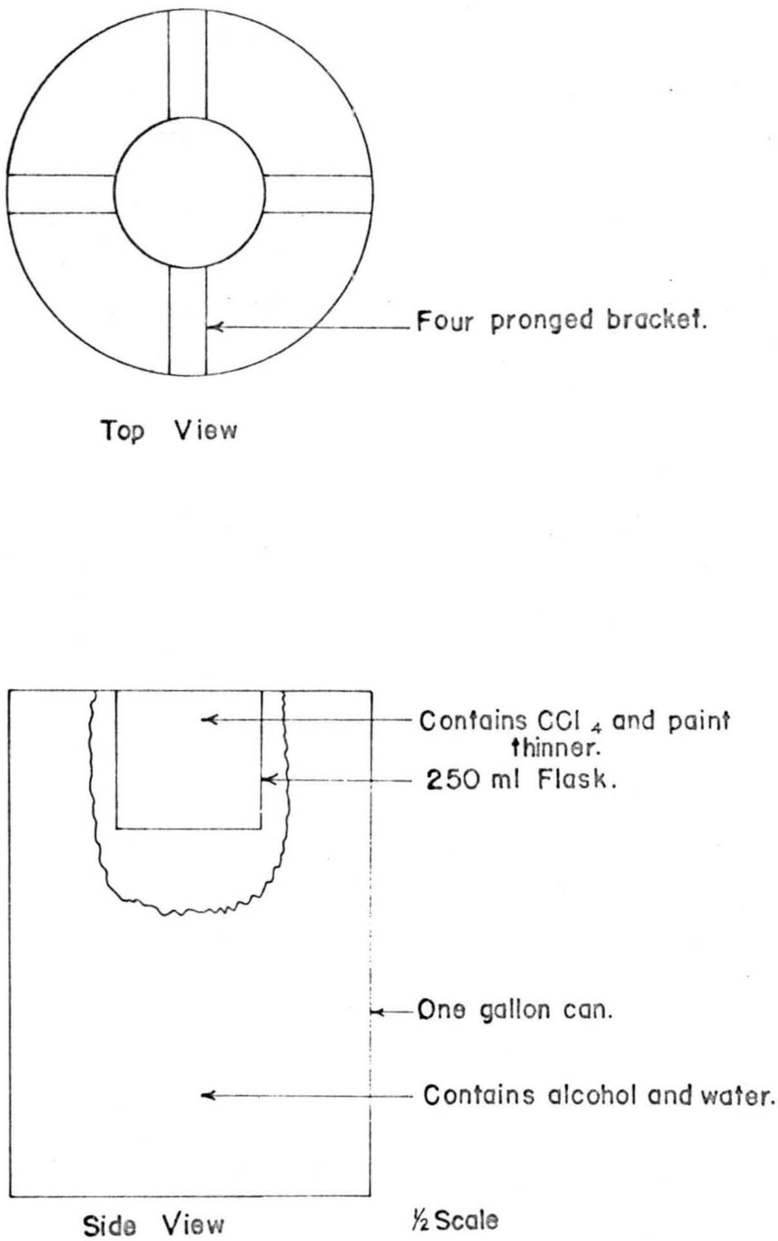

Figure 2. Density kit used for measuring the densities of hailstones.

B. Procedures in the Field

The majority of hailstones collected during the summer of 1962 were collected by cooperators in northeastern Colorado and southwestern Nebraska. When it hailed, the cooperators would collect a sample, store it in the refrigerator and mail a Report of Hail to Colorado State University. The hail samples would then be picked up and stored in a refrigerator.

A few hail samples were collected in cold boxes. These cold boxes consist of a small portable refrigerator with a canvas funnel mounted on top of the portable refrigerator in such a manner that the hailstones would fall inside the refrigerator. The advantage of catching hailstones in a cold box is that it allows for a more random sample. Cooperators tend to pick the largest and most unusual hailstones.

Slicing hailstones in the field was similar to the operation performed in the laboratory. However, there were a few minor changes. For a power supply, six volts were obtained from a car battery. To freeze the hailstones to the brass cart, the brass cart was cooled with dry ice. Other than these changes, the slicing was done in the same manner as in the laboratory procedures.

Due to the lack of a 110 volt power supply, the photobox was mounted in a styrofoam ice chest filled with dry ice. A portable flash unit was used in place of the 110 volt photoflood light mounted in the base of the photobox. Other than these changes the procedures for taking black and white air bubble and crystal pictures was the same as the procedures used in the laboratory.

It was discovered that due to the time element in taking colored photographs (focusing, changing cameras, etc.), it was difficult to take a colored picture, because the hailstone slice would start to melt.

Density measurements were made in the same manner as in the laboratory. Hailstones were used to cool the alcohol and water solution.

ANALYSIS OF HAILSTONE PARAMETERS

Nine different hailstone parameters were recorded from hailstones collected during the summer of 1962. These parameters are: size, shape, density, ice crystal volume ratio, number of wet growth rings, number of dry growth rings, radius of wet embryo, radius of dry embryo, and shape of embryo.

The diameter of the hailstone was measured and recorded in centimeters. If the hailstone was an ellipsoid or some odd shape, the greatest length of the hailstone was recorded.

The hailstone shapes were designated by five different classes. These classes were: spheroid, ellipsoid, saucer stone, conical stone, star stone. The saucer stone was a hailstone which had a shape similar to that of a saucer, and generally had a dimple on one or both faces. The conical hailstone had the shape of a cone or a tear drop. The star hailstone had the same basic shape of the classical shapes plus a very distinctive icicle type projection on the surface.

The density of the hailstones were measured with the density kit.

The ice crystal volume ratio was calculated from color slides of the hailstone slices when they were available, and from the black and white photos when the color slides were not available. When color slides were used, the volume of large ice crystals and small ice crystals was calculated by projecting the picture of a hailstone slice onto a circular grid. The assumption was made that every hailstone was made up of spherical or elliptical shells, consisting of either "small" or "large" ice crystals. With this assumption and using the grid to find the radius of the different ice crystal shells, the volume of shells composed of large and small ice crystals was calculated. The photograph of the hailstone slice was always centered on the grid at the embryo center, which is not necessarily the geometric center. If the shells of small and large ice crystals were elliptical, it was assumed that the shells were ellipsoids and the volume of the ellipsoids was calculated.

If there were no color slides available of a hailstone slice, a black and white crystal structure photo was used for calculating the volumes of "large" and "small" crystals. For black and white photos a plastic grid was used which contained fifteen circles with a common center. The grid was placed on the hail slice photograph and centered on the hailstone embryo. The radius of the circular shells of the small and large ice crystals was then calculated. Knowing the radius of each different shell the volume of the small and large ice crystal shells was calculated. The same assumptions were used that were used for calculating the volume of ice crystal shells using colored photos.

It was impossible to slice and photograph small hailstones, but they were cut with a razor blade and the ice crystal ratio determined by approximating the volumes of small and large ice crystals by looking at the sliced hailstone through a magnifying glass. The density and size were then measured.

The colored slides were much better than black and white photographs for calculating the volume of ice crystal shells, since it was possible to obtain large magnification factor of twelve was used. It was also much easier to distinguish between small and large ice crystals when using color slides.

The ice crystal volume ratio was determined for every hailstone analyzed after computations of the volumes of large and small crystals were completed.

From the colored slides and black and white photographs of the hailstone slices, the number of wet and dry growth rings was recorded.

From the colored photographs and the black and white photographs, the radius of the hailstone embryo was measured and it was determined whether the embryo consisted of large or small ice crystals. The shape of the embryo was recorded according to the category to which it belonged. These categories were the following: spherical, elliptical, and conical.

For every sample containing hailstones with a diameter equal to or greater than 1.17 centimeters, ten hailstones were analyzed. If there were less than ten hailstones in the hail sample, then as many stones were analyzed as possible. There were very few samples that did not have ten hailstones analyzed.

For every sample of hailstones with a diameter less than 1.27 centimeters, five hailstones were analyzed.

A total of 610 hailstones were analyzed for density, size, and ice crystal volume ratio. Of these, 345 were also analyzed for number of wet and dry growth rings, shape of hailstones, radius of wet or dry hailstone embryo, and the shape of the embryo.

The density measurements were considered to be measured to an accuracy of $\pm$ .002 gm/cm^3.

The accuracy of our stone data is as follows: hailstone size (diameter) $\pm$ 3 millimeters, and density $\pm$ .002.

RESULTS

A. Mean hailstone properties

The mean density of hailstones analyzed was .888, and the range was from .853 to .916. The hailstones with the lowest densities were predominantly rime ice. (Small ice crystals surrounded by many air bubbles.) The hailstones with the higher densities were almost completely composed of clear ice.

The mean diameter of the 610 hailstones analyzed was 1.83 centimeters.

The hailstones were separated into three different categories. The frequency of occurrence of hailstones of each category is shown in Table 1. Table 1 shows that 68 percent of the individual stones were small and medium size. However, these data are biased towards the occurrence of large hailstones, because the cooperators tend to collect the largest hailstones for a hail sample. Thus the data of Table 1 are not representative of the size distribution of all hailstones.

The frequency of occurrence of ice crystal volume ratios larger or smaller than unity was determined. The results are shown in Table 2. As may be seen from Table 2, 46 percent of the hailstones had ice crystal volume ratios greater than unity (hailstones containing a greater volume of small ice crystals) and 54 percent had ice crystal volume ratios smaller than unity (hailstones containing greater volume of large ice crystals).

Table 1. Frequency of occurrence of small, medium, and large hailstones for hailstones analyzed for density and size.

Diameter	May	# Samples	June	# Samples	July	# Samples	Total	Individual Stones
Small (1.5 cm)	68%	15	57%	12	53%	26	47%	302
Medium (1.5-3.0 cm)	27%	6	19%	4	14%	7	21%	139
Large (3.0 cm)	5%	1	24%	5	33%	16	32%	208
Total		22		21		49		649

Table 2. Frequency of occurrence of ice crystal volume ratios (r) smaller or larger than unity.

	TOTAL		MAY		JUNE		JULY	
		# Samples		# Samples		# Samples		# Samples
$r \leq 1$ (greater volume of large crystals)	54%	341	63%	14	29%	6	61%	30
$r > 1$ (greater volume of small crystals)	46%	293	37%	8	71%	15	39%	19
Total		634		22		21		49

The total volume of ice from the 610 hailstones that were analyzed was 13, 382 cm^3. This volume was calculated by assuming each hailstone to be a spheroid having a diameter equal to the greatest length. The volume of small ice crystals was 6, 415 cm^3, and the volume of the large ice crystals was 6, 967 cm^3. This indicates that during the summer there was a greater volume of hail formed from large ice crystals than from small ice crystals.

Analysis was made of 257 hailstones to determine the number of wet and dry growth rings. The average number for both wet and dry growth rings was found to be 1. 3. This indicates that the mean hailstone for 1962 contained about one dry growth ring and one wet growth ring. However, there were many hailstones with 3 growth rings and a few that contained as many as 8 growth rings.

The mean embryo diameter for 257 hailstones analyzed was 0. 8 centimeters. The range was from 0. 1 to 1. 6 centimeters.

Analysis of shape was made for 427 hailstones. The results are given in Table 3. Table 3 shows that the greatest number of hailstones were shaped as spheroids or ellipsoids. (Since it is sometimes difficult to distinguish the difference between a spheroid and an ellipsoid, the spheroids and ellipsoids may be considered as one shape. The other categories are very easily distinguishable from one another.)

Table 3. Frequency of occurrence of different shapes of hailstones.

	percent	Number of stones
Spheroids	56%	240
Ellipsoids	23%	96
Saucer	15%	66
Conical	3%	13
Star	3%	11
TOTAL	100%	426

Analysis of shape of embryo was made for 407 hailstones. The results are shown in Table 4. The "undetermined" shapes are the hailstones which had no distinguishable embryo. Table 4 shows that the majority of hailstone embryos were shaped as spheroids or ellipsoids.

Table 4. Frequency of occurrence of embryo shape for 407 hailstones.

	percent	Number of stones
Spheroids	68%	277
Ellipsoids	5%	19
Conical	5%	19
Undetermined	22%	92
TOTAL	100%	407

The type of embryo (wet or dry) was analyzed from 326 hailstones. Dry embryos were observed 54% of the time and wet embryos 46% of the time.

From the foregoing calculations, the mean hailstone structure for the summer of 1962 can be summarized as follows:

MEAN HAILSTONE STRUCTURE

Size (diameter	=	1.83 cm
Shape	=	Spheroid or Ellipsoid
Density	=	.888
Ice crystal volume ratio	=	1 or less
Number of dry growth rings	=	1
Number of wet growth rings	=	1
Diameter of embryo	=	0.8 cm
Shape of embryo	=	Spheroid or Ellipsoid

B. Hailstone parameter means and variability by months

The hailstone data were categorized by months. The mean and standard deviation of each parameter were computed by months, and comparisons made between months. The results are shown in Table 5.

Table 5. Mean hailstone parameters ($\bar{x}$), standard deviations (s), and number of samples (N)

Parameter	MAY			JUNE			JULY		
	$\bar{x}$	s	N	$\bar{x}$	s	N	$\bar{x}$	s	N
Density	.886	.015	145	.883	.014	107	.895	.012	358
Ice crystal ratio, r	38	24	145	4.8	8.8	107	4.6	30.6	358
Stone dia., cm	1.4	.6	145	1.9	1.8	107	2.2	1.7	358
Embryo dia. (dry) cm	0.6		75	0.6		67	0.8		310
Embryo dia. (wet) cm	0.8		75	1.0		67	0.8		310

From Table 5 it may be seen that the hailstones analyzed for the month of June had the lowest density and those analyzed for the month of July had the highest density. The difference between May and June (0.003) is not considered significant, since it is of the same order as the accuracy of measurement.

If the density measurements are correct, one would expect that the ice crystal ratio of the hailstones for May and June would be larger than the ice crystal ratio of hailstones for July. The greater the amount of small ice crystals in a hailstone the less dense the hailstone becomes because the small ice crystals are surrounded by many more air bubbles than are the large ice crystals. From Table 5 it may be seen that May and June do have larger ice crystal ratios than July, which indicates that the hailstones in May and June have proportionally more small ice crystals than in July.

Table 5 shows that the mean hailstone diameter was smallest in May (1.4 cm) and largest in July (2.2 cm). These data are consistent with the idea of thunderstorms in late June and early July having higher cloud tops and being more vigorous than the thunderstorms in May and early June.

Hailstone diameters were divided into three different size categories for May, June and July. The frequency of occurrence was then determined for each category for each month. (See Table 1.) From Table 1 it may be seen that May had the greatest frequency of small hail, and the lowest frequency for large hail. June had less small hail than May, and more large hail than May, and July had the least amount of small hail and the greatest amount of large hail. These data also lend support to the idea that late June and early July are the months with the most vigorous thunderstorms.

From Table 5 it may be seen that the diameter of the wet and dry embryos are uniformly distributed for the three months.

SIMPLE CORRELATIONS

A. Hailstone parameter correlations for all hailstones.

Using the 1620 IBM computer, simple correlations between hailstone size (diameter), density, ice crystal volume ratio, number of dry growth rings, number of wet growth rings, and diameter of embryo were made. These correlations were first made for all hailstones analyzed. The results are given in Table 6.

Looking at Table 6, we see that only two parameters (number of wet growth rings and the number of dry growth rings) have a significant correlation with hailstone diameter. There is significant negative correlation between ice crystal volume ratio and density. This result indicates that as the ice crystal volume ratio increases, the density of hailstones decreases. This result is reasonable, since a large ice crystal ratio should mean that there are more small ice crystals than large ice crystals, and therefore, a lower density.

Table 6. Simple correlation coefficients for all (257) hailstones

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	-0.026	0.145*	0.251**	-0.056	0.040
Ice crystal volume ratio		1.00	-0.123*	-0.045	-0.052	-0.164**
No. of wet growth rings			1.00	0.284**	-0.095	0.073
No. of dry growth rings				1.00	0.179**	0.011
Diameter of embryo					1.00	-.080
Density						1.00

* indicates significance at the 5 percent level
** indicates significance at the 1 percent level

There is a significant positive correlation between the number of wet growth rings and the number of dry growth rings.

There is a significant negative correlation between the number of dry growth rings and the diameter of the embryo.

B. Hailstone parameter correlations by months

Correlations of each hailstone parameter with other parameters were made for each month separately. The number of observations for each month was as follows: May = 27, June = 50, July = 180. The results are given in Tables 7, 8 and 9.

Table 7. Simple correlation coefficients for May (27) hailstones.

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	.433	0.200	0.115	0.175	0.186
Ice crystal volume ratio		1.00	-0.217	0.077	-0.227	0.273
No. of wet growth rings			1.00	0.341*	-0.318	0.292
No. of dry growth rings				1.00	-0.373	0.047
Diameter of embryo					1.00	0.220
Density						1.00

* Indicates significance at the 5 percent level.

Table 8. Simple correlation coefficients for June (50) hailstones.

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	0.170	0.177	0.347*	0.038	0.549**
Ice crystal volume ratio		1.00	-0.203	0.212	-0.103	-0.161
No. of wet growth rings			1.00	0.081	-0.167	-0.093
No. of dry growth rings				1.00	-0.452**	-0.033
Diameter of embryo					1.00	-0.307*
Density						1.00

* Indicates significance at the 5 percent level.
** Indicates significance at the 1 percent level.

Table 9. Simple correlation coefficients for July (180) hailstones.

	Diameter	Ratio	No. of wet growth rings	No. of dry growth rings	Diameter of embryo	Density
Diameter	1.00	-0.066	0.171*	0.204**	-0.109	0.246**
Ratio		1.00	-0.113	-0.068	-0.056	-0.196**
No. of wet growth rings			1.00	0.368**	-0.054	0.057
No. of dry growth rings				1.00	-0.093	0.068
Diameter of embryo					1.00	0.041
Density						1.00

* Indicates significance at the 5 percent level.
** Indicates significance at the 1 percent level.

Looking at Tables 7, 8 and 9 it may seem that the significant correlations are as follows:

May

Diameter vs ice crystal volume ratio
Number of wet growth rings vs number of dry growth rings.

June

Diameter vs density
Diameter vs number of dry growth rings
Number of dry growth rings vs diameter of embryo (negative)
Diameter of the embryo vs density (negative)

July

Diameter vs number of wet growth rings
Diameter vs number of dry growth rings
Ice crystal volume vs density (negative)
Number of wet growth rings vs number of dry growth rings

ANALYSIS OF VARIANCE

A. F tests

An analysis of variance was performed to determine if there were significant differences in hailstone diameter between months. The results indicated highly significant differences (at the 1 percent level).

A similar computation indicated highly significant differences in hailstone density between months.

B. Students "t" tests

Students "t" tests were then applied to determine which of the above factors were significantly different when considered on an individual basis.

The results of this test applied to the parameter of hailstone diameter indicated that the only significant difference was between May vs June and July.

The results of the test applied to the hailstone density also indicated a significant difference between May vs June and July.

SUMMARY AND CONCLUSIONS

Eight hailstone parameters were determined from samples of hail collected in Colorado during the summer of 1962. The mean and variance of each hailstone parameter was determined by various groupings. Correlation coefficients between the hailstone parameters were determined. An analysis of variance using the "F" test was applied to determine significant difference of hailstone parameters between months and geographic areas.

The average hailstone for the summer of 1962 had the following mean parameters:

Size (diameter)	=	1.83 centimeters
Shape hailstone	=	Spheroid or Ellipsoid
Density	=	.888
Ice crystal volume ratio	=	1
Number of dry growth rings	=	1
Number of wet growth rings	=	1
Diameter of embryo	=	0.8 centimeters
Shape of embryo	=	Spheroid or Ellipsoid

On a seasonal basis, May had the smallest mean hailstone diameter and July had the largest. June had the least dense hailstones and July had the most dense hailstones. The other hailstone parameters (ice crystal volume ratio, embryo diameter, and the number of wet and dry growth rings) varied little during the summer.

An analysis of variance using the F test and students "t" tests showed that there were significant seasonal differences in hailstone diameter and density.

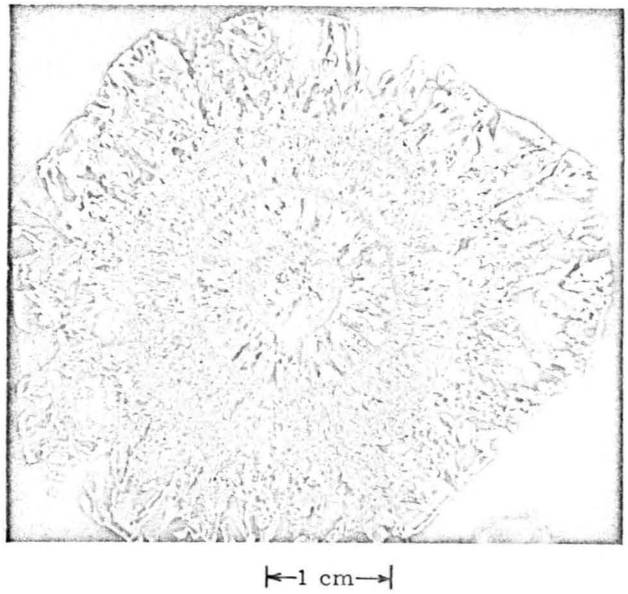

Figure 3. Cross-section of a hailstone slice under cross-polarized light showing concentric distributions of large and small ice crystals.

APPENDIX F

THE EFFECT OF TERRAIN AND LOW-LEVEL WIND ON HAIL GENESIS

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INTRODUCTION

This appendix is a summary of preliminary work done by Loren Blandin and first published in the Civil Engineering Report CER61RAS59, "Characteristics of Hailstorms in the Colorado State University Network, 1960-61", by Richard A. Schleusener and Lewis O. Grant, Colorado State University; the work has been expanded to include the 1962 season.

In 1961 and 1962 a study was made in an effort to determine what effect the topography of northeastern Colorado had on the genesis locations of storms that later became identified as hailers.

METHOD

New echoes that developed within a 75-nautical mile radius of the Atmospherics Incorporated radar located at New Raymer, Colorado, during the first two hours of operation each day were examined in a study of the effects of terrain and low-level wind flow. From data obtained within the Colorado State University hail network and from examination of the crop-hail insurance claims these echoes were categorized as hailers or non-hailers. Echoes that were first reported as lines, or groups of cells, or cells that developed in close proximity to an earlier cell were not included in this analysis.

To examine possible effects of terrain on the genesis of these echoes, a genesis point was determined arbitrarily ten miles up-motion from the first radar echo. At this genesis point and at four additional points located in the cardinal directions on a twenty mile radius from the genesis point, a topographic lift factor was computed. This factor is a measure of the amount of low-level lift produced by topographic effects. The wind direction and velocity at 8, 000 feet msl were determined from a combination of the standard upper-level wind reports and the special pilot balloon observations taken regularly at 0800 MST at Sterling, Colorado. Topographic lift was computed by determining elevation differences between the upwind and downwind sides of a point along the 8, 000 foot wind direction. "Topographic lift" equals the elevation differences in feet per mile times the wind velocity in miles per hour.

The 1962 topographic lift study followed the 1961 pilot study quite closely, the major change being that the computations were accomplished by use of the IBM 1620 computer. The most important change in the method of calculation was a different technique of obtaining elevations. In 1961, individual elevations were read directly from the topographical map. In 1962, the area of interest was divided into squares which were 25, 000 feet on a side. The boundaries of these squares were determined from the Colorado Plane Coordinate System, Northern Zone; and each square was given a pair of coordinates according to this system. Then a mean elevation (to the nearest ten feet) was determined for each square by a visual integration of the elevations within that square.

RESULTS

For both 1961 and 1962, a comparison was then made of this lift parameter at the genesis point and with the average of the four surrounding points. Results of this 1961-62 study are shown in Table 1. A positive difference indicates that the topographic lift factor was higher over the area where the radar echo first developed than for an average of the surrounding points. Table 1 shows no signigicant difference in the topographic lift parameter at the genesis point as compared to the average of the four surrounding points. It is concluded that it is not possible to use the topographic lift parameter for prediction of areas of first development of hail-producing echoes.

TABLE 1. Difference in Topographic Lift Parameter, ft/hr, (Genesis Point Minus Average of Four Surrounding Points), and Chi Square Significant Difference Test.

Elevation Class	Number of Cases		Chi Square	
	Positive	Negative	Value	Probability
I All Echoes	95	77	1.02	>.995
II Below 7000 ft. msl	53	45	.38	>.995
III Below 5000 ft. msl	38	20	2.78	>.955

APPENDIX G

METEOROLOGICAL PARAMETERS AND HAIL OCCURRENCES

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In this section of the report, certain meteorological parameters are related to the occurrence of hailfall. A comparison is made of the intensity of hailfall during the 1960-64 period and the mean flow patterns at 700 mb, the presence of a jet maximum overhead and the occurrence of hail, and the relationship of the 500 mb west wind and the occurrence of hail in the lee of the Rockies. Development of a hail forecast equation is also discussed.

A. MEAN 700-MB FLOW PATTERNS

Using the information obtained from the Colorado State University cooperator network, the years 1960-64 are classified according to the intensity of hailfall. This classification is based on the number of reports of hail received, the number of damaged passive hail indicators, the most common stone size observed during the season, the maximum stone size observed during the season, and the maximum hail impact energy recorded. Table 1 shows the ranking of the years 1960-64 according to these hail severity parameters. The results of this classification yield the following ranking according to intensity: 1962, 1960, 1961, 1964, and 1963. The most severe hail year was 1962. There was little difference in intensity among the other three years.

Figures 1-5 show the mean 700-mb charts for the period 15 May - 31 July for the individual years 1960-64. These composite mean 700-mb charts for the period 15 May - 31 July were derived from the individual mean charts for May, June, and July over the 1960-64 seasons (Monthly Weather Review, 1960-64). These mean charts illustrate the contour heights (in tens of feet) for the western United States, and reveal the position of the long-wave trough during the hail season.

Figure 1 gives the mean 700 mb pattern for the most intense hail season, 1962. It can be seen that the location of the long-wave trough lies approximately 400 nautical miles west of northeastern Colorado. No other year in the 1960-64 period has had such a favorable mean position of the long-wave trough. This position of the mean long-wave trough is favorable for hail-bearing thunderstorms in northeastern Colorado.

In 1960, the 700 mb mean contour pattern is somewhat different. In Figure 2 it can be seen that the long-wave trough position was displaced east of northeastern Colorado, allowing northwesterly flow to dominate. It may be premised here that the thunderstorm formation was the result of surface airmass heating rather than general dynamic lifting of unstable air which was exhibited in 1962. Also, some westward deviation of the long-wave trough from its mean position just east of northeastern Colorado could offer an explanation for thunderstorm activity, since thunderstorm activity is known to occur in the center and slightly west of trough lines.

The year 1961 marks the beginning of changes in the upper flow patterns and corresponding decreases in hail intensity for the three remaining years of 1961, 1964, and 1963. During the 1961 hail season, anticyclonic flow patterns developed over northeastern Colorado, as given in Figure 3. This ridging is believed to be the result of the intensification and formation of long-wave trough systems 1,000 nautical miles to the west and 1,500 nautical miles to the west of Colorado. The subtropical high pressure zone was not as influential as will be shown for 1963 and 1964; however, the mean flow at 700 mb suggests mean subsiding motions and an explanation for the absence of heavy hail damage from hail-bearing thunderstorms in 1961.

The westward intrusion of the subtropical high pressure southeast of Colorado is a primary feature of the 1964 700-mb mean flow, shown in Figure 4. The long-wave trough location is over the eastern Pacific Ocean. While there was evidence of southwesterly flow over northeastern Colorado, the effect of subsiding air due to the subtropical anticyclone overcame any tendency for large areas of upward vertical motion. A similar flow pattern at 700 mb, shown in Figure 5, was also witnessed during the 1963 season. The intrusion of the subtropical anticyclone was slightly weaker in 1963. Thunderstorm activity in both 1963 and 1964 was limited to times of passages of moderate-strength short waves over northeastern Colorado. Consequently, the entire Plains area of Colorado was subjected to severe drought conditions during these years with both rainfall and hailfall much below normal.

Table 1. Ranking of years 1960-64 according to hail severity parameters.

Percentage of possible number of cooperator reports		Percentage of possible number of damaged hail indicators		Seasonal average most common stone size diameter (in.)		Seasonal average maximum stone size diameter (in.)		Maximum hail impact energy ft-lb/ft^2	
1962	1.8	1962	1.0	1962	3/4	1960	7/8	1964	2800
1961	1.3	1963	0.7	1960	5/8	1962	3/4	1961	2660
1960	1.2	1964	0.3	1963	1/2	1963	3/4	1962	2100
1964	0.6	1961	0.3	1964	1/2	1964	3/4	1960	2100
1963	0.5	1960	0.2	1961	1/2	1961	3/4	1963	700

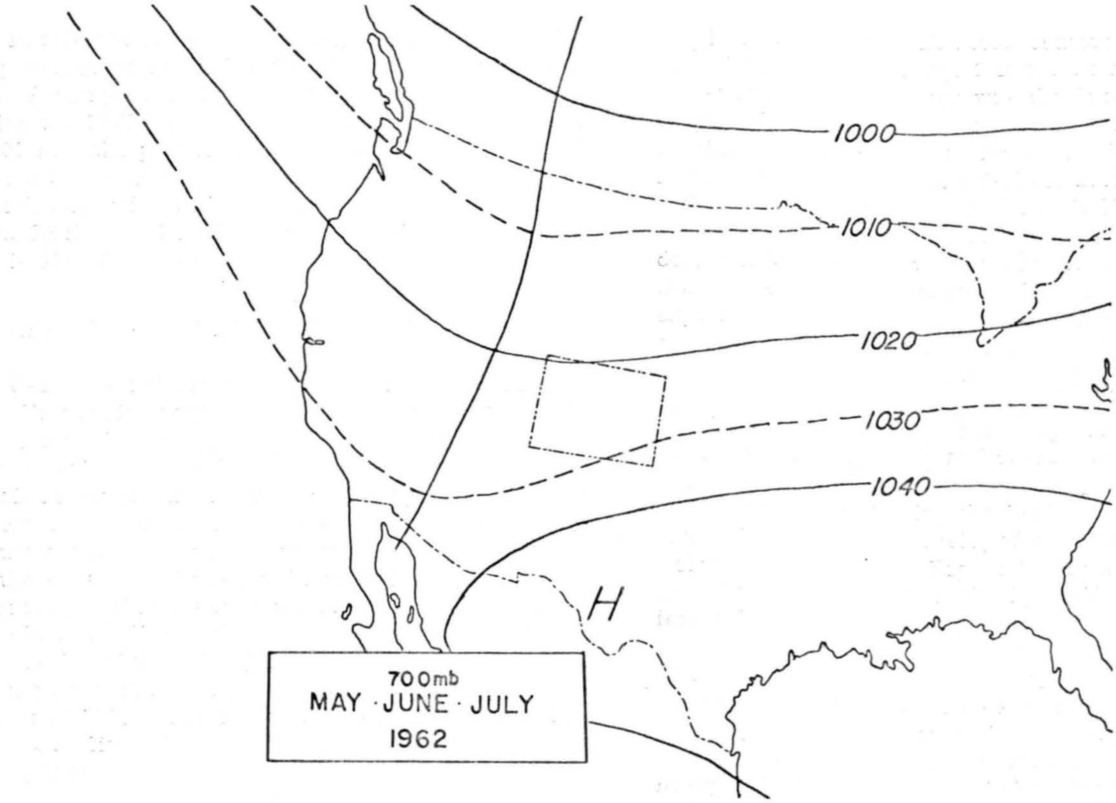

Figure 1. The mean 700-mb chart for the period 15 May-31 July, 1962. Contour heights are in tens of feet.

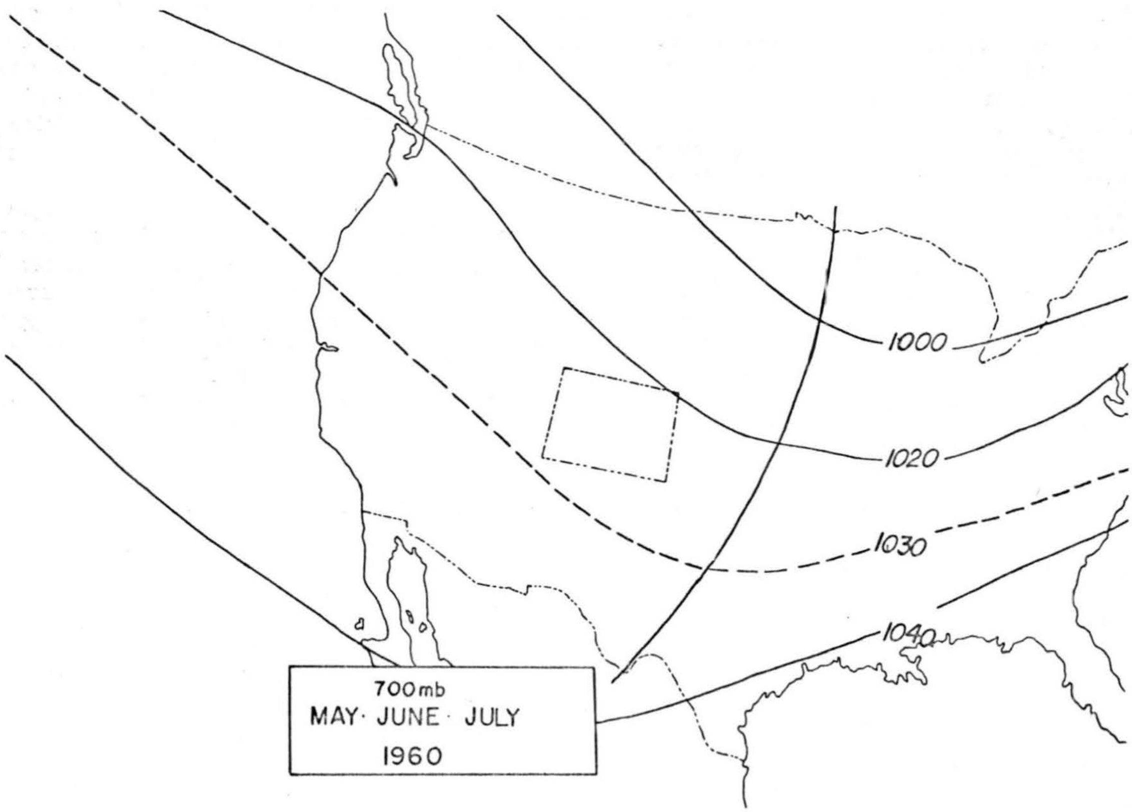

Figure 2. The mean 700-mb chart for the period 15 May-31 July, 1960. Contour heights are in tens of feet.

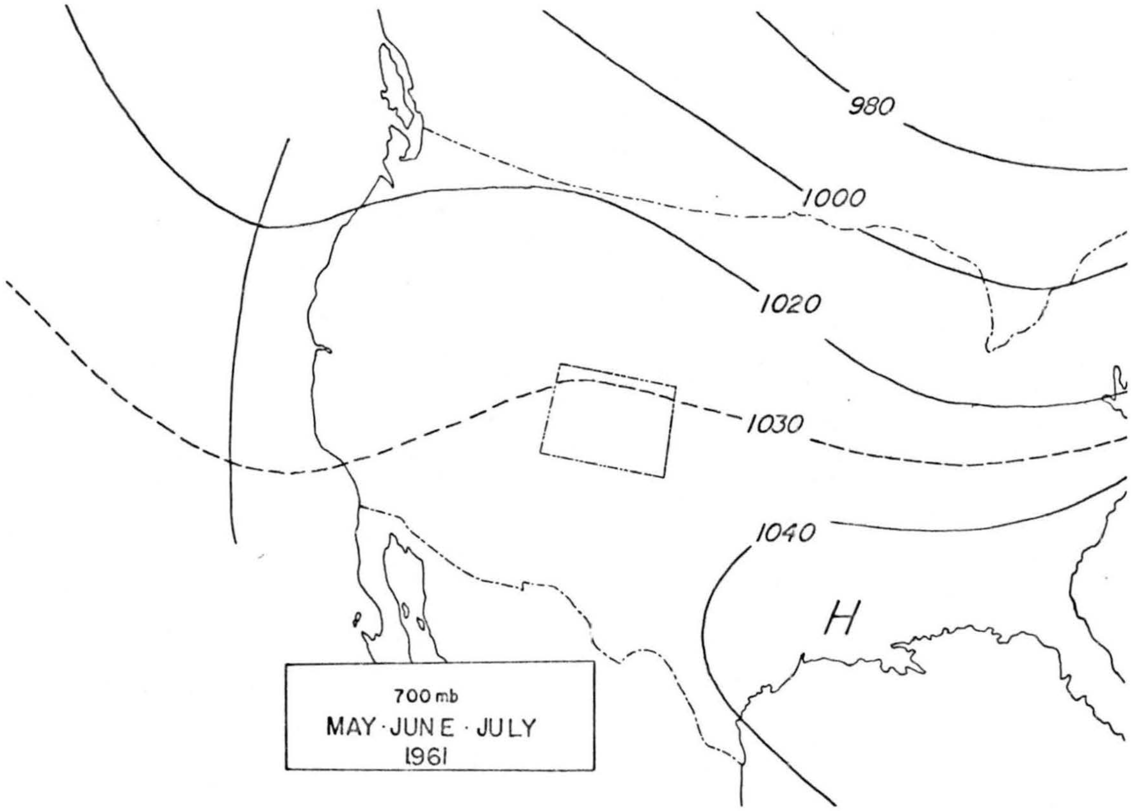

Figure 3. The mean 700-mb chart for the period 15 May-31 July, 1961. Contour heights are in tens of feet.

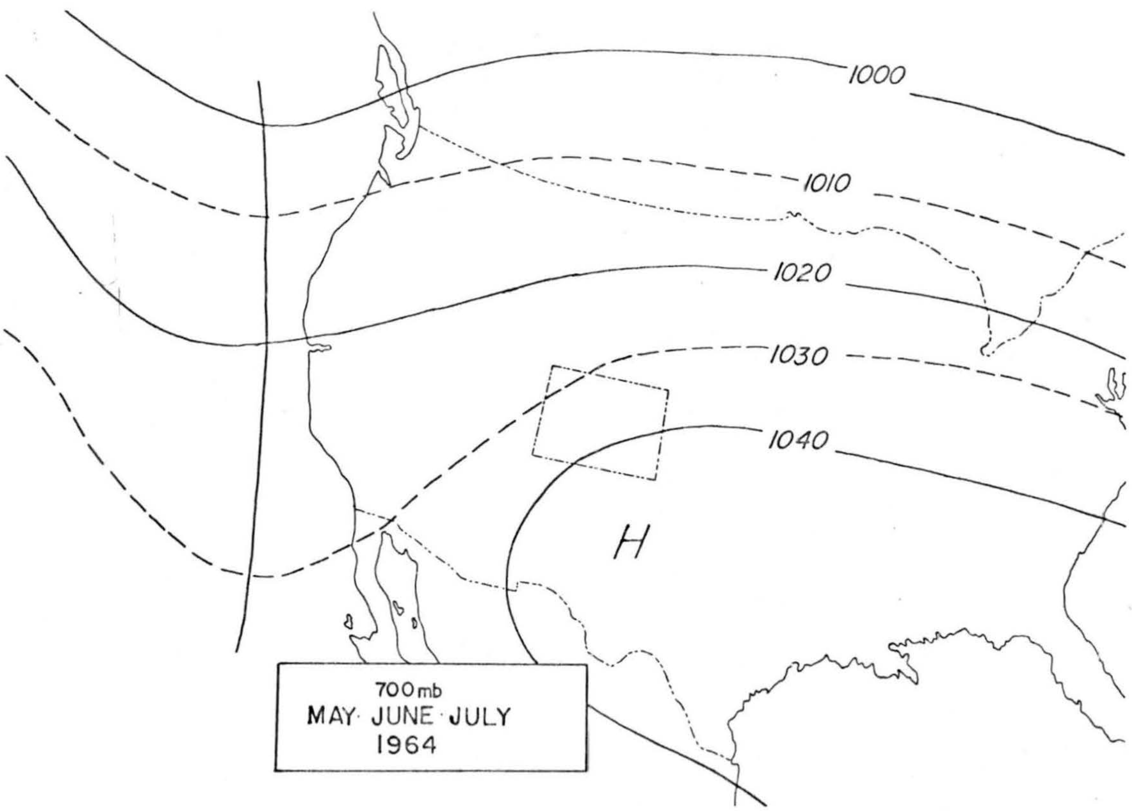

Figure 4. The mean 700-mb chart for the period 15 May-31 July, 1964. Contour heights are in tens of feet.

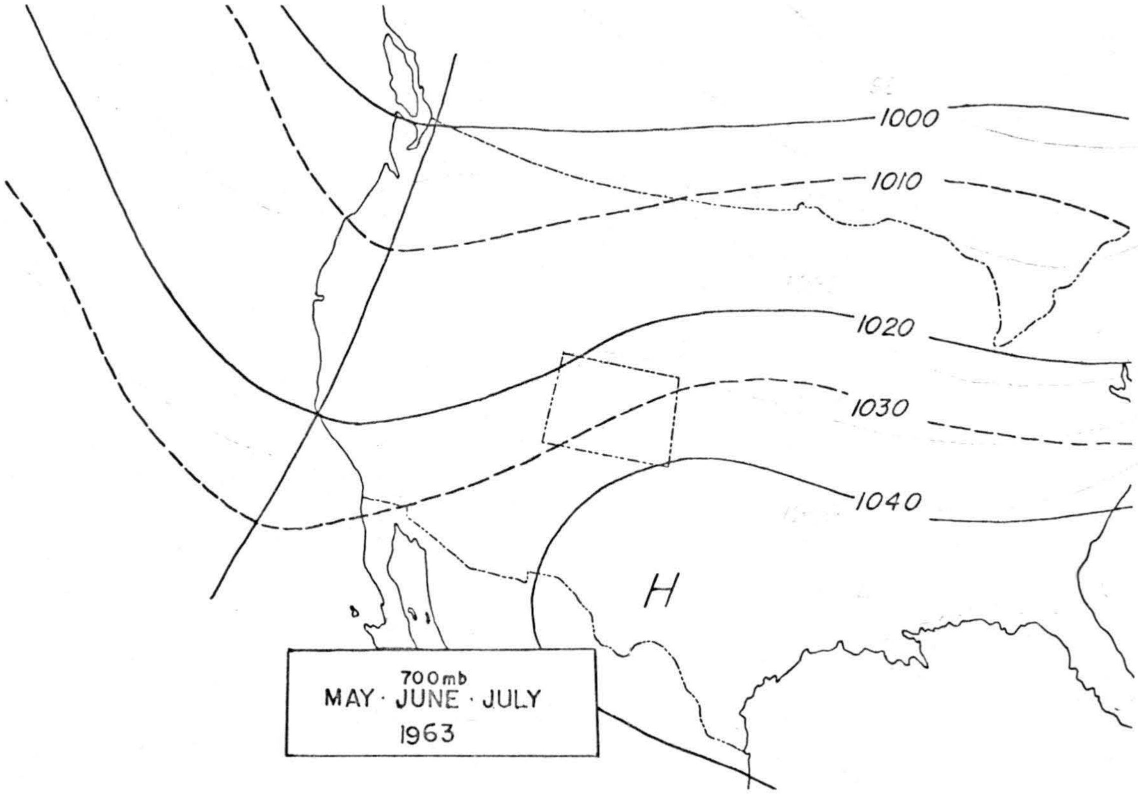

Figure 5. The mean 700-mb chart for the period 15 May-31 July, 1963. Contour heights are in tens of feet.

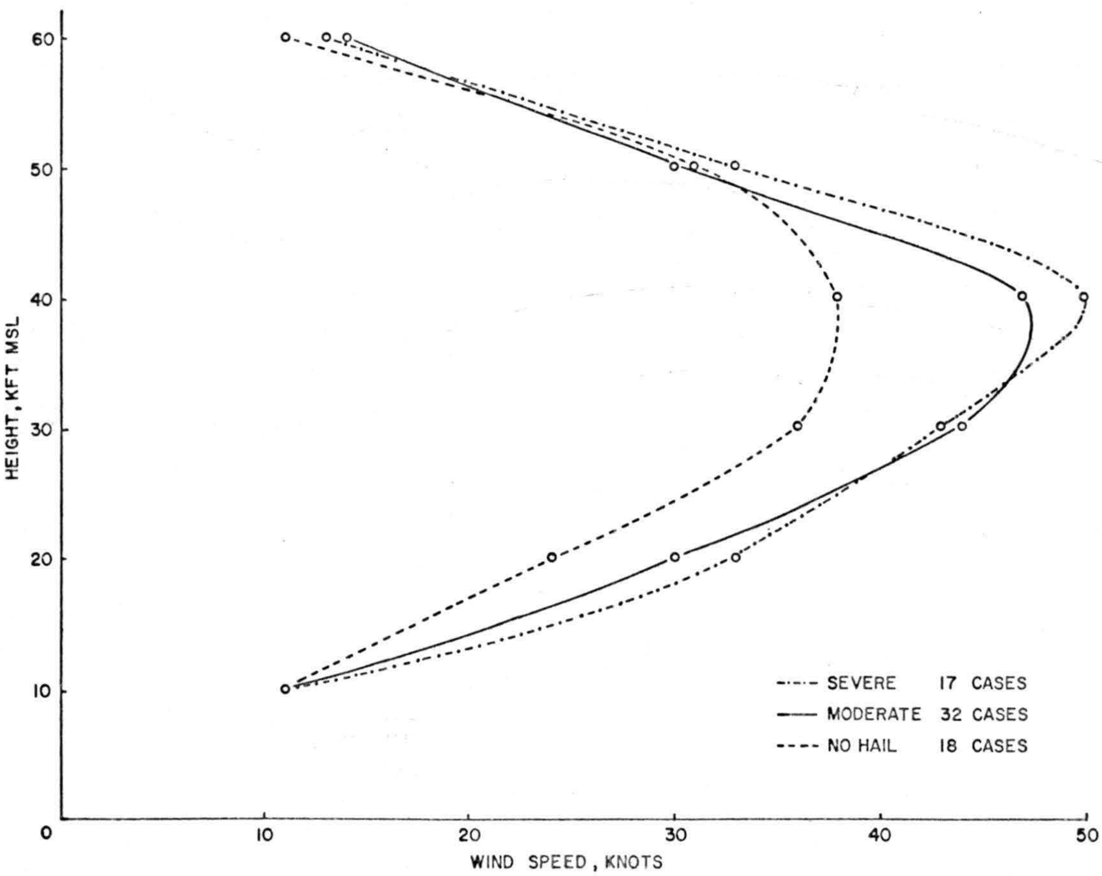

Figure 6. Average wind profiles over northeastern Colorado for May, 1960-63, for days of severe, moderate, and no hail.

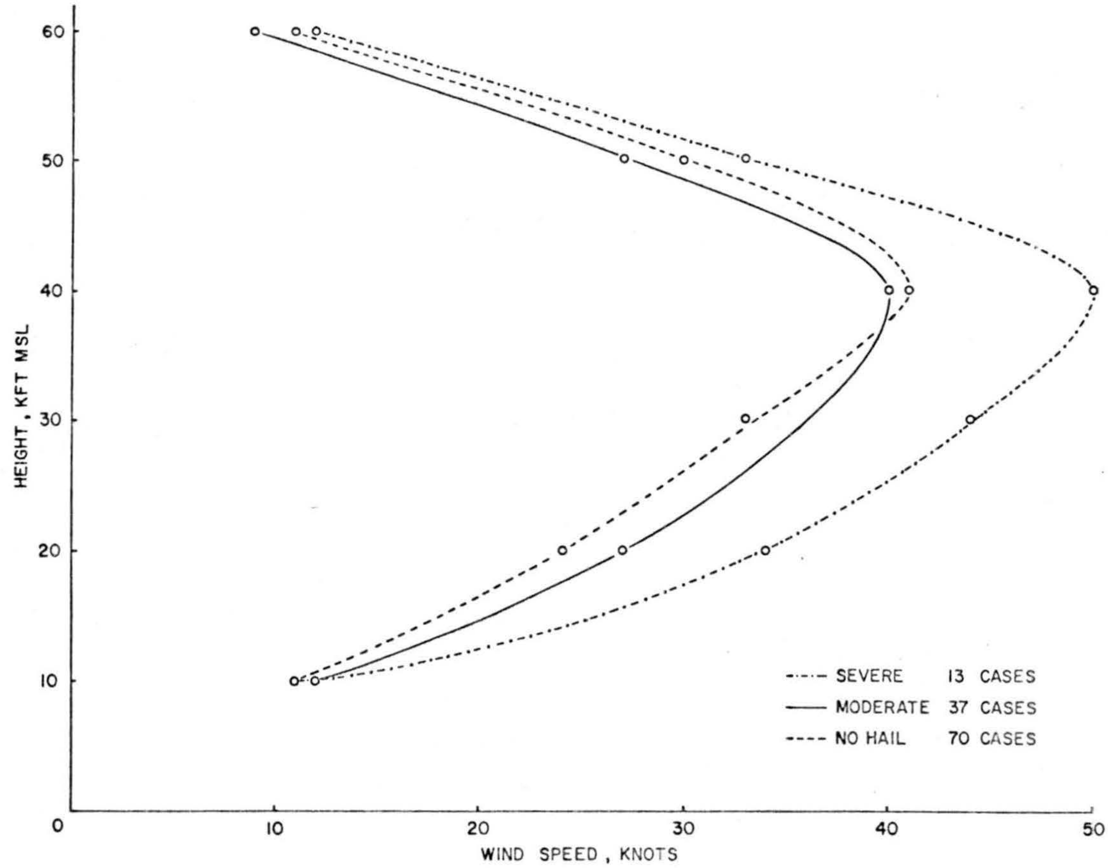

Figure 7. Average wind profiles over northeastern Colorado for June, 1960-63, for days of severe, moderate, and no hail.

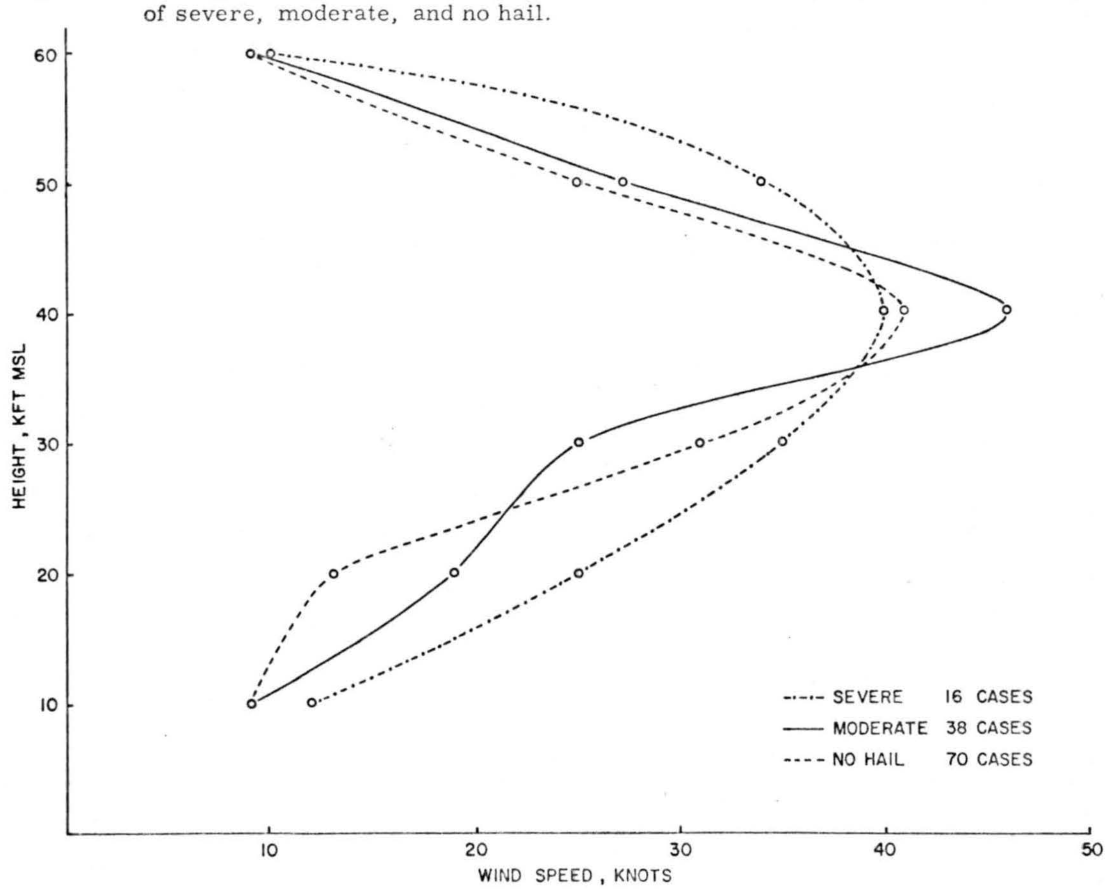

Figure 8. Average wind profiles over northeastern Colorado for May, 1960-63, for days of severe, moderate, and no hail.

No reference is made here to the existence of low level moisture needed for thunderstorm genesis; however, the supply of available moisture is governed by the stability and flow patterns mentioned above. For example, the presence of troughing to the west usually results in weak cyclogenesis in southeastern Colorado or southwestern Kansas, thereby feeding Gulf moisture into the Plains of Colorado.

B. WIND PROFILES

An analysis of wind shear was made for days of severe, moderate, and no hail occurrence for the period 15 May - 31 July, 1960-63. The average wind from the surface to 60,000 feet MSL was determined for Denver, Colorado; Lander, Wyoming; and North Platte, Nebraska. These three stations best describe the winds aloft over northeastern Colorado. Subjective analysis was used to classify the daily hailfall intensities.

Wind profiles for the months of May, June, and July, 1960-63, are shown in Figures 6, 7, and 8. In examining the severe days, the existence of a jet maximum overhead of 50 knots indicates a day of severe rather than moderate or no hail occurrence; the exception is the month of July with a 40 knot maxmum. For the severe hail days, the value of the jet maximum ranged between 30 and 110 knots. Values of the wind speed aloft for days with moderate hail exhibited slightly slower winds between 40 and 50 knots. A primary difficulty in this study was an inability to find a wind profile which distinguished days of moderate and no hail occurrence. As seen from Figures 7 and 8, there was little difference in the jet speeds, the value being around 40 knots for the months of June and July. In summary, there does appear to be a slight tendency for the occurrence of hail to favor the wind profiles with faster winds at all altitudes to 60,000 feet MSL.

The foregoing data indicate slightly higher wind speeds aloft for days with severe hail. These data concur with the findings of Dessens (1960) who postulated that strong wind aloft might be conducive to production of destructive hailstorms. Ratner (1961) questions any relationship between severe hail and strong winds aloft in the United States. Newton and Newton (1959) reveal that the importance of vertical shear is the production of kinetic energy transport which supports vigorous convection assumed necessary for hail formation.

C. 500-MB WEST WIND COMPONENT

This portion of the appendix is a summary of the Civil Engineering Report CER61RAS46, "On the Relation of the Latitude and Strength of the 500-Millibar West Wind Along 110 Degrees West Longitude and the Occurrence of Hail in the Lee of the Rocky Mountains" by R. A. Schleusener, Colorado State University, expanded to include the period 1959-64.

This study is concerned with the relation of the occurrence of hail during May, June, and July in the lee of the Rocky Mountains and the Latitudinal distribution and strength of the 500-mb west wind component along the 110 degree west longitude. The objective of this study was to attempt to relate the occurrence or non-occurrence of hail in portions of the regions in the lee of the Rocky Mountains to the latitudinal position and strength of the 500-mb west wind along 110 degrees west longitude. A better understanding of this relationship should permit improved forecast of hail as a severe weather phenomenon as increased skill is gained in prediction of upper-level wind and pressure fields. The latitudinal position of relative maxima and minima offers some encouragement for possible use of a time-section of zonal wind speed as a forecasting aid, provided some relationship can be found between the zonal westerly wind and the weather phenomenon for which forecasts are desired.

Time sections of the zonal wind speeds at 110 degrees west longitude were prepared for the seasons of 1959 through 1964. Figure 9 shows such a time section for the period 1-31 July, 1962. Data such as that shown in Figure 9 have been examined for a qualitative relationship between the zonal winds and weather phenomena, such as the number of hail-producing thunderstorms.

A hail day within the Colorado State University hail observing network for purposes of this study was defined, prior to 1962, as a day on which there were three or more reports on hail occurrences in northeastern Colorado; for the years 1962 and after, a hail day was defined as a day on which two or more radar echoes were classified as hailers.

The basic data for Figure 9 were obtained by computing the geostrophic west wind component at 500 mb along 110 degrees west for each five degrees of latitude between 30 degrees north and 70 degrees north.

Data for the 0000Z 500-mb west wind calculations were obtained from the U. S. Weather Bureau's Daily Weather Map. The average values of this west wind component for each of the years 1959 through 1964 and for normal values (U. S. Weather Bureau Technical Paper No. 21, 1952) are shown in Table 2. Table 2 illustrates that marked differences occur from 30 degrees north to 70 degrees north and that large variations occur from year to year along a particular latitude. For example, at 65 degrees north latitude for the month of May, variations in the mean wind speed from 1.7 to 23.0 knots occurred during the six-year interval studied. This is a 14-fold variation, and constitutes a departure from normal, ranging from 13 percent of normal to 176 percent of normal. From these differences it is evident that a method of comparison is necessary which is not influenced by the year-to-year variation in the strength of the zonal westerly wind component. In order to compare between days with hail and days without hail, the following procedure was used to define a difference in departures from normal in the westerly wind component along 110 degrees:

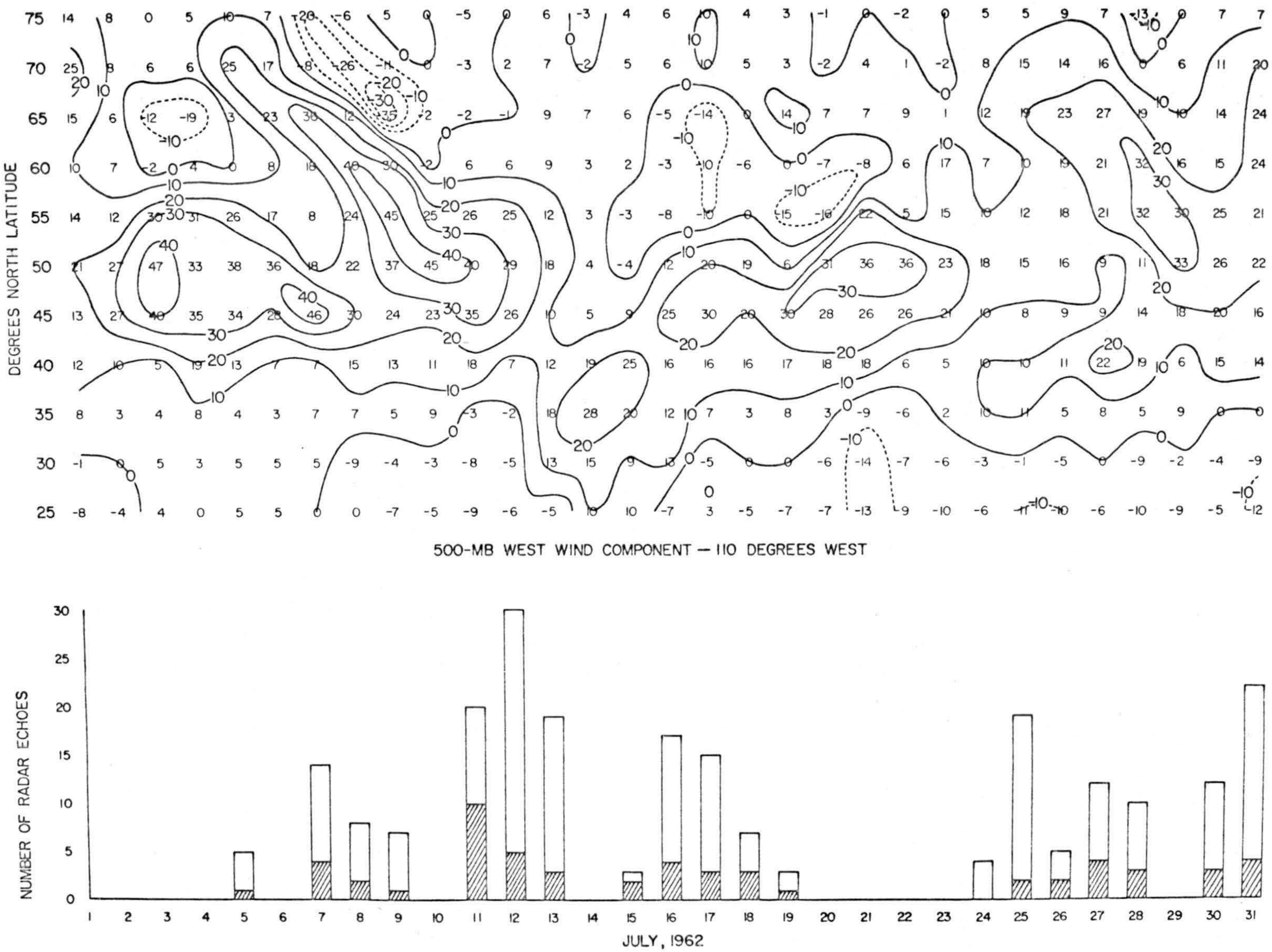

Figure 9. Time section of geostrophic zonal wind speed (knots) at 500-mb for July, 1962. Daily number of radar echoes tracked over the Colorado State University hail reporting network are shown as open boxes. Daily number of radar echoes identified as hailers are shaded.

1) The average 500-mb geostrophic west wind component (x') was determined (U. S. Weather Bureau Technical Paper No. 21);

2) The actual west wind component (x) was determined for each day;

3) The difference (x-x') was determined for each day;

4) Each day was classified as a hail day or a non-hail day by methods previously described;

5) For each of these two categories, the mean difference Δ was determined. This procedure can be summarized by the following equation:

$$\Delta = \frac{\Sigma(x-x')_H}{n_H} - \frac{\Sigma(x-x')_{NH}}{n_{NH}}$$

where

Δ = difference (knots) in departures from normal of the geostrophic 500-mb west wind component along 110 degrees west.

x = 500-mb west wind component (knots) for a particular day.

x' = mean 500-mb west wind component (knots).

n = number of days.

The subscripts of H and NH refer to days of hail and no hail, respectively. This parameter Δ was used in studies of hail occurrences in the Colorado State University network.

In order to determine the changes that took place before a hail event, the values of Δ were computed for the day of hail occurrence (D), for the first day prior to hail (D-1), and for the second day prior to hail (D-2).

Figure 10 shows the differences in departures from normal (Δ) of the westerly wind component at 500 mb along 110 degrees west between days with and without hail.

Figure 10 shows that in May a maximum value of Δ exists between 55 and 60 degrees north for D-2. This maximum remains at 60 degrees north for D-1 and then moves slightly to 55 degrees north position. This suggests a maximum west wind residing in this latitude belt, which is believed to be the reflection of the polar jet stream. For D-2, D-1, and D, there is evidence of a west wind minimum through the latitude belt of 50-40 degrees north. The distribution of Δ for May yields a gradual increase of the west wind component in the latitudes south of the hail occurrence areas; namely, 40 to 30 degrees north. For D-2 there is a distinct minimum, increasing to near normal for D-1, and finally progressing to a maximum value in Δ at 30 to 40 degrees north for the day of hail, D.

This variation of Δ with time suggests a wind regime in which above normal westerly winds would appear in lower latitudes without exhibiting continuity from higher latitudes. Such an explanation could be that of the passage of a 500-mb trough over the 110 degrees west longitude. This passage would exhibit higher values of Δ in the latitude belt 60 to 65 degrees north as the preceding ridge moves eastward two days prior to hail occurrence (D-2). At D-1 the trough is now providing nearly all meridianal flow over 110 degrees west longitude accounting for the observed minimum value of Δ at latitudes of 45 to 55 degrees north; however, some westerly wind component is still conserved at the top of the trough, and also west wind components are increasing at the bottom of the trough as it progresses eastward. Finally, on the day of hail, the trough moves into position over 110 degrees west providing a maximum value of Δ at 35 degrees north. The polar jet stream reflection is still observed at the higher latitudes, which can be explained by a possible cutting-off of the trough. With this interpretation, the apparent discontinuity in latitudinal movement of maximum values of Δ is accounted for. Also, the persistent minimum values of Δ can be explained since for both D-2 and D the west wind component is in existence but may be quite weak because of the wind distribution around the trough. In the case of D-1, the winds around the trough can be quite strong, but their strongest contribution is in the meridianal direction not the zonal direction. This interpretation seems tolerable in view of the tendency of hailstorms to move from the west-southwest during May and June (Schleusener 1963).

Another possible explanation for the observed behavior of Δ shown in Figure 10 could be that the subtropical jet may move slightly northward and interact with the polar jet. The rapid increase in the west wind component above normal values might be attributed to the subtropical jet, since there is weak continuity in the values of Δ increasing from more northerly latitudes. It is because of this weak continuity that the idea of subtropical jet and polar jet interaction is suggested. The rapid rise in value of Δ near 35 degrees north latitude would have to be explained by either a generation of new and stronger west winds, or by a possible merger with the subtropical jet. It is unlikely that such a generation of stronger west winds would appear in a mean or average parameter like Δ, since any generation of stronger winds would not favor a particular geographic location, but rather would be a function of the dynamics of an individual system. Thus, it is thought that perhaps the progression of the northern edge of the subtropical jet to latitudes of 30 to 35 degrees north over the period from two days previous to hail to the day of hail may be responsible for hail occurrence in northeastern Colorado for the latter half of May.

This phenomenon appears again in a similar manner in the month of June. For D-2, the west wind maximum is located at 65 degrees north, still maintaining itself between 65 and 60 degrees north for D-1, then residing only at 60 degrees north for the day of hail, D. During June the value of Δ is at a minimum for each day, D-2 through D; and, as in May, there is a steady increase in the value of Δ at 35 degrees north from D-2 to D. Here again it seems reasonable

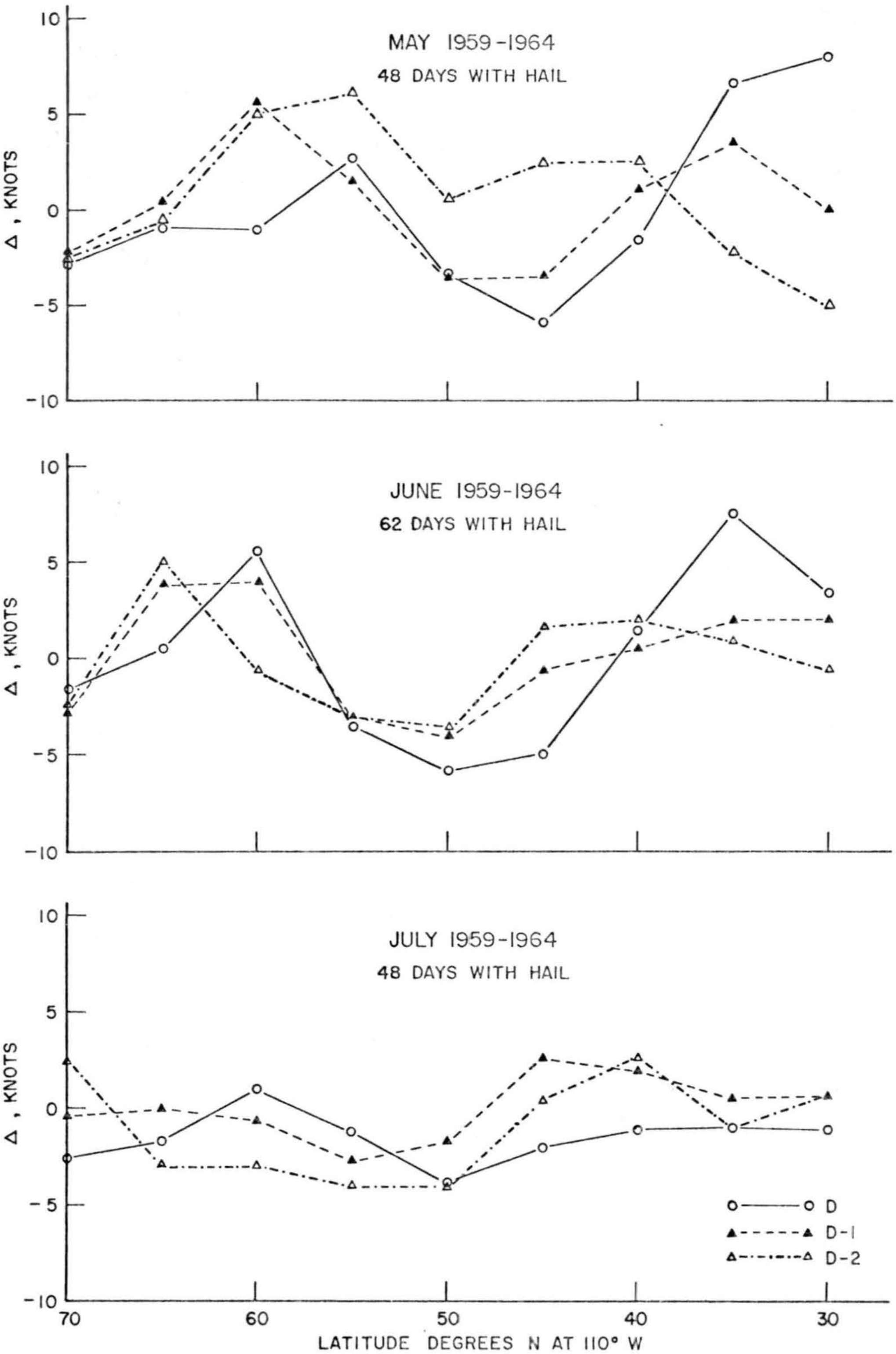

Figure 10. Differences in departures (Δ) from normal of the westerly wind component (knots) along 110°W for the month indicated for hail days in northeastern Colorado. The values of Δ were computed for the day of hail occurrence (D), for the first day prior to hail (D-1), and for the second day prior to hail (D-2).

Table 2. Average values of 500-mb west wind component (knots) for various latitudes at 110 degrees west for May, June, and July. The column titled TP21 contains normal west wind components derived from U. S. Weather Bureau Technical Paper No. 21.

MAY

Lat Deg N	1959	1960	1961	1962	1963	1964	TP21
70	6.6	7.4	14.1	14.2	15.5	10.7	12.0
65	17.3	1.7	23.0	17.0	22.1	11.8	13.0
60	17.2	3.1	12.5	12.1	18.4	16.3	18.0
55	15.5	13.2	7.9	11.4	21.2	15.2	20.0
50	9.6	20.9	7.1	6.1	22.2	27.7	17.0
45	11.7	10.6	20.4	6.3	15.3	22.5	15.0
40	24.0	14.4	19.2	14.7	15.2	13.2	16.0
35	26.4	22.5	17.2	31.8	16.1	17.6	17.0
30	24.2	24.5	17.1	35.1	16.4	17.0	18.0
Total	152.5	118.3	138.5	148.7	163.4	152.0	136.0
Mean	16.9	13.1	15.4	16.5	18.2	16.9	15.1

JUNE

Lat Deg N	1959	1960	1961	1962	1963	1964	TP21
70	5.7	11.9	8.7	9.3	11.6	24.8	13.0
65	13.7	3.5	13.7	5.1	10.6	26.8	14.0
60	15.5	2.4	12.6	7.0	12.0	14.5	14.0
55	24.1	13.0	14.1	15.1	16.4	14.3	13.0
50	26.3	29.1	16.8	20.9	20.2	16.4	12.0
45	22.6	29.6	14.2	17.0	18.8	14.6	15.0
40	13.5	20.8	10.1	15.1	17.2	17.7	19.0
35	6.5	10.3	4.9	14.0	16.7	17.8	18.0
30	4.8	2.9	0.2	10.6	15.5	9.6	7.0
Total	132.7	123.5	95.3	114.1	139.0	156.5	125.0
Mean	14.7	13.7	10.6	12.7	15.4	17.4	13.9

JULY

Lat Deg N	1959	1960	1961	1962	1963	1964	TP21
70	7.9	9.8	11.6	5.3	17.6	17.3	9.0
65	16.4	12.2	12.9	6.9	15.7	15.7	13.0
60	19.9	22.5	9.2	8.8	14.2	13.7	16.0
55	20.9	24.9	11.6	14.7	16.8	17.8	18.0
50	25.5	24.1	20.3	24.0	21.9	27.0	18.0
45	24.0	14.7	20.0	22.4	23.6	22.8	18.0
40	13.2	8.0	9.8	13.3	15.6	9.0	17.0
35	0.3	0.1	-1.2	6.0	8.3	4.4	10.0
30	-7.6	-4.1	-8.8	-0.9	6.8	5.4	0.0
Total	120.5	112.2	85.4	100.5	140.5	133.1	119.0
Mean	13.4	12.5	9.5	11.2	15.6	14.8	13.2

to suggest that either the passage of a trough or the northward movement on the day of hail of the subtropical jet may be correlated to hail occurrences in northeastern Colorado during June.

These phenomena do not appear in the same manner in the month of July. The values of Δ indicate no strong westerly wind component in existence either on D-2, D-1, or D. The values of Δ do not deviate more than 4 knots from the normal. The slight decrease in values of Δ at 40 degrees north suggests either a decrease in westerly wind component or an increase in the northerly wind component for days with hail in July. The latter explanation seems more reasonable in view of the tendency of hailstorms to move from north to south during July (Schleusener, 1963).

For each of the months, May through July, it can be noted that the difference in Δ values between 35 and 45 degrees north tends to increase prior to a hail day. If one defines the gradient of this difference as

$$\text{Gradient}_{40} = \Delta_{35} - \Delta_{45}$$

where

Gradient_{40} = change Δ at 40 degrees north

and

$\Delta_{35, 45}$ = values of Δ at 35 and 45 degrees north, respectively, then one observes an increase in gradient as shown in Table 3. This tendency for an increased Gradient_{40} is evident in each month.

Table 3. Changes in departures from normal west wind component across 40 degrees N latitude from the second day prior to a hail day (D-2) to a hail day (D) for the months of May, June, and July. Hail data are from northeastern Colorado. (See text for more complete information.)

$$\text{GRADIENT}_{40} = \Delta_{35} - \Delta_{45}$$

	May	June	July
D-2	-4.5	-0.7	-1.2
D-1	6.5	2.7	-2.1
D	12.3	12.4	1.3

The foregoing data illustrate a probable relationship between the broad-scale circulation patterns and the occurrence of a specific severe weather event, hail. It appears that the broad-scale pattern may provide a necessary (but not sufficient) condition for hail occurrence in the lee of the Rockies. The specific features that appear to be favorable for hail occurrences are:

1. Passage of relative velocity maxima in Colorado in May and June (Figure 10).
2. An increase in the positive anomaly south of the latitude of hail occurrence as shown in Table 3.

Neither of these features was found to hold true for hail occurrences in July.

The data of Table 2 show that large departures from normal values of west wind occur from year to year. This fact emphasizes the hazard of any direct comparisons from one year to another without any consideration of large-scale circulation differences.

The indication of a relation between a relative velocity maxima and the occurrence of hail is consistent with the data of Dessens (1960) who showed a relation between strong winds aloft and the occurrence of large hail.

The reason for the association between hail occurrences and a 500-mb west wind component deserves further study. It is possible that the maximum 500-mb west wind is associated with the zone of the polar front and, hence, represents a latitude for favored passages of cyclonic disturbances which, in turn, trigger the severe weather. Further investigation may be in order i; to the premise that the subtropical jet may edge slightly northward on days of hail, and possibly interacts with the polar jet. Due to the proximity of the Continental Divide of the Rocky Mountains, and other individual high peaks, findings concerning the effect of lee-wave modification on High Plains thunderstorms should be ascertained.

Answers to the foregoing questions are required in order to proceed from the conventional pressure-pattern prognostic chart presentation to improved forecasts of hail occurrence, though no one single meteorological parameter is expected to provide improved forecasts.

Finally,this study points out the importance of considerations of the larger-scale weather patterns, even when the item of particular interest is of a smaller scale, such as the occurrence of hail.

D. HAIL FORECAST EQUATION

Stepwise screening regression techniques were utilized in an attempt to derive a hail forecast equation using meteorological parameters associated with hailfall in northeastern Colorado.

The stepwise equation is of the form:

$$Y = K + C_1X_1 + C_2X_2 + \ldots + C_nX_n \quad (1)$$

where $Y = \log_{10} E_{max}$; E_{max} being the maximum hail impact energy (ft-lb/ft^2) expected; and X_n is the appropriate meteorological parameter.

Meteorological parameters were divided into groups representing hailfall during 15 May-30 June and during 1-31 July. The independent variables were obtained from data found on the Department of Commerce Daily Weather Map during the 1960-62 season. Equations (2) and (3) are the results of the 1962 data calculations and represent the hail forecast equations for May-June and July, respectively. The appropriate constants are listed in Table 4;

identification of meteorological parameters (X_n) is found in Table 5.

May-June

$$Y = K_a + C_1X_1 + C_{2a}X_2 + C_3X_3 + C_5X_5 + C_7X_7 + C_{10}X_{10} + C_{11a}X_{11} + C_{12a}X_{12} + C_{13a}X_{13} + C_{14a}X_{14} + C_{17}X_{17} + C_{18a}X_{18} + C_{20}X_{20} + C_{21}X_{21}. \quad (2)$$

July

$$Y = K_b + C_{2b}X_2 + C_4X_4 + C_6X_6 + C_8X_8 + C_9X_9 + C_{11b}X_{11} + C_{12b}X_{12} + C_{13b}X_{13} + C_{14b}X_{14} + C_{15}X_{15} + C_{16}X_{16} + C_{18b}X_{18} + C_{19}X_{19} + C_{22}X_{22}. \quad (3)$$

Equations (2) and (3) could be programmed to give an arbitrary "cutoff" after a specified number of variables since no further reduction in variance was accomplished by adding additional variables.

Independent data from the Daily Weather Map for the 1963 and 1964 seasons were substituted into equations (2) and (3). These results were then compared to the actual maximum hail impact energy observed over the Colorado State University hail reporting network. (See Table 6.) A paired t test was used to examine the hypothesis that no difference exists between the forecast and observed hail impact energies for the independent data. The first comparison for significance included all days for the 1963 and 1964 seasons. For a total of 155 samples, it was found that a difference, significant at the 5 percent confidence level, did exist between the respective forecast and observed impact energies. When considering only those days on which the forecast hail impact energy exceeded 10 ft-lb/ft^2 (i. e., $Y = \log_{10} E_{max} > 1$), again it was found that a difference, significant at the 5 percent level, did exist for a total of 80 samples. Thus, in conclusion it may be said that the use of the stepwise regression equation resulted in a value of the forecast hail impact energy which was significantly different from the actual value of the hail impact energy observed in the network and, hence, indicates that the stepwise equation did not give satisfactory forecasting skill.

Table 4. Constants for the Stepwise Regression Equations

May-June		July	
K_a	12.3000	K_b	0.4630
C_1	-0.0650	C_{2b}	0.0470
C_{2a}	-0.0580	C_4	-0.0369
C_3	0.0205	C_6	0.0358
C_5	-0.0132	C_8	0.0016
C_7	-0.0942	C_9	0.0278
C_{10}	0.1730	C_{11b}	0.0720
C_{11a}	0.1410	C_{12b}	-0.0334
C_{12a}	-0.0256	C_{13b}	0.0158
C_{13a}	0.0196	C_{14b}	0.0237
C_{14a}	0.0115	C_{15}	0.0106
C_{17}	-0.0084	C_{16}	-0.0258
C_{18a}	0.0495	C_{18b}	0.0666
C_{20}	0.4366	C_{19}	-0.0698
C_{21}	-0.1361	C_{22}	0.1625

Table 5. Meteorological Parameters Used in Stepwise Regression Equation. All parameters except X_{22} are obtained from the Department of Commerce Daily Weather Map. Times quoted refer to observation times (MST) of the Daily Weather Map.

X_1	:	24-hr. change (Today - Yesterday) in the difference of the reduced sea level pressure (mb) between Cheyenne, Wyoming, and Trinidad, Colorado (2300 MST)
X_2	:	24-hr. change (Today - Yesterday) in the difference of the reduced sea level pressure (mb) between Kansas City, Missouri, and Amarillo, Texas (2300 MST)
X_3	:	24-hr. change (Today - Yesterday) in the dew point temperature (° F) at Goodland, Kansas (2300 MST)
X_4	:	24-hr. change (Today - Yesterday) in the dew point temperature (° F) at Oklahoma City, Oklahoma (2300 MST)
X_5	:	24-hr. change (Today - Yesterday) in the dew point temperature (° F) at Cheyenne, Wyoming (2300 MST)
X_6	:	24-hr. change (Today - Yesterday) in the maximum 500-mb wind (knots) over Arizona or New Mexico (1700 MST)
X_7	:	24-hr. change (Today - Yesterday) of the 500-mb temperature (° C) over Denver, Colorado (1700 MST)
X_8	:	24-hr. change (Today - Yesterday) of the 500-mb height (tens of feet) over Denver, Colorado (1700 MST)
X_9	:	24-hr. change (Today - Yesterday) of the maximum temperature (° F) observed the previous day in Wyoming.
X_{10}	:	The difference of the reduced sea level pressure (mb) between Cheyenne, Wyoming, and Trinidad, Colorado (2300 MST)
X_{11}	:	The difference of the reduced sea level pressure (mb) between Kansas City, Missouri, and Amarillo, Texas (2300 MST)
X_{12}	:	Dew point temperature (° F) at Goodland, Kansas (2300 MST)
X_{13}	:	Dew point temperature (° F) at Cheyenne, Wyoming (2300 MST)
X_{14}	:	Maximum 500-mb wind (knots) over Utah or Colorado (1700 MST)
X_{15}	:	Maximum 500-mb wind (knots) over Arizona or New Mexico (1700 MST)
X_{16}	:	The 500-mb temperature (° C) over Denver, Colorado (1700 MST)
X_{17}	:	The 500-mb height (tens of feet) over Denver, Colorado (1700 MST)
X_{18}	:	Previous day's maximum temperature (° F) in Colorado (2300MST)
X_{19}	:	Previous day's maximum temperature (° F) in Wyoming (2300 MST)
X_{20}	:	Previous day's maximum precipitation (inches) in Wyoming (2300 MST)
X_{21}	:	Previous day's maximum precipitation (inches) in Kansas (2300 MST)
X_{22}	:	Previous day's $\log_{10} E_{max}$ (maximum hail impact energy, $ft\text{-}lb/ft^2$) in Colorado or Nebraska

Table 6. Skill scores for forecasting hail impact energy numbers greater than 1, 10, and 100 ft-lb/ft^2, respectively, using the stepwise regression equation on independent data.

$E_{max} = 1$		Observed	
		yes	no
Forecast	yes	39 (25%)	111 (72%)
	no	3 (2%)	2 (1%)

$E_{max} = 10$		Observed	
		yes	no
Forecast	yes	15 (10%)	65 (42%)
	no	23 (15%)	52 (33%)

$E_{max} = 100$		Observed	
		yes	no
	yes	3 (2%)	11 (7%)
	no	24 (15%)	117 (76%)

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APPENDIX H

RADAR STUDIES IN NORTHEASTERN COLORADO, 1961-64*

*This appendix was prepared by Mr. August H. Auer, Jr. The assistance of Mr. Dale Peterson is acknowledged for compilation of some of the basic data.

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This appendix is a summary of investigations concerning the radar systems in use for the Colorado State University Hail Suppression Project. A description of the radar systems may be found in Appendix A, Table 1.

NEW RAYMER RADAR STUDIES

Severe storm surveillance by radar for northeastern Colorado was provided by a 3-cm radar system leased from Atmospherics Incorporated. The radar site was located about one mile southeast of New Raymer, Colorado. This radar system possesses a vertical beam width of 2 degrees. A study was undertaken to determine the average heights, both uncorrected and corrected for beam width, of hailers and non-hailers in northeastern Colorado. The results of this study are shown in Tables 1 and 2.

Table 1 shows the number of observations, the average height (in thousands of feet MSL) uncorrected for beam width, and the standard deviation for all echoes (Case I), echoes identified as hailers (Case II), and echoes identified as hailers (Case III) for ranges of less than 40 nautical miles, 40-79 nautical miles, 80-119 nautical miles, and greater than 120 nautical miles. The period of observation is divided into 15-31 May 1961-64, June 1961-64, and July 1961-64. It can be seen that in all cases the average height of an echo identified as a hailer is higher than the mean height of the family of all echoes and also for the echoes identified as non-hailers. In most instances the standard deviation of the echo height is smaller for the hailers.

The average heights of the radar echoes are reproduced in Table 2 after correction for beam width was applied. Beam width correction was determined in the following manner. Distances of 30, 60 and 90 nautical miles were assumed as average distances valid for the radar ranges of less than 40, 40 to 79, and 80 to 119 nautical miles. The height of any echo in these respective radar ranges was corrected by subtracting the height at that range due one-half the beam width (1° in this case). The correction at 30 nautical miles range was 4,000 feet; correction at 60 nautical miles, 7,000 feet; correction at 90 nautical miles, 10,000 feet.

In addition, a student's t test was applied to the difference between average heights of hailers and the average heights of non-hailers (corrected for beam width) to determine if any significant difference between hailers and non-hailers existed at the 5 percent confidence level.

Table 3 shows that a significant difference exists between height of radar echoes identified as hailers and those identified as non-hailers for both June and July between the ranges of 40 to 70 nautical miles. Other significant differences exist for ranges less than 40 nautical miles in July and for ranges of 80 to 119 nautical miles during June. The remaining significant difference for radar tops of hailers and non-hailers during May for ranges of 80 to 119 nautical miles should be considered in the light that very few samples were involved in this statistic. The underscored echo heights in Table 2 correspond to those values of echo heights for hailers and non-hailers which proved to be significantly different.

Table 1. Mean Height (thousands of feet, MSL), uncorrected for beam width, of all echoes (Case I), hailers (Case II), and non-hailers (Case III). The number of observations n and the standard deviation s also accompany the average values of echo heights h for the ranges of less than 40, 40 to 79, 80 to 119, and greater than 120 nautical miles. Observations were taken at New Raymer, Colorado by Atmospherics, Inc. Radar.

Case I (All Echoes) Period of Sample	40			40-79			80-119			120		
	n	h	s	n	h	s	n	h	s	n	h	s
May 1961-64	160	36.2	7.5	76	41.9	6.5	16	47.8	6.9	5	49.8	7.0
June 1961-64	168	36.4	12.0	205	41.5	6.4	31	49.7	7.1	7	56.8	7.5
July 1961-64	300	37.1	8.1	192	40.8	6.4	6	52.1	7.2	4	52.8	7.3

Case II (Hailers) Period of Sample	40			40-79			80-119			120		
	n	h	s	n	h	s	n	h	s	n	h	s
May 1961-64	122	36.8	6.6	51	42.5	7.5	15	49.3	8.7	3	63.0	11.3
June 1961-64	107	38.6	6.6	155	42.1	8.9	23	50.7	6.7	5	54.4	7.4
July 1961-64	178	39.0	7.8	96	43.5	8.5	4	54.8	7.6	4	52.8	5.7

Case III (Non-hailers) Period of Sample	40			40-79			80-119			120		
	n	h	s	n	h	s	n	h	s	n	h	s
May 1961-64	38	34.3	9.3	25	40.8	11.3	1	24.7	0.0	2	30.0	0.6
June 1961-64	61	32.4	17.2	50	39.7	6.8	8	46.6	6.4	2	62.9	4.7
July 1961-64	122	34.5	7.7	96	38.1	7.5	2	46.7	2.5	0	0.0	0.0

Table 2. Mean Height (thousands of feet, MSL) corrected for beam width, of all echoes, hailers, and non-hailers for the ranges of less than 40, 40 to 79, and 80 to 119 nautical miles observed at New Raymer, Colorado by Atmospheric Inc., Radar. Underlined values indicate significant difference exists between the echo heights of hailers and non-hailers at the same radar range for the same month.

Period of Sample	All Echoes			Hailers			Non-Hailers		
	<40	40-79	80-119	< 40	40-79	80-119	< 40	40-79	80-119
May 1961-64	32.2	34.9	37.8	32.8	35.5	39.3	30.3	33.8	34.7
June 1961-64	32.4	34.5	39.7	34.6	35.1	40.7	28.4	32.7	36.6
July 1961-64	33.1	33.8	42.1	35.0	36.5	44.8	30.5	31.1	36.7

Table 3. The Value of the statistic t based on the difference between the radar echo heights of hailers and non-hailers at the specific radar ranges (in nautical miles) observed at New Raymer, Colorado by Atmospherics, Inc., Radar. An Asterisk (*) denotes values significant at the 5 percent confidence level.

	< 40	40-79	80-119
May 1961-64	1.538	0.683	11.031*
June 1961-64	0.887	2.008*	2.544*
July 1961-64	4.940*	4.675*	1.942

CPS-9 RADAR STUDIES

Cooperative effort between the United States Air Force and Colorado State University made possible the use of the CPS-9 weather radar system located at Lowry Air Force Base, Denver, Colorado during 1962-64. Previous studies have shown that it is possible to estimate thunderstorms intensity from radar measurements taken with the CPS-9 "step-gain" system. Using the procedures outlined below, it is possible to estimate the intensity of the storm at the time of the radar observation.

The following is the suggested recommended procedure for estimating the intensity of a thunderstorm using the CPS-9 "step-gain" system at Lowry Air Force Base. For the larger and more significant cells, determine the echo top at gain step "0"; use the A/R scope to determine the top of the cells in thousands of feet MSL. Then select the appropriate elevation angle from Table 4 to scan at 30,000 feet MSL those echoes which have tops greater than 30,000 feet MSL. Step through the gain-reduction steps and note the step at which the echo disappears from the A/R scope. From Figure 1 relating gain step versus range, determine the 10 log Z, where Z is the radar reflectivity factor. The observation should be interpreted according to Table 5. This procedure should be limited to ranges less than 100 statute miles. The interpretation given in Table 5 should be considered as an estimate only.

In order to forecast the occurrence of severe weather at some time in the future, it is desirable to know the probability of a given echo persisting in time. A pilot study was undertaken to examine this question. Because of lack of sufficient time, the results of this study must be considered preliminary.

Table 4. Elevation Angle Required to give 30,000 feet MSL (CPS-9, Lowry AFB, Colorado

Range Statute Miles	Elevation Angle Degrees
20	13.5
30	8.7
40	6.5
50	5.0
60	4.2
70	3.4
80	2.9
90	2.5
100	2.2

Radar data taken on the Lowry CPS-9 during the summer of 1962 were examined in order to determine the time sequences of RHI tops measured at gain-step "0" and reflectivity measured at 30,000 feet MSL (i.e., 10 log Z_{30}). Measured values of RHI tops and 10 log Z_{30} were plotted as a function of time for each echo identified as "hailer" or "non-hailer at some time during their life cycle. From these

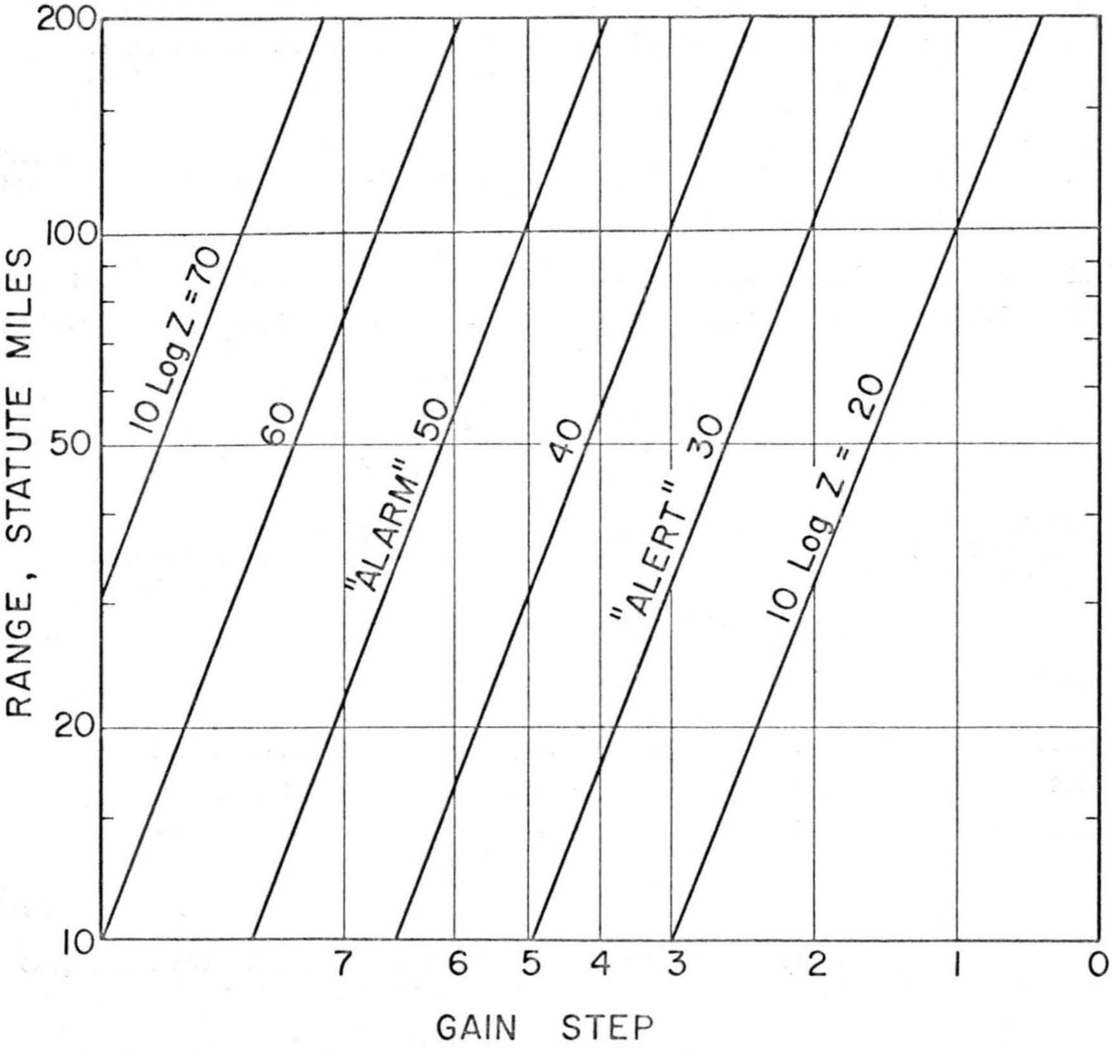

Figure 1. Reflectivity as a function of range and gain step for Lowry AFB CPS-9

Table 5. Probable weather expected from radar echoes as a function of radar echo top (KFT MSL) and 10 log Z_{30}.

10 log Z_{30}	Echo top Step "0"	Probable Weather
30 and/or	30	Hail possible
50 and/or	40	Hail and/or damaging winds

Table 6. Mean values of six radar parameters, including the number of observations n and the standard deviation s, for all echoes, hailers only, and non-hailers only. Observations were taken at the CPS-9 radar, Lowry Air Force Base. Underlined values indicate significant difference exists between the radar parameters of hailers and non-hailers.

	ECHO TOPS (thousands of feet, MSL)			Elevation of Z_{mx} (thousands of feet, MSL)			$10 \log Z_{mx}$			$10 \log Z_{20}$			$10 \log Z_{30}$			$10 \log Z_{40}$		
	n	h	s	n	$h_{Z\,mx}$	s	n	$10 \log Z_{mx}$	s	n	$10 \log Z_{20}$	s	n	$10 \log Z_{30}$	s	n	$10 \log Z_{40}$	s
May 1962-64																		
ALL ECHOES	134	32.5	5.1	134	17.3	5.7	134	35.5	9.9	133	32.2	10.8	86	28.2	10.7	7	29.7	8.2
HAILERS	18	33.3	6.3	18	18.9	4.8	18	42.2	6.4	17	41.0	5.7	15	35.7	9.3	4	33.3	4.7
NON-HAILERS	36	33.4	3.9	36	19.3	7.0	36	34.9	9.1	36	33.4	6.0	25	29.6	7.3	0	0.0	0.0
June 1962-64																		
ALL ECHOES	596	34.2	5.3	594	17.5	4.8	593	39.3	7.6	586	36.8	7.8	459	30.3	10.0	88	24.6	10.4
HAILERS	153	34.4	6.1	152	17.2	6.0	152	41.8	6.1	147	39.2	7.1	125	34.2	7.8	28	28.9	11.1
NON-HAILERS	100	33.0	3.8	100	17.6	3.9	100	37.2	6.5	100	34.7	6.5	73	24.2	9.5	3	16.3	6.8
July 1962-64																		
ALL ECHOES	861	35.9	6.1	849	17.2	5.2	829	42.8	8.8	808	39.7	9.4	598	36.2	9.9	187	34.0	9.0
HAILERS	186	37.8	6.2	186	17.3	5.3	182	47.7	8.9	179	45.3	9.2	158	40.8	9.8	75	35.5	8.8
NON-HAILERS	162	33.9	5.5	157	16.1	4.6	149	39.7	8.4	141	35.8	8.7	79	32.4	8.4	15	32.9	7.3

time plots the values of RHI tops and 10 log Z_{30} were computed by linear interpolation between the time that tops first exceeded 30,000 feet MSL and the time the echo heights last exceeded 20,000 feet MSL. From these data the following results were computed:

1. Average RHI tops for hailers by months for each fifteen-minute time interval after the echo exceeds 30,000 feet MSL (Figure 2).

2. Average RHI tops for hailers and non-hailers for each fifteen-minute interval after the echo first exceeds 30,000 feet MSL (Figure 3).

3. Average 10 log Z_{30} for hailers by months and all season for each fifteen-minute time interval after the echo first exceeds 30,000 feet MSL (Figure 4).

4. Average change in RHI tops of hailers at fifteen-minute time intervals after the echo first exceeds 30,000 feet MSL (Figure 5).

The results of this 1962 study can be summarized as follows. From Figure 2 it can be seen that the cells remained higher than 30,000 MSL for approximately 1.5 to 2.0 hours. From Figure 3 it may be seen that the RHI tops for the hail cases remained above 30,000 feet MSL for an average of about 1.75 hours, and the non-hailers about 1.25 hours. The average values of 10 log Z_{30} as a function of time after the RHI tops first exceed 30,000 feet MSL are shown in Figure 4. The average value of 10 log Z_{30} remained above 30 for about 1.4 hours for echoes averaged for the 1962 season. Figure 5 illustrates the average changes in RHI tops for various time intervals (15, 30, 45, and 60 minutes) as a function of time after the RHI tops were first observed to exceed 30,000 feet MSL. Also from Figure 5 it may be noted that for zero lapsed time, the change in height was positive for all of the time increments except 60 minutes. For 30 minutes lapsed time or longer, all increments gave negative changes in RHI tops.

The data of this study were limited to one initial condition: the time the RHI echo heights first exceeded 30,000 feet MSL. For this condition, the results of the study indicate a strong degree of persistence of echo tops higher than 30,000 feet MSL, and the value of 10 log Z_{30} greater than 30 for time periods of from one to two hours. Both of these criteria are indicative of probably severe weather. From the viewpoint of forecasting severe weather, this study indicates that if a thunderstorm echo exceeds 30,000 feet MSL at gain-step "0", the best forecast is for it to persist for at least one hour, and possibly for 1.5 hours, with some likelihood of hail.

Using the CPS-9 radar system at Lowry Air Force Base, which was equipped with the step gain system, measurements were made of RHI tops, maximum reflectivity factor Z, elevation of the maximum reflectivity factor, and the reflectivity factor at 20,000, 30,000 and 40,000 feet MSL. A statistical analysis, similar to the one described earlier, was performed using the Student's _t_ test to determine whether significant differences at the 5 percent confidence level occurred in the above-mentioned parameters between echoes identified as hailers and those identified as non-hailers. The number of cases, means, and standards deviations of the various parameters are shown in Table 6. A comparison of the CPS-9 echo height data (Table 6) is in order with the identical data obtained utilizing the 3-cm radar system located at New Raymer, Colorado, (Table 1). While the CPS-9 has a range of 200 nautical miles, it is utilized most frequently in northeastern Colorado at ranges less than 100 nautical miles. The comparison indicates that in most cases the CPS-9 tops are slightly less than the echo tops obtained at New Raymer for the respective classes of storms. This lower value of echo heights at the CPS-9 may be explained in that the CPS-9 possesses a smaller vertical beam width (1°) than does the Atmospherics Inc. system (2°).

Table 7 illustrates the values of the statistic _t_ for determining the significant differences between the means of the radar parameters measured for the purpose of detecting any differences between hailer echoes and non-hailers echoes. As seen from Table 7, a significant difference does exist between radar tops of echoes identified as hailers and those identified as non-hailers for both June and July. There appears to be no difference in the elevation of the maximum reflectivity for hailers and non-hailers. The value of the reflectivity at 20,000 feet MSL shows significant differences between hailers and non-hailers for the months of May and July only. Most paramount in this comparison is the fact that the values of the maximum reflectivity and the reflectivity at 30,000 feet MSL are significantly different for hailers and non-hailers for all three months. Statistical tests involving the reflectivity factor at 40,000 feet MSL are not considered satisfactory because very few samples are available for the calculations.

In summary, it can be said that both the maximum reflectivity and the reflectivity at 30,000 feet MSL offer the method for determining the existence of hail or no hail in an echo. In July the best evidence for distinguishing between hailers and non-hailers exists using the CPS-9; five of the six parameters studied indicate significant differences at the 5 percent confidence level.

SO-12 RADAR STUDIES

In order to study the vertical structure of thunderstorms, a Navy SO-12 horizontal scanning radar was modified to give vertical scanning capability. A study was made in 1963 to determine what difference exists between the values of the radar reflectivity factor, Z, as measured with the RHI capabilities of the CPS-9 3-cm weather radar and the modified vertically scanning SO-12 3-cm system. The SO-12 was operated by Colorado State University at New Raymer, Colorado. A similar comparison was made between the observed radar echo tops using the same radar sites. Cross-sectional profiles of reflectivity were obtained by the SO-12 radar at New Raymer.

The comparison was between two radar systems

Table 7. The value of the statistic t based on the difference between various radar echo parameters of hailers and non-hailers observed with the CPS-9, Lowry Air Force Base. An asterisk (*) denotes values significant at the 5 percent confidence level.

Period of Sample	Echo Top	Elev. Z_{mx}	t 10 log Z_{mx}	10 log Z_{20}	10 log Z_{30}	10 log Z_{40}
May 1962-64	-0.061	-2.460	3.411*	4.444*	2.171*	-----
June 1962-64	2.251*	-0.639	5.630*	0.514	7.575*	2.825
July 1962-64	1.979*	1.495	8.394*	9.415*	5.600*	2.921*

Table 8. The mean values of the differences in five radar parameters (CPS-9 value - SO-12 value), including the number of observations n and the standard deviation s, for simultaneously observed radar echoes in northeastern Colorado in 1963. The results of a paired t test are shown with an asterisk (*) denoting values significant at the 5 percent confidence level.

	n	Mean	s	t
Echo Top (Thousands of Feet)	17	0.82	6.6	0.514
Elev. Z_{mx} (Thousands of Feet)	17	-1.06	6.1	-0.712
	16	8.00	7.1	4.560*
	14	9.36	5.2	6.711*
	11	3.00	9.1	1.100

looking at the same identical cell; the identification of the observed cell as a hailer or non-hailer did not enter into the comparison. The most difficult problem in such a study is the assurance that both the CPS-9 and SO-12 radars are monitoring the same cell. However, the resolution of the SO-12 horizontal scan is of such increment (1° - 2°) that the position of a cell that both radars are nearly simultaneously observing can be accomplished with sufficient accuracy.

Table 8 shows the results in the comparison of the various radar parameters between the CPS-9 and the SO-12. A paired t test was used to test for significance, at the 5 percent confidence level, the hypothesis that the mean difference of the radar parameters observed on the two radar systems was not different from zero. For our data, Table 8 reveals that the only significant differences existing between the two radar systems occurs when observations are made of the maximum reflectivity factor and the reflectivity factor at 20,000 feet MSL. The fact that there is no significant difference in observations of echo tops between the two radar systems is encouraging. The difference in observations of the elevation of the maximum reflectivity and the value of the reflectivity at 30,000 feet MSL are likewise found not to be significantly different.

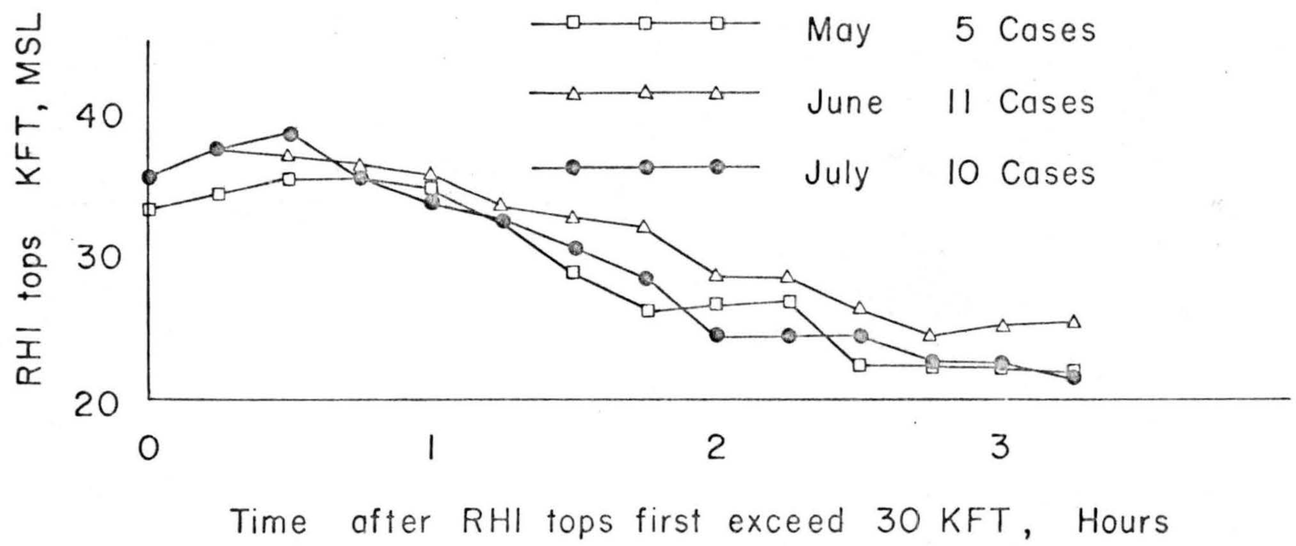

Figure 2. Echo tops versus time after echo tops first exceeded 30 KFT for hailers.

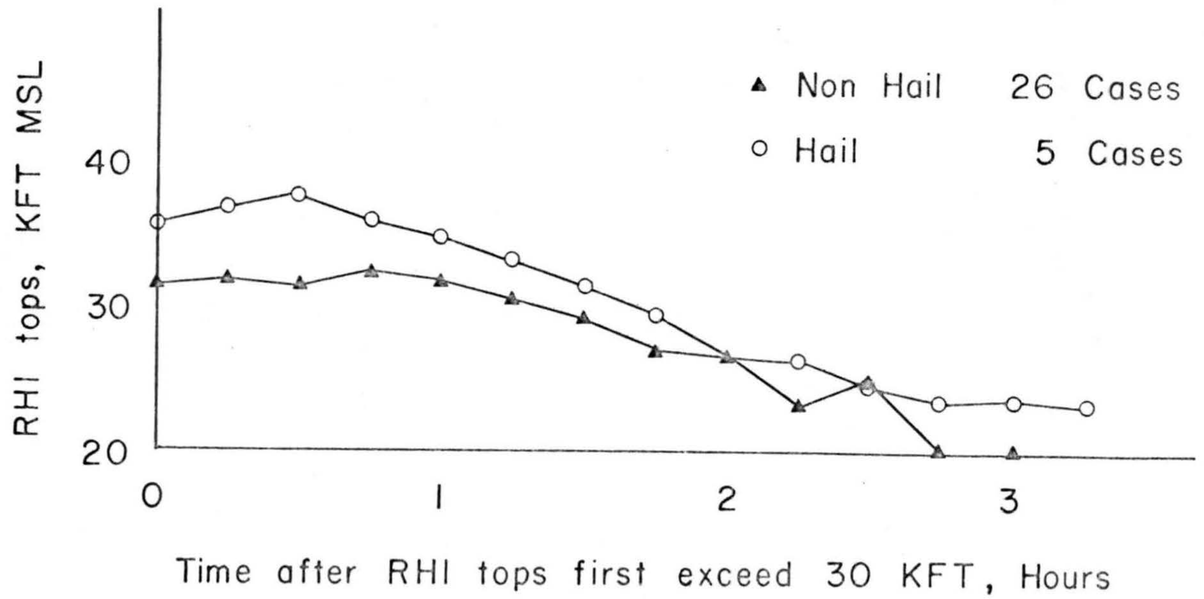

Figure 3. Average echo tops as a function of time after top first exceeded 30 KFT for hailers and non-hailers.

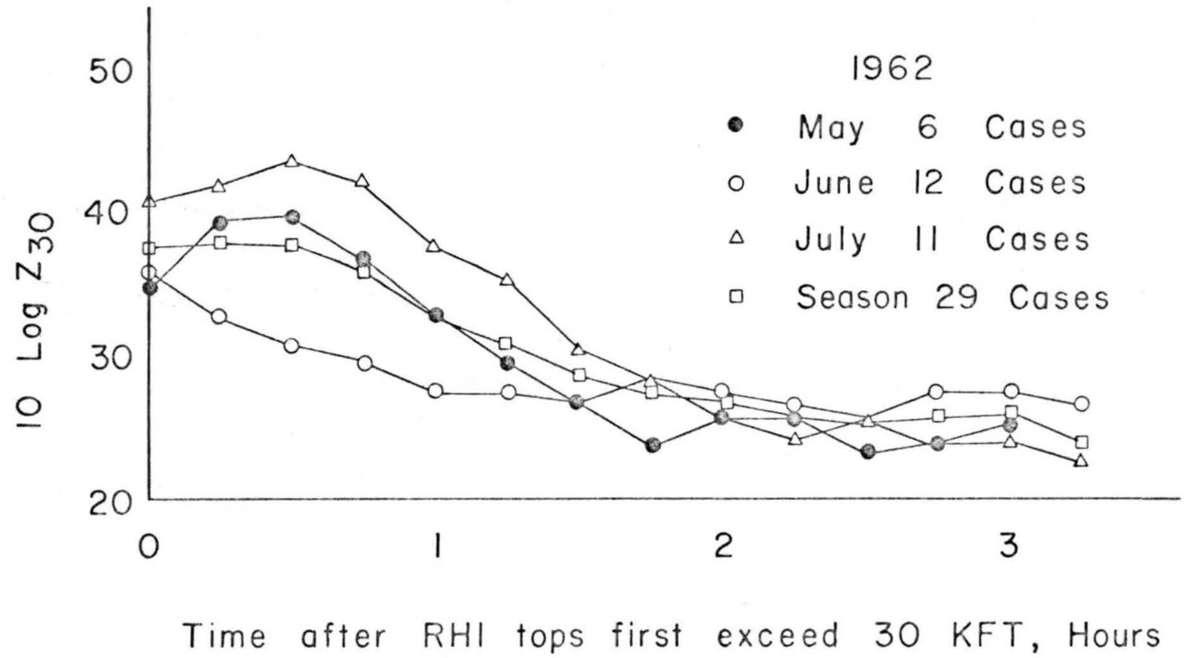

Figure 4. Average 10 log Z_{30} as a function of time after echo tops first exceeded 30 KFT for hailers.

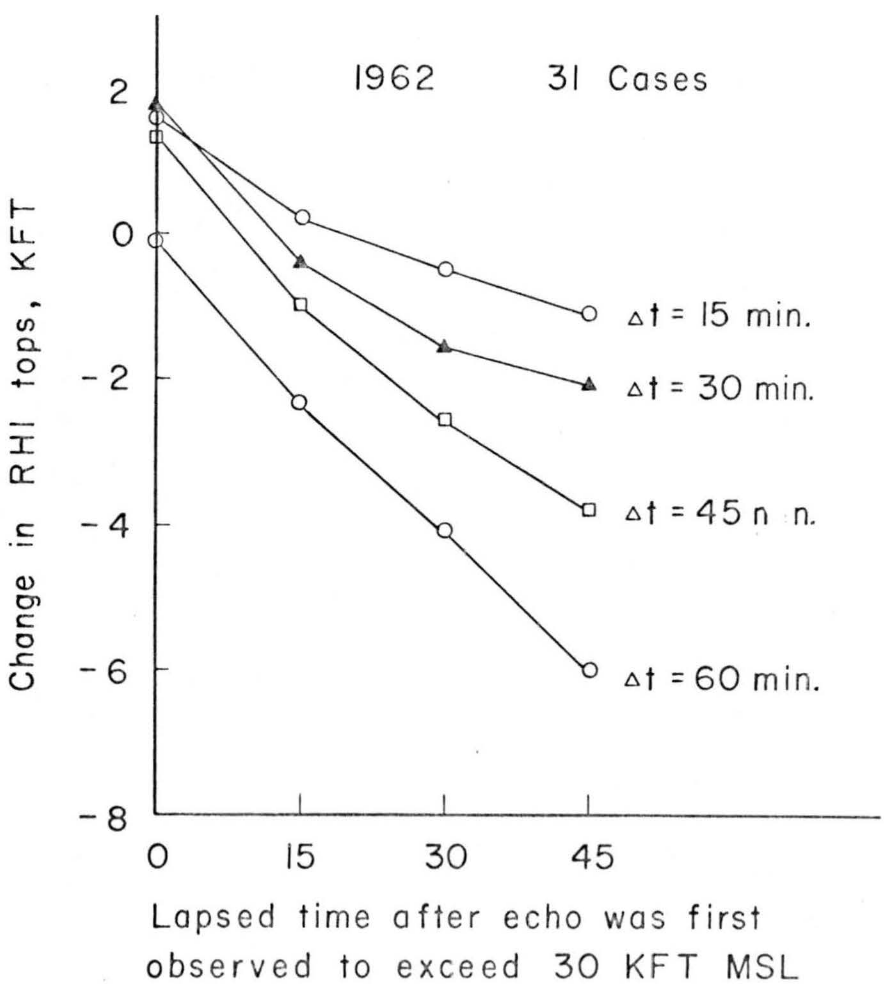

Figure 5. Average change in echo tops for various time intervals as a function of time after the echo was first observed to exceed 30 KFT.

APPENDIX I

DESIGN OF THE SEEDING EXPERIMENT, 1964

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DESIGN OF THE SEEDING EXPERIMENT, 1964

The eventual purpose of the Colorado State University hail suppression research program is the development of a systematic attempt to modify the hail-bearing thunderstorm of northeastern Colorado. This appendix summarizes the techniques used during the 1964 hail season.

The experimental procedures for the 1964 season were designed to provide comparisons of physical parameters of the hailstorms at successive times for an interval before, an interval during, and an interval after the seeding of storms selected at random and for other control storms left unseeded (also selected randomly) for corresponding periods. Differences between seeded and unseeded storms are to be evaluated for significance after the accumulation of a significant number of cases.

On days for which hail was forecast the seeding aircraft was placed on "stand-by". At the time of development of individual thunderstorms, the aircraft was ordered airborne and vectored to a location for possible seeding. The aircraft made measurements of updrafts and downdrafts in the vicinity of the thunderstorm which was being observed by radar during this preliminary time. When the radar echo was observed to exceed 30,000 feet MSL, and at the same time to have updrafts underneath the cloud exceeding 500 feet per minute, a decision order was given by the radar controller for the pilot to open a field envelope containing a random decision to "seed" or "not seed". If the decision resulted in seeding the storm, the pilot attempted to place the silver iodide in the strongest updraft of the storm and continued seeding until either the storm dissipated, passed beyond the radar range, or the aircraft and/ or generator ran low of fuel. For a "no seed" decision the pilot remained airborne to observe during the same period of time as though seeding were actually taking place. In either situation the test cases were carried on for approximately one hour. The pilot and the observer on board the seeding aircraft were the only personnel that knew at the time whether or not the thunderstorm was being seeded.

Ground radar observations during the case period included the following: radar echo tops, echo maximum reflectivity, elevation of maximum reflectivity, and plan position track. Other ground observations consisted of both 16 mm time lapse movies and conventional 35 mm photographic slides; changes in cloud appearance were also noted. Field surveys determined the extent and intensity of hail, maximum stone size, estimated impact energy numbers, and precipitation (see Appendix A). Pilot balloons were released to determine environmental air patterns.

During the test case the seeding aircraft was used to record various types of information. Such recorded information was: altitude, outside air temperature, time, indicated airspeed, magnetic heading, engine power settings, gear and flap positions, G-meter readings, and vertical speed. The observer also took numerous 35 mm slides and 8 mm movies from the aircraft. Following the termination of seeding or equivalent time for the "no seed" cases, the aircraft was used for aerial reconnaissance of areas of rain and hail on the ground.

An observation airplane was used in 1964 for all test cases. It carried an observer that took photographs and made observations of the test thunderstorms being studied.

Test cases were selected on eight different days in 1964. Four of these days provided "seed" test cases and three of these days provided "no seed" test cases; on the remaining day a decision was made to seed, but one generator became inoperative after experiencing severe turbulence the day before, so this day was not considered to be a test case. Also during the 1964 season there were two additional days of seeding. The operations during these days consisted of seeding small cumulus clouds and observing them for any effects.

A description of the data and the results obtained for the test cases during the 1964 season may be found in the report by Schleusener and Sand (1964).