The 1959 Hail Suppression Effort in Colorado, And Evidence of its Effectiveness

By
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Presented at the International Congress on the Physics of Clouds (Hailstorms)
at Verona 9-13 August 1960

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SOMMARIO

Nel 1959 nel Nord-Est del Colorado furono fatti tentativi in larga scala per ridurre i danni della grandine in un'area di circa 3.400 miglia quadrate.

Da una ditta commerciale furono seminate le nubi usando circa 125 generatori a terra di ioduro d'argento, e cinque aeroplani.

Ognuno di questi fu dotato di due generatori di ioduro di argento.

Furono fatti confronti fra le caratteristiche della grandine dei temporali che furono seminati con quelle delle aree non seminate. Tali confronti furono fatti sia sulla distribuzione delle dimensioni che sul numero dei chicchi per unità di superficie.

Fu costruito un impattore per la grandine al fine di determinare l'energia d'impatto della grandine per unità di superficie.

Apparentemente i dati che risultano dalla semina delle nubi sono in alcune occasioni favorevoli. In altre occasioni non si sono avute differenze. In pochi casi vi fu pure un apparente sfavorevole effetto nei riguardi della grandine associata con la semina delle nubi. Dai controlli effettuati col radar risulta che si ha un aumento delle precipitazioni associato con la semina delle nubi.

SUMMARY

A large-scale attempt was made to reduce hail damage in an area of about 3400 square miles in northeastern Colorado in 1959. Clouds were seeded by a commercial firm, using about 125 ground-based silver iodide generators and five aircraft. The aircraft were each equipped with two silver iodide generators.

Comparisons were made of hail characteristics between those storms considered to have been seeded and those in adjacent areas that were not. Such comparisons were made of size distribution and number of stones per unit area. A hail impact meter was developed as a passive recorder to interpret hail falls in terms of impact energy per unit area.

The data indicate apparently favorable results from the cloud seeding on some occasions. On other occasions no differences could be detected. In a few cases there was an apparent unfavorable effect on hail associated with the cloud seeding.

A target-control analysis indicates a positive precipitation anomaly associated with the cloud seeding.

1. Introduction.

The problem of hail damage to crops in certain regions is of major concern to the agricultural industry. The amount of damage caused annually by hail is much larger than generally realized. Flora [1]* points out that "More property damage is caused by hail throughout the United States than by tornadoes, and in some years hail damage comes surprisingly close to that of hurricanes... In many parts of the High Plains between the 100th Meridian and the Rocky Mountains hail destroys, on the average, 8 to 10 per cent of all crops annually". The high rate of hail incidence is reflected in the cost of insuring a crop against hail damage. In many sections of northeastern Colorado the cost of insuring wheat against hail damage is as high as $ 22.00 for $ 100.00 of insurance under a standard "10 per cent deductible" policy [2].

In addition to agriculture, the aircraft industry has an interest in hail because of the damage that may be incurred by airplanes when in flight (3,4) or on the ground.

The highest hail occurrence in the nation occurs approximately at the meeting of the Nebraska, Wyoming and Colorado borders. The high crop losses in this region prompted the residents near Scottsbluff, Nebraska, to attempt hail suppression measures as early as 1953 and to continue them through 1958 [5]. For the same reasons, a hail suppression operation was organized in northeastern Colorado during the 1958 hail season, and was expanded in 1959. The location of the 3400 square mile area is shown in Fig. 1. The funds necessary to perform the operation were raised by voluntary contributions. The recommended rate was $ 0.15 per acre for dry land and $ 0.50 for irrigated land. The contributions averaged about $ 60.00 per donor. Very few contributions exceeded $ 100.00 [6]. The contributors incorporated as the Northeast Colorado Hail Suppression Association of Sterling, Colorado, and contracted with the Weather Modification Company of San Jose, California in 1959, for conducting the seeding operation. The operation began on 15 May, utilizing 5 aircraft, and approximately 125 ground-based silver iodide generators. Each aircraft was equipped with two silver iodide generators.

An independent study was made of this operation in 1959 at the request of residents of the suppression area.

2. Objective.

The objective of the study was two-fold:

1) To study the characteristics of hail events in northeastern Colorado.
2) To utilize such information as would be available from a one-year study to attempt to evaluate the effects of the cloud-seeding program on hail and precipitation.

* Numbers refer to appended references.

3. Procedure.

Data for the study were collected from two major sources: 1) reports of hail and precipitation by voluntary observers; and 2) hail indicators, which were designed to record impressions of hailstones. Fig. 2 shows the reporting form used by the voluntary observers. Fig. 3 is a schematic drawing of a hail indicator, described in detail elsewhere [7].

Requests for hail reports were mailed to residents of the area

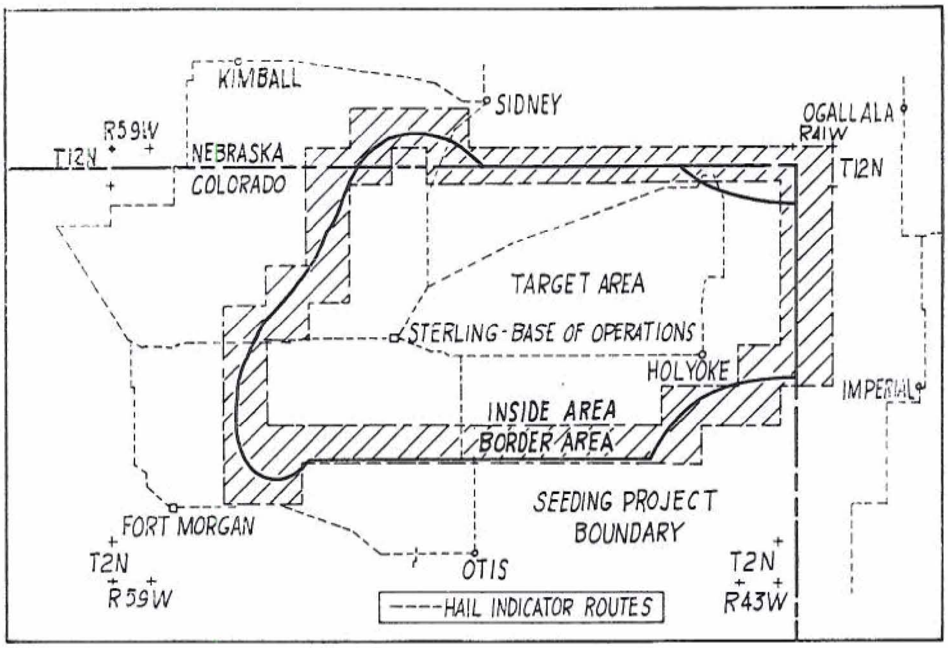
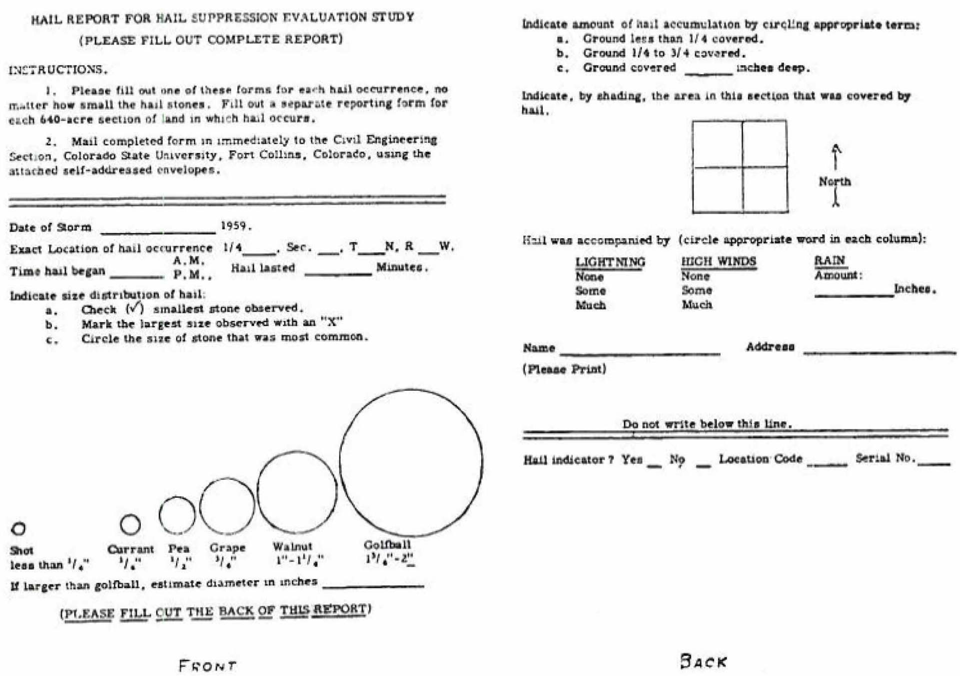


Figure 1 - Study area in northeastern Colorado; including location of routes along which hail indicators were located and the area in Colorado covered by volunteer observers (T2N-12N; R43W-59W). "Oustside Area" designates the region in Colorado north of TIN and east of R60W outside the perimeter of the "border" area.

living in or near Sections 8 and 18 in each Township in Colorado between Townships 3 and 12N and 42 and 89W inclusive. Cooperators were requested to report hail occurrences by mail, using the forms shown in Fig. 2. A total of 389 such reports were received between 15 May and 15 September 1959.

Approximately 250 hail indicators were located in or near the target area. The routes along which the indicators were located are shown in Fig. 1. Damage to indicators occurred in 358 cases. For these cases the impact energy of the hail (ft-1bs per sq ft) was estimated at the location of the indicators from measurements of the number of dents per square inch and the size of the dents [7].


HAIL REPORT FOR HAIL SUPPRESSION EVALUATION STUDY
(PLEASE FILL OUT COMPLETE REPORT)

INSTRUCTIONS.

1. Please fill out one of these forms for each hail occurrence, no matter how small the hail stones. Fill out a separate reporting form for each 640-acre section of land in which hail occurs.

2. Mail completed form in immediately to the Civil Engineering Section, Colorado State University, Fort Collins, Colorado, using the attached self-addressed envelopes.

Date of Storm ________ 1959.

Exact Location of hail occurrence 1/4____, Sec. ___, T___N, R ___W.

Time hail began ______ A.M. P.M., Hail lasted ______ Minutes.

Indicate size distribution of hail:

a. Check (√) smallest stone observed.
b. Mark the largest size observed with an "X"
c. Circle the size of stone that was most common.

If larger than golfball, estimate diameter in inches ________

(PLEASE FILL OUT THE BACK OF THIS REPORT)

FRONT

Indicate amount of hail accumulation by circling appropriate term:

a. Ground less than 1/4 covered.
b. Ground 1/4 to 3/4 covered.
c. Ground covered ______ inches deep.

Indicate, by shading, the area in this section that was covered by hail.

Hail was accompanied by (circle appropriate word in each column):

LIGHTNING	HIGH WINDS	RAIN
None	None	Amount:
Some	Some	______ Inches.
Much	Much	

Name ________ Address ________
(Please Print)

Do not write below this line.

Hail indicator ? Yes __ No __ Location Code ____ Serial No. ____

BACK

Figure 2 - Hail reporting form used by volunteer observers.

Other sources of data for the study include:

1) Reports from the Weather Modification Company on locations and times of ground-generator operation and routes and times of seeding by aircraft.
2) Information on the amount and type of hail damage to sugar beets between 1929 and 1959 from the Ovid, Sterling, and Fort Morgan Factory Districts of the Great Western Sugar Company.
3) Reports of precipitation and other weather data from the U. S. Weather Bureau cooperative observers in and near the area.

From these data, a subjective decision was made as to whether or not a particular hail event (reported by cooperators or recorded on an indicator) was considered to have been seeded in time to have possibly affected the hail occurrence. Once made, this decision was not changed in subsequent analyses.

4. Results.

A. Presentation of basic data

Summary of events

Fig. 4 gives a summary of pertinent events such as number of days with hail, precipitation, and dates of cloud seeding during the

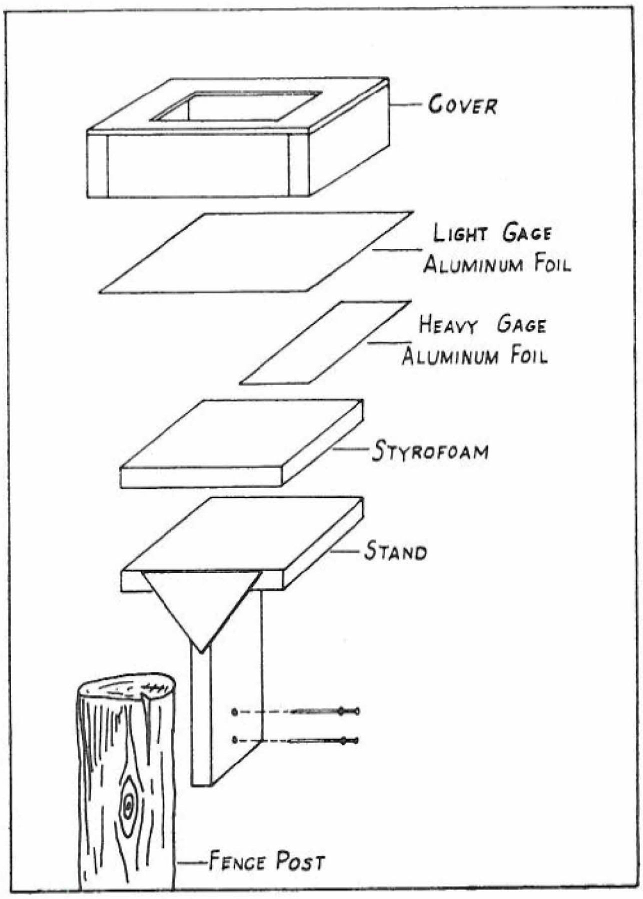


Figure 3 - Schematic drawing of hail indicator.

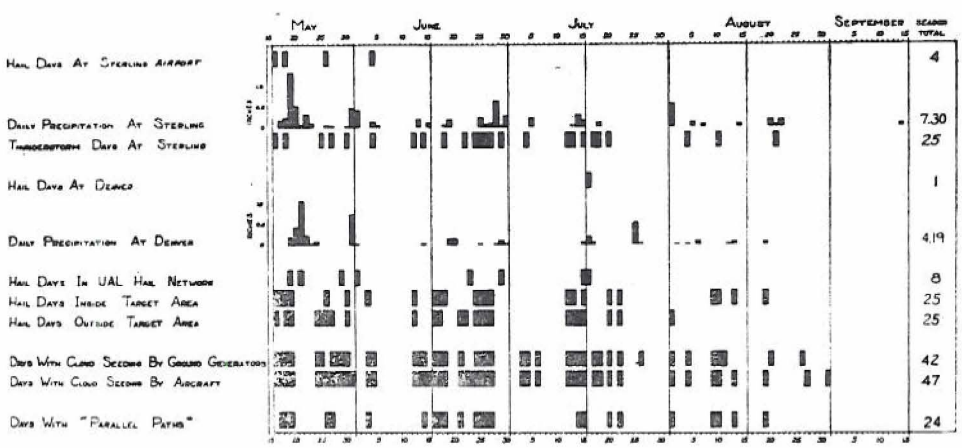


Figure 4 - Summary of events for 15 May - 15 September 1959. For purposes of comparison, significant events in the UAL (United Air Lines) hail network and at Denver (Stapleton Airfield) are included. The meaning of "Days with Parallel Paths" is given in the accompanying text.

1959 hail season for northeastern Colorado. Pertinent data for the vicinity of Denver are given for comparison.

Time of hail onset

The time (MST) of hail onset for northeastern Colorado as reported by the cooperative observers is shown in Fig. 5. A comparison with Beckwith's data [8] for Denver is shown in Fig. 6 in terms of accumulative relative frequency. It can be seen that hail tends to occur later in northeastern Colorado than it does in the Denver area.

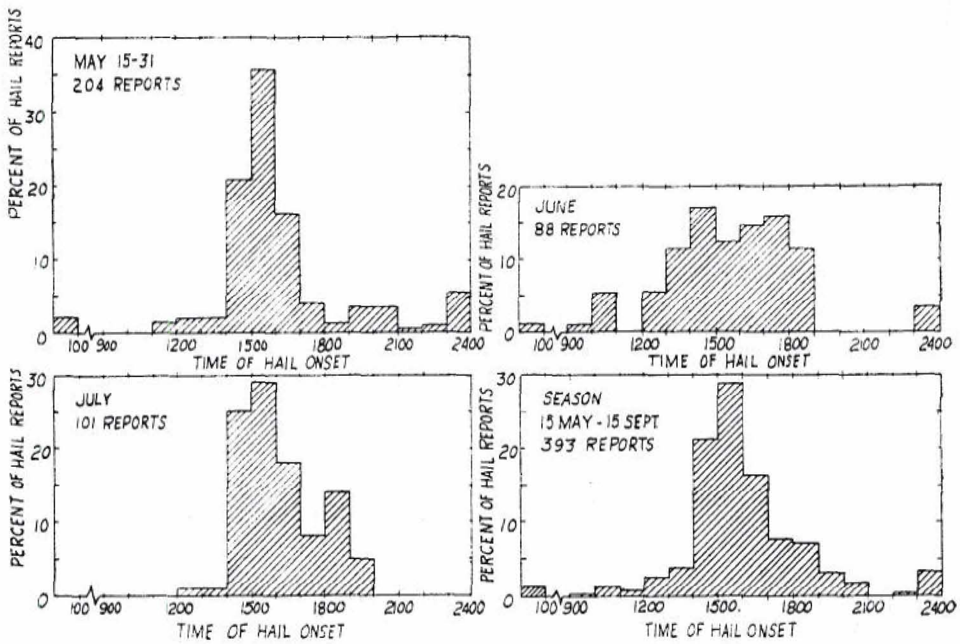


Figure 5 - Time of hail onset, based on reports from volunteer observers in northeastern Colorado, shown as a percentage of total reports for each hour.

This observation, since the target area is farther from front range than Denver, lends support to the hypothesis that the front range of the Rocky Mountains may play a prominent part in the formation of thunderstorm activity which moves from the continental divide eastward across the plains.

Duration of hailfall

Fig. 7 illustrates the frequency distribution of duration of hailfalls in northeastern Colorado for the 1959 season. It will be noted that approximately one-third of the hail events lasted five minutes or less at a given reporting point.

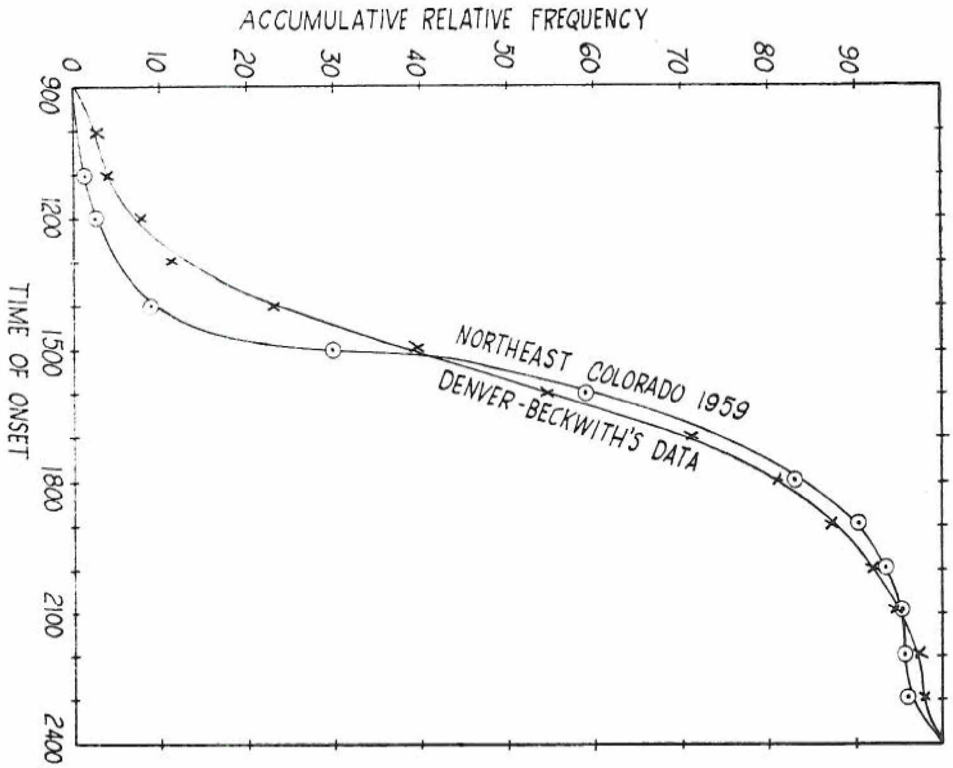


Figure 6 - Comparison of time of onset of hail in northeastern Colorado with Beckwith's data for Denver.

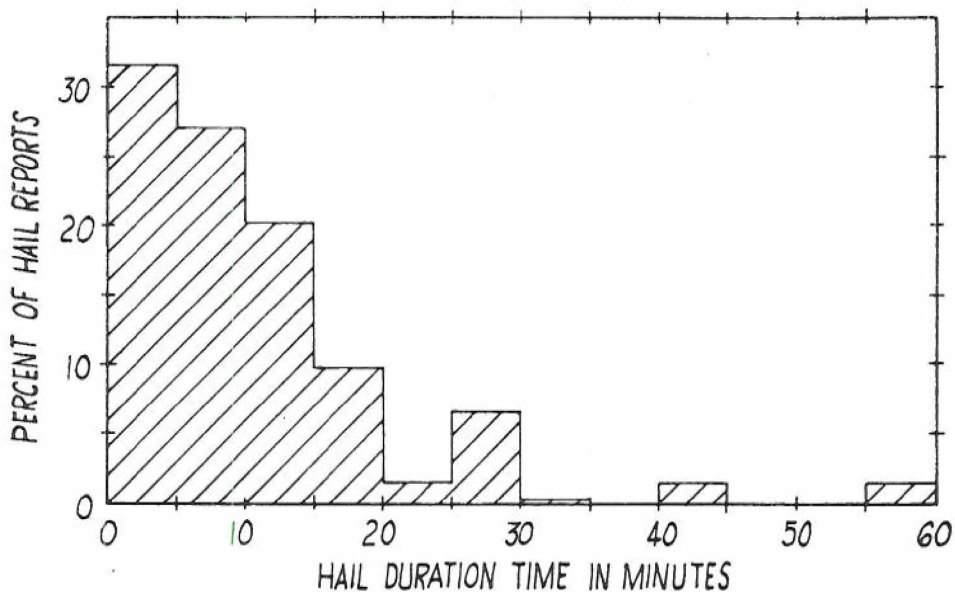


Figure 7 - Frequency distribution of duration of hail fall in northeastern Colorado for the period 15 May - 15 September 1959, based on 356 individual reports from volunteer observers.

Frequency distribution of number of stones per unit area

The frequency distribution of number of stones per square inch for hailstorms in the region as determined from the hail indicators is shown in Fig. 8. Approximately one-half of all the hailstorms produced fewer than one stone per square inch.

Hail damage paths and cloud-seeding routes

Fig. 9 shows hail damage paths and aircraft seeding paths by months. A hail damage path was arbitrarily defined as hail reported at two or more locations separated in time by thirty minutes or more. The aircraft seeding paths plotted are the mean directions of

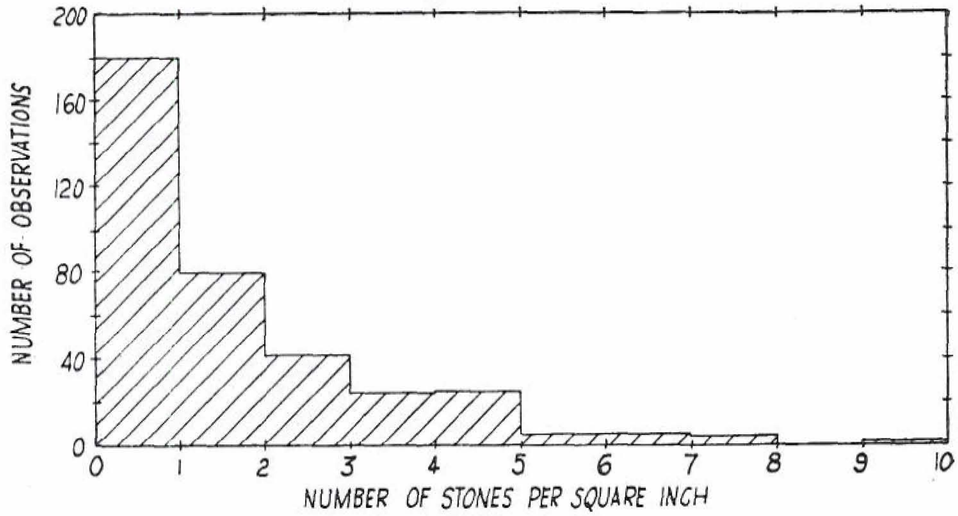


Figure 8 - Frequency distribution of the number of stones per square inch for hailstorms in 1959 in northeastern Colorado, based on counts of dents on hail indicators.

the zig-zag paths flown by the aircraft when seeding a thunderstorm cell. From the figures it is seen that the general direction of hail paths is from east to west in May, shifting to a generally north-to-south alignment by July.

From Fig. 9, it may be seen that many cells were seeded that did not produce hail, since the relative density of the seeding flights

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* Let n = total number of observation of x

fi = the number of x's that fall in the i^{th} class of x

$\frac{fi}{n}$ = the relative frequency with which the observed x's fall into the i^{th} class

Then the accumulated relative frequency in per cent for x ≤ the x for the k^{th} class is: i = k

$$ARF = \frac{\sum_{i=1}}{n} \times 100$$

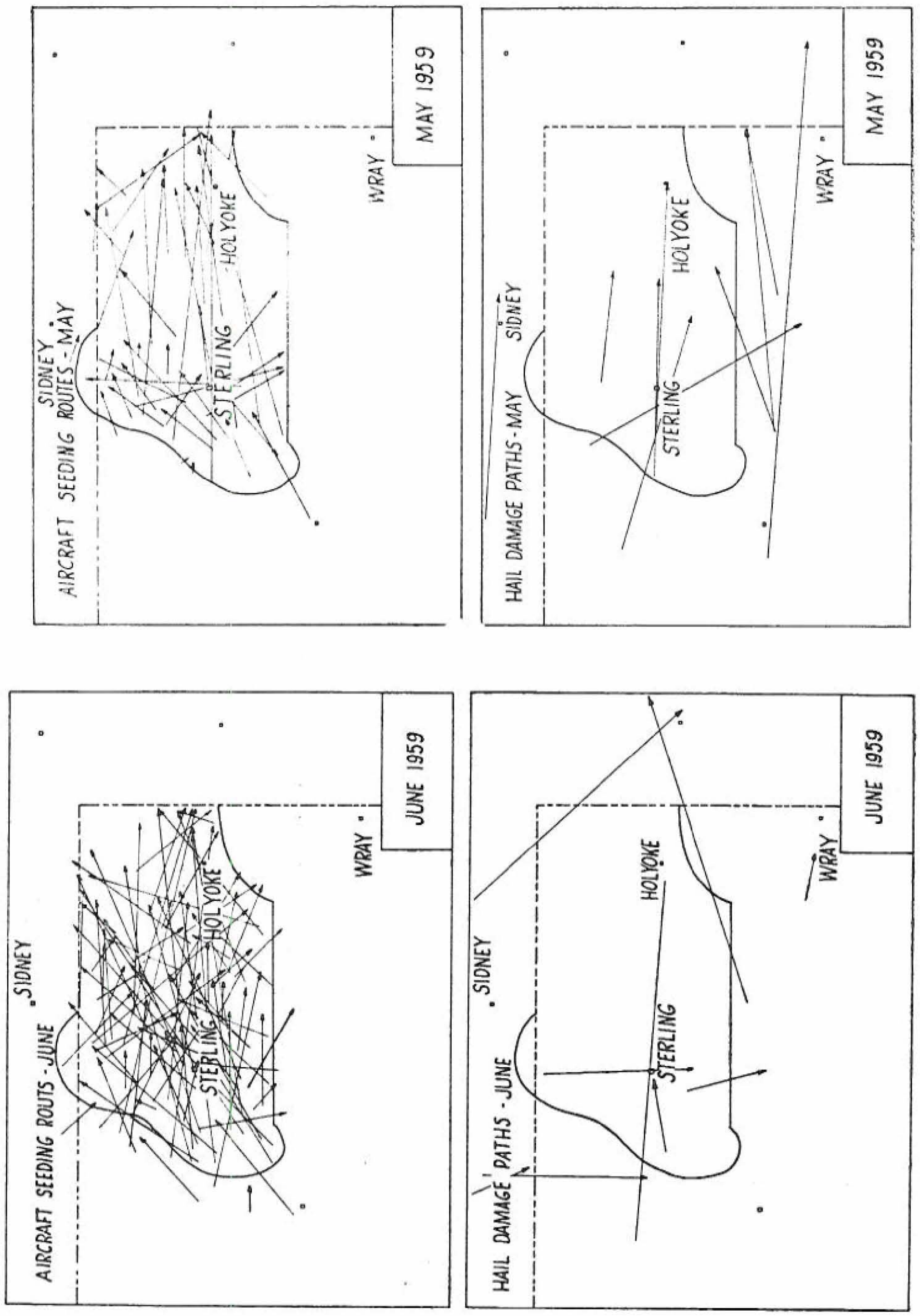

Figure 9a

Figure 9b

Figure 9a, 9b, 9c - Hail damage paths and aicraft seeding routes.

was from five to ten times that of the hail damage paths throughout the season. These seeding flights represent the occurrence and direction of thunderstorm cells considered to be potential hail producers by the meteorologists of the Weather Modification Company.

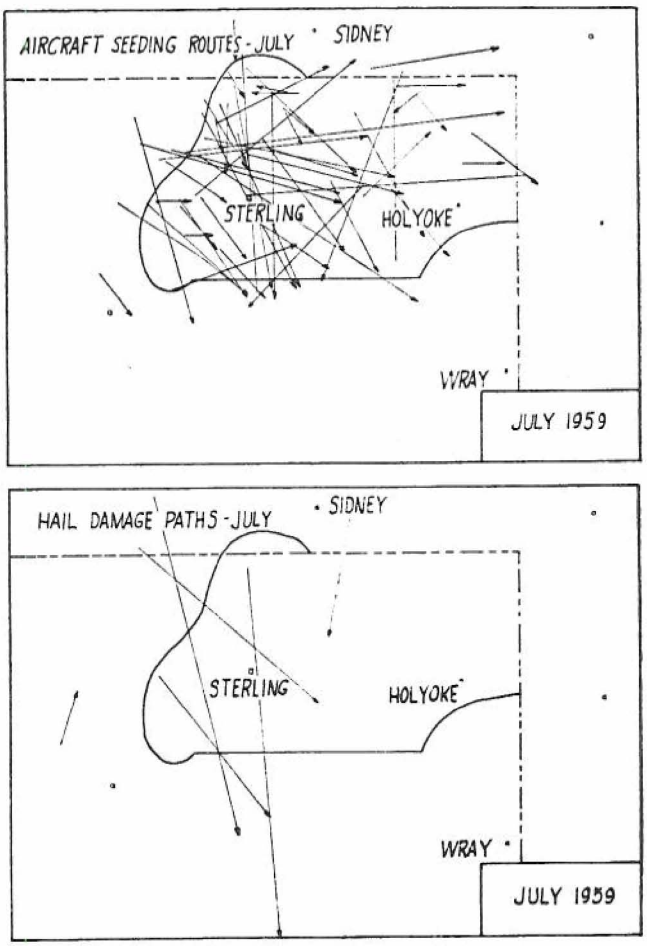

Figure 9c

Hail in relation to 500 mb winds

Fig. 10 illustrates the direction of the 500 mb wind and the deviation of the direction of the hail path from the 500 mb wind on days with hail in northeastern Colorado for 15 May - 15 September 1959.

The 550 mb wind shown in Fig. 10 is the average of Denver and Goodland. The mean direction of this average 500 mb wind for days with hail in northeastern Colorado was 290 degrees. The mean 500 mb wind given by Beckwith [8] for days with hail in the Denver area was 240 degrees for the period 1949-55. The direction of the hail damage paths follow closely that of the 500 mb wind directions; 65 per cent paths are included in a ± 30 degree deviation from the 500 mb wind direction.

Frequency distribution of hail impact energy values

Accumulated relative frequency of hail impact energy values for non-seeded hail cases for the study region is shown on Fig. 11.

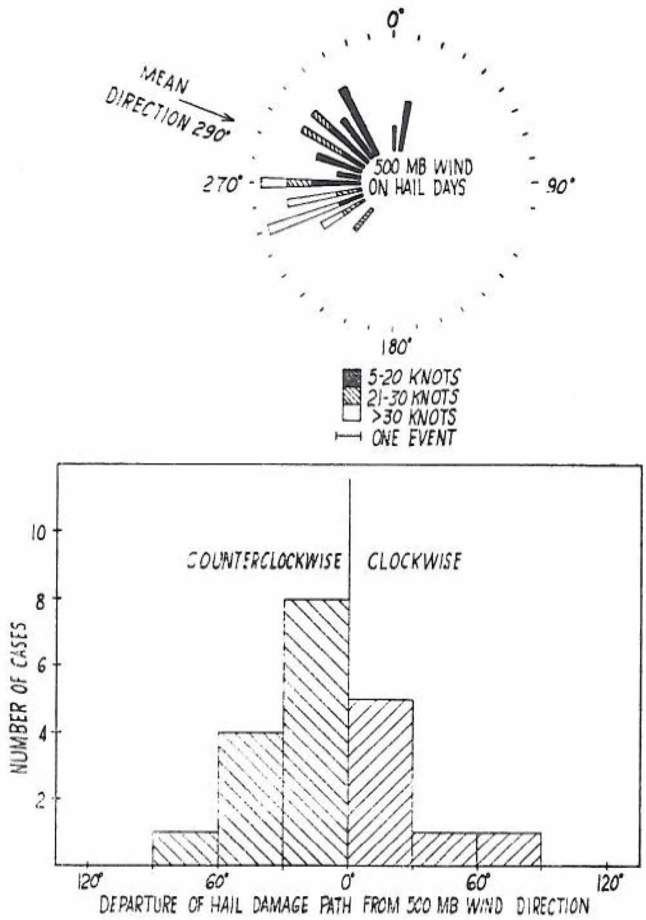

Figure 10 **- Upper winds data at the 500 mb level for days on which hail fell in northeastern Colorado from 15 May - 15 September 1959. Winds are averages of DEN and GLD. (a) Wind rose: for days with hail. (b) Departure from the 500 mb wind direction of the hail damage path.**

Impact energy values were estimated from measurements of the number and sizes of dents produced by the hail on the indicator. The estimates were based on laboratory calibrations [7]. The figure shows that 50 per cent of the energy values were less than about 10-15 ft-lbs per square foot. Field experience by the author indicates that for most field crops grown in the area, such as wheat, corn, and sugar beets, damage becomes noticeable for an impact energy value of about 10 ft-lbs per square foot and is usually severe or complete for energy values greater than about 100 ft-lbs sq ft. It has been shown by Schleusener [9] that if cloud seeding were to reduce the diameter of hailstones, then the impact energy resulting from the

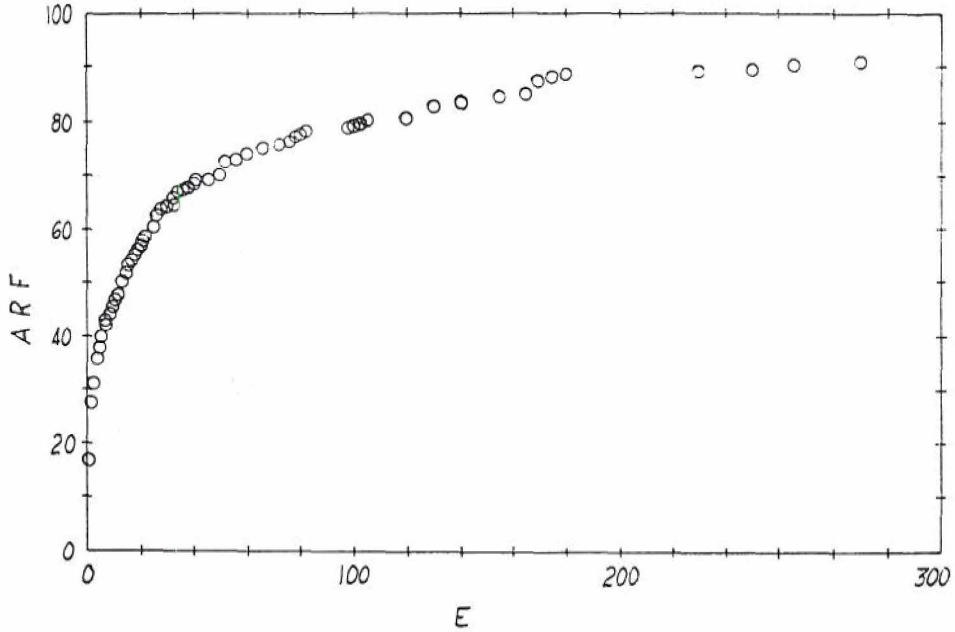

Figure 11 - Accumulated relative frequency (ARF) of hail impact energy (E) for nonseeded storms, based on estimates derived from 150 hail indicators in northeastern Colorado between 15 May and 15 September 1959.

vertical fall of hail would be reduced if there were no change in the total quantity of precipitation that occurred as hail. However, it is possible that any such beneficial effect could be offset by an increase in the total quantity of precipitation if precipitation were increased by seeding and the proportion that falls as hail remains constant [9].

Precipitation anomalies

Precipitation anomalies for a target area and adjacent areas are shown in Fig. 12.

Hail - Precipitation relations

A rank correlation test [11] was performed to test for a relationship between the impact energy estimated from hail occurrences and the total precipitation concurrent with the hailstorm. The results of the tests are in Table I. Impact energy values were approximated from reports of numbers and sizes of stones and attendant wind received from volunteer observers.

The test indicates that there is a high probability of a positive relationship existing between these two variables. This is consistent with the findings of Beckwith [8] of a relation between summer

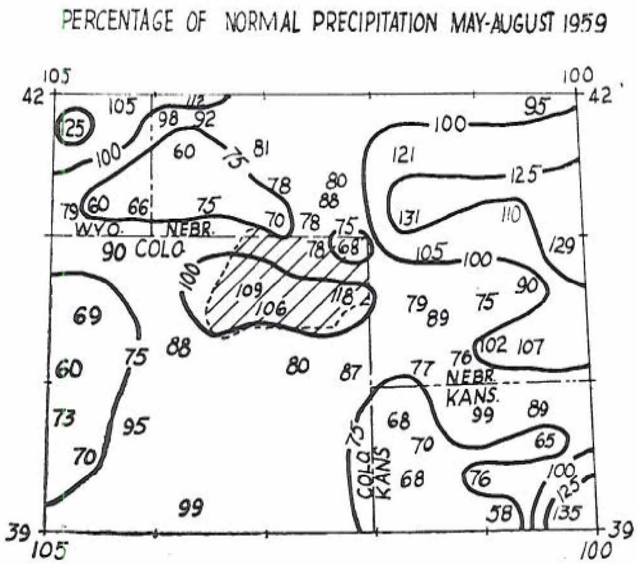

Figure 12 - Precipitation anomalies in and near the study area for the period 1 May - 30 August 1959.

precipitation and number of hail days. No such correlation could be found by Schleusener [9] between seasonal precipitation and hail damage to sugar beets.

TABLE I

Results of rank correlation test between hail impact energy (ft-lb/ft²) and concurrent precipitation (inches)

	Seeded		Non-seeded	
Month	Number in Sample N	Rank Correlation Coefficient r	Number in Sample N	Rank Correlation Coefficient r
May	85	0.183*	93	0.205*
June	34	–0.129	63	0.219*
July	47	0.383**	38	0.127*
Aug.	5	0.90*		

* Significant at the 95 per cent level
** Significant at 99 per cent level

B. Comparisons made in connection with the cloud-seeding program

Target-control analysis of precipitation anomalies

A target-control analysis was applied to attempt to detect precipitation anomalies associated with the seeding program. The technique employed was the same as that described by Thom [10], except that all storm periods were used. The source of data used in the analysis is given in Table 2.

TABLE II

Data used in target-control analysis

Month	Targed	Control	Years of Record	Number of Storm	Correlation Coefficient
May	Sterlin, Ovid, Leroy, Holyoke, Fleming	Greeley, Ft. Collins, Ft. Lupton	1942-48, 1950	26	0.77
June	Sterling, Ovid, Leroy, Holyoke, Fleming	Akron, Yuma, Wray	1942-44 1944-50	40	0.90
July	Sterling, Ovid, Leroy, Holyoke Fleming	Pine Bluffs Kimball	1944-50	45	0.66
Aug.	Sterling, Ovid, Leroy, Holyoke Fleming	Akron, Yuma, Wray	1942-46 1948-49	36	0.65

The results are shown in Fig. 13. Eleven storms occurred in 1959 between 15 May and 15 September. No single storm in 1959 departed from regression by more than two standard errors; hence, no single storm would be considered to depart significantly from what could be expected by chance.

It may be noted from Fig. 13 that of the eleven storms in the 1959 season, one storm fell on the regression line; two fell below, and eight were above the regression lines. The probability of occurrence of eight cases or more out ten indicating a positive anomaly might be compared to the likelihood of tossing an unbiased coin ten times and getting an 8-2, 9-1, or 10-0 distribution.

Using this type of analysis, the probability of getting eight or more positive anomalies out of 10 by chance from an unbiased population is .0547.

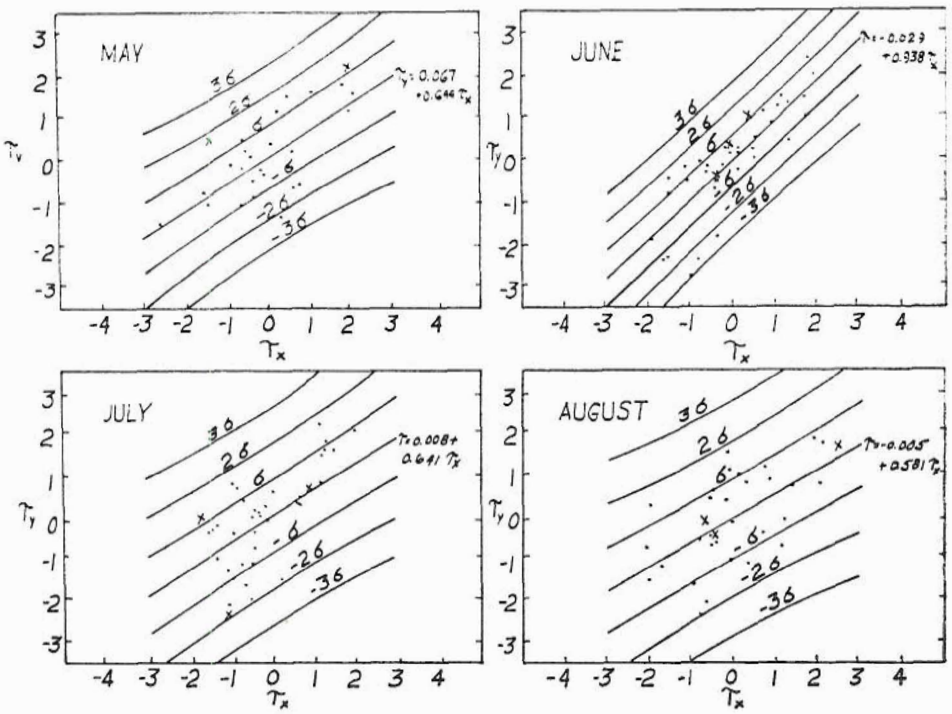

Figure 13 - Target - control analysis for precipitation anomalies. Values given are the normalized transformed precipitation totals for control (τx) and target (τy) stations. Storms in 1959 are marked "x".

Frequency distribution of maximum hailstone size

Fig. 14 shows a comparison of the frequency of various maximum sizes of hailstones through the hail season for hailstorms occurring inside and outside the target area of hail suppression operations. (See Fig. 1).

Frequency distribution of most common hailstone size

Fig. 15 shows a similar comparison for the most common stone sizes. Marked differences in stone sizes between seeded and unseeded cases are not evident from Figs. 14 and 15.

Comparison of hail impact energy values for seeded vs. nonseeded areas

Fig. 16 shows a comparison of accumulated relative frequency of occurrence of hail impact energy for seeded and non-seeded hail events. Fig. 16 indicates an apparent favorable effect from seeding for the month of May, an apparent unfavorable effect for June and July, and an apparent favorable effect for the season. Table 3 summarizes the results of the Kruskal and Wallis [12] test that was

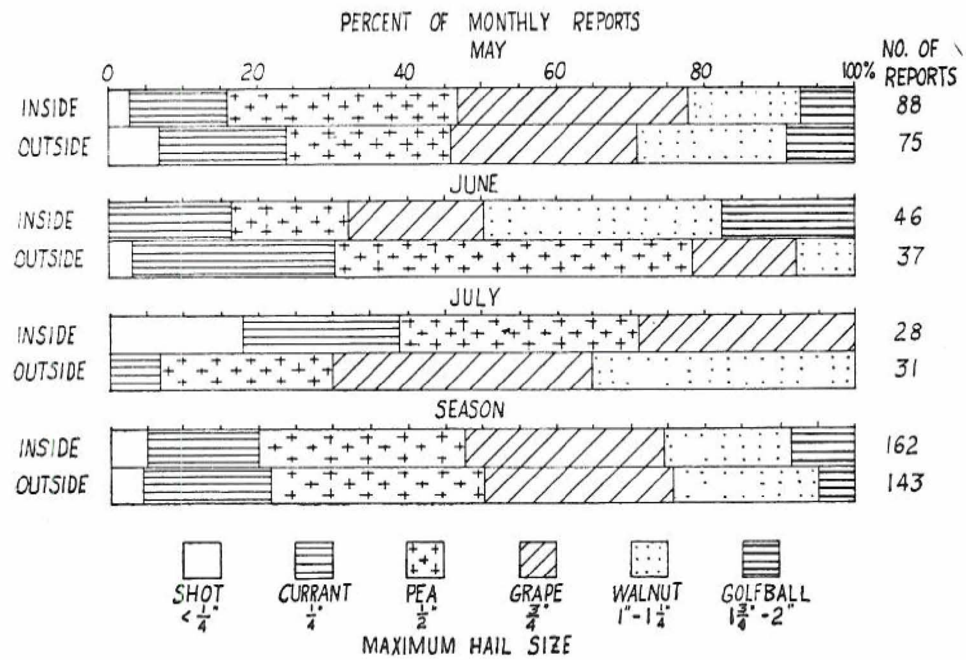

Figure 14 - *Relative frequency of occurrence various maximum hailstone sizes for* hailstorms occurring inside and outside the target area of hail suppression operations for the period 15 May - 15 September 1959.

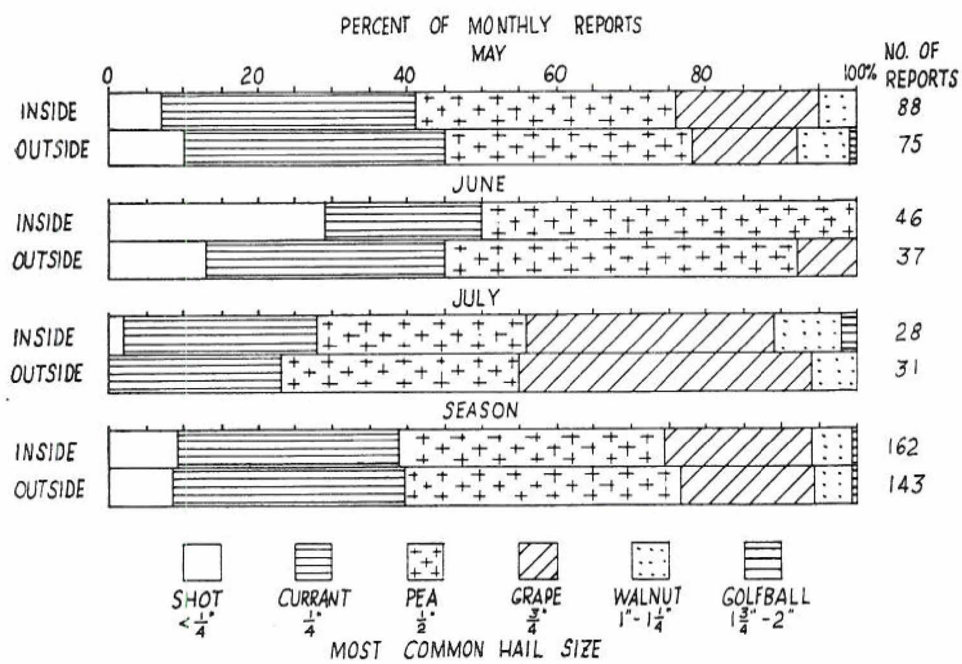

Figure 15 - Comparison of relative frequency of occurrence of various sizes of hailstones that were most common for hailstorms inside and oustside the target area of hail-suppression operations for the period 15 May - 15 September 1959.

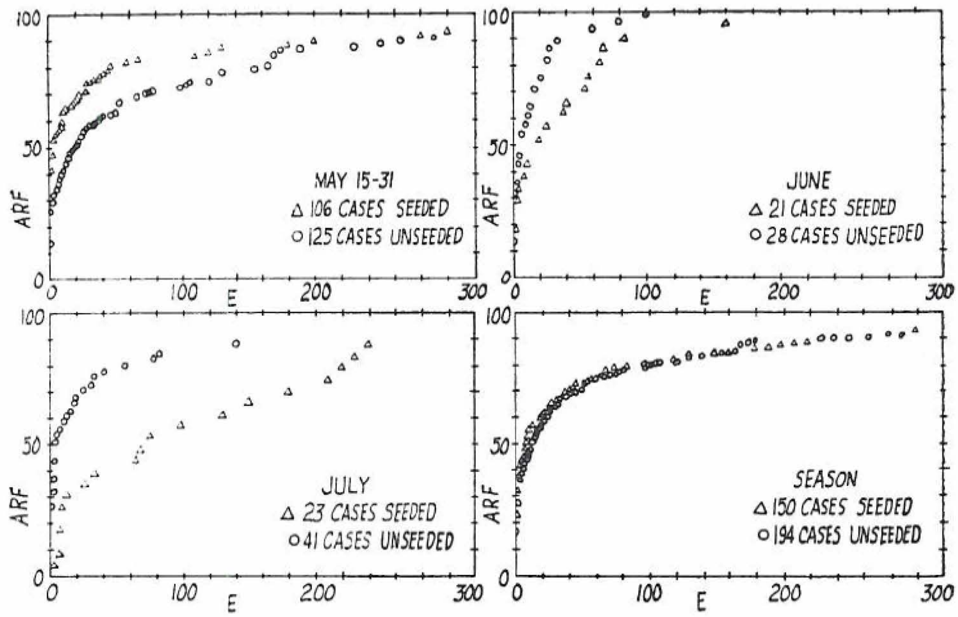

Figure 16 **- Comparison of accumulated relative frequencies (ARF) of hail impact energy values (E) (ft-lbs per sq. ft) for seeded and non-seeded hail cases, based on measurements from 344 hail indicators in northeastern Colorado in 1959.**

applied to attempt to detect differences between the seeded and non-seeded cases.

TABLE III

Summary of Kruskal and Wallis « H » test for differences in the populations of hail impact energy values (E) represented by the samples shown in Fig. 16

	May	June	July
Seeded median E	4	20	75
Non-seeded median E	20	7	5
N, number in sample	231	49	64
H, adjusted	10.502	1.847	11.864
Probability of exceeding H	.0012**	.17	.0006**

The characteristics of the ranking test are described by Kruskal and Wallis as follows:

« The calculations are simplified... only very general assumptions are made about the kind of distributions from which the observations come. The only assumptions underlying the use of ranks... are that the observations are all independent, that all those within a given sample come from a single population, and that the (two) populations are of approximately the same form... » (12:585).

The results of this ranking test indicate statistically significant differences in the population of hail impact energy values-but opposite in effect-for May and July. This could be interpreted as evidence for a favorable effect (decrease in hail intensity) for May, but an unfavorable effect (increase in hail intensity) for July.

Comparisons based on case histories

This conflicting evidence of the effects of cloud seeding on hail from the statistical tests leads to a detailed examination of case histories to attempt to find differences connected with the seeding operation. In making such comparisons several approaches are possible. For example, it would be possible to credit the seeding operation with success on those days on which seeding took place and no hail was reported. Such a procedure, however, would be biased in favor of the seeding operation since not all thunderstorms produce hail at the ground. The statistical analysis used above may suffer from an opposite bias since comparisons were made only for those cases in which hail did reach the ground for seeded case. This approach does not give any credit for a possible effect of complete suppression of hail.

The approach followed in making case history studies was as follows: Cases were examined in which it was possible to make comparisons of changes in hail (in terms of impact energy values, and areal extent), either between seeded and unseeded storms, or before and after seeding of a single storm. When such comparisons were possible, evidence was sought to test possible hypotheses regarding the effect of seeding operations on hail. The hypotheses and their implications are:

1) Seeding operations produce an increase in hail.

   a) From a storm producing hail, an increase in hail accompanies seeding treatment.

   b) When meteorological conditions are similar, a seeded hailstorm is more severe than a non-seeded one.

2) Seeding operations produce no effect on hail.

   a) From a storm producing hail, no significant change in hail accompanies seeding treatment.

   b) When meteorological conditions are similar, seeded and unseeded hailstorms are similar.

3) Seeding operations produce a decrease in hail.

   a) From a cloud producing hail, a decrease in hail accompanies seeding treatment.

   b) When meteorological conditions are similar, a seeded hailstorm is less severe than a non-seeded one.

The first hypothesis is refuted by incidents of seeding and no hail increase. The second is refuted by cases of seeding and a marked change in hail intensity, and the third hypothesis is refuted by incidents of seeding and no decrease in hail intensity.

In addition to examining evidence related to these three hypotheses, the occurrence of « days with parallel storm paths » was noted. A « day with a parallel storm path » was defined as a day in which there were one or more seeded storm paths that did not produce hail that were parallel to a hail path. The significance of such a day is that the occurrence of a hail path indicates that meteorological conditions were such that hail was possible (because it was observed at the ground). In addition, the existence of such parallel paths that were seeded indicate that a complete suppression of hail might have occurred.

Examples and a discussion of three case histories are given in the appendix. A summary of case history analyses for the 1959 season is given in Table 4.

TABLE IV

Summary of cases in northeastern Colorado in which comparisons were possible between seeded and unseeded storms, or before and after seeding of a single storm *

	Comparisons based on	
	Seeded vs. unseeded storms.	Before and after seeding a single storm.
Hypothesis 1 - That seeding operations produce increase in hail intensity.		
Number of days in which comparisons could be made	7	10
Number of days supporting	0	0
Number of days refuting	7	8
Number of days with conflicting evidence	0	2
Hypothesis 3 - That seeding operations produce a decrease in hail intensity		
Number of days in which comparisons could be made	7	10
Number of days supporting	7	7
Number of days refuting	0	1
Number of days with conflicting evidence	0	2

* Based on a total of 40 seeded days between 15 May and 31 July 1959. Hail events in August and September were too infrequent for inclusion in the analysis.

Days that did not produce evidence in support of the first or third hypothesis must be considered as being compatible with the second hypothesis. Cases of this type included those in which hail occurred in unseeded areas alone or seeded areas alone, and cases in which seeding was present and no hail occurred. Cases for which records were relatively incomplete tended to support the second hypotheses.

As indicated in Fig. 4, there were a total of 24 days on which there existed a seeded storm path that did not produce hail that was parallel to another storm path that did produce hail.

These case-history comparisons tend to support the hypothesis that seeding operations produced a decrease in hail. The days with « parallel paths » indicate occasions in which there could have been complete hail suppression effect.

Complicating factors

Attempts to determine the effects of seeding on hail intensity during 1959 in the study are complicated by two additional factore. The area included in the target has a higher crop-hail insurance rate than the adjacent area that was used in comparing hail events*, indicating that the former area probably has a higher natural hail hazard. In addition. parts of the target area received a greater amount of precipitation in 1959 than adjacent areas used for comparison purposes. The target-control analysis mentioned previously suggests that this anomaly may have been associated with the seeding operation, but it is not possible to determine if the proportion of precipitation that fell as hail was more or less than would have occurred in the absence of the seeding operation.

Summary of Comparisons

Table 5 summarizes the comparisons that were made in attempts to find differences associated with the seeding program.

The apparently unfavorable indication from July for hail impact energy (item 4 in Table 5) merits further attention, since this comparison is the primary evidence for a possible unfavorable effect from the seeding operation. There are several possible explanations:

1) The effect may be real.
2) The effect may be caused by a lack of independence in the observations in July. The spacing of the hail indicators on the routes shown in Fig. 1 averaged about 5 miles on east-west lines and about 1 mile on north-south lines. Since the general direction of movement of the storms changed from west-to-east in May to north-to-

* Average rate inside the area was $ 17.75, and the average rate outside was $ 15.30. Median rates were $ 18.00 and $ 15.00 per hundred dollars, respectively.

TABLE V

Summary of comparisons used to attempt to find differences associated with the cloud-seeding operation

Phenomenon Compared	Comparisons Between	Reference	Indications
1. Precipitation amounts	Tared vs. control	Fig. 13	Probable precipitation increase
2. Frequency distribution of maximum hailstone size	Inside vs. outside	Fig. 14	Inconclusive
3. Frequency distribution of most common hailstone size	Inside vs. outside	Fig. 15	Inconclusive
4. Hail impact energy	Seeded vs. non-seeded	Fig. 16 and Table 3	Conflicting: Favorable for May; unfavorable for July
5. Case histories study *a*) Changes in hail intensity	Seeded vs. non-seeded storms	Table 4	Favorable effect
b) Changes in hail intensity	Before and after seeding a single storms	Table 4	Favorable effect
c) Days with « Parallel Paths »	Seeded vs. non-seeded storms	Fig. 4	Favorable effect

south in July (Fig. 9), the observations in July may not meet the requirement for independence.

3) In July the observational program was somewhat curtailed, particularly outside the target area. This factor could tend to produce the apparent unfavorable effect noted in July.

Summary of Evaluation of the Seeding Operation

The results of this study are based on limited observations made during an operational program and are not based on complete observations taken during a designed experiment. For this reason, the results cannot be considered as conclusive, but rather of a preliminary nature. The evidence at hand suggests the following preliminary evaluation of the effects of cloud seeding on hail and precipitation:

1) Cloud seeding probably was associated with decreases in hail intensity and areal extent in some cases during the summer of 1959 in northeastern Colorado.

2) In other cases no changes could be detected in hail intensity and areal extent associated with cloud seeding.

3) A few cases suggest that there might have been an increase in hail intensity associated with the cloud seeding.
4) A comparison of hail events from 15 May - 15 September indicates a reduction in hail impact energy (considered to be related to crop damage) associated with the seeding (Fig. 16). However, the differences observed are small, and are not considered statistically significant.
5) A target-control analysis of precipitation indicates a positive precipitation anomaly for the area included in the cloud seeding program.

As is true with evaluation of precipitation increases, the determination of what hail would have been without seeding is most difficult. Analyses of data from a carefully designed experiment offers the promise of providing more positive and complete information in a minimum of time.

5. Summary.

Hailstorms in northeastern Colorado exhibit characteristics comparable to those of storms in the vicinity of Denver.

Comparisons of hailstone sizes for seeded and non-seeded hailstorms do not provide conclusive evidence for effects of cloud seeding

Comparisons of hailstorms on a case-history basis seem to provide the strongest evidence for a decrease in hail associated with cloud seeding. This apparently favorable effect is also suggested for the season by comparing hail impact energy values for seeded and non-seeded cases. In a target-control analysis of precipitation, 8 out of 10 storms in 1959 indicated a positive precipitation anomaly associated with the seeding program. The likelihood of getting 8 or more positive anomalies out of 10 cases by chance from an ubiased population is .0547.

The study was based on observations made during an operational program of cloud seeding and was not a designed experiment. Conclusions reached regarding the probable effect of cloud seeding are tentative. Further study is essential for greater confidence in the results.

6. Acknowledgments.

The author gratefully acknowledges the assistance of the residents of the study area who supplied reports, and the cooperation of the Weather Modification Company for providing information on the cloud-seeding operation.

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APPENDIX

CASE HISTORY STUDIES FOR 19 MAY, 30 MAY AND 12 JULY

Storm of 19 May 1959

Synoptic situation: Between 1100 and 2300 MST a cold front moved from southeastern Wyoming through the target area to a position between Omaha and Dodge City. Winds at 500 mb were from the southwest at 35-45 knots in advance of a through line located between Salt Lake City and southern California.

Areas of hail damage reports: Fig. 17 shows that most of the reports of hail came from south of the target area.

Special observation: Personal observation by the author from a point about 20 miles east of Sterling indicated distinct differences in cloud forms apparently associated with the seeding operation. Surface and upper air winds were from the south prior to passage of the line of thunderstorms. It is therefore reasonable to believe that thunderstorms that were north of the southern border of the target area were seeded, and that those that were south of this line were not. Differences in cloud form were estimated to correspond approximately to this dividing line. North of this line clouds had a decided ice crystal appearance, but to the south were distinctly water-droplet type clouds.

Comparisons: This day was one in which comparisons could be made between seeded storms (inside the target area) and unseeded storms (south of the southern border of the target area). The reports received indicate less hail in the seeded region.

Comparison of rainfall amounts as shown in Fig. 18 indicates that considerably more precipitation occurred in the seeded region inside of the target area than in the non-seeded region immediately south of the southern border of the target area.

Conclusion: Analysis of this case history indicates good evidence for a favorable effect from the seeding operation in that it was apparently associated with a reduction in hail damage and an increase in precipitation.

Storm of 30 May 1959

Synoptic situation: A wave moved from western Colorado into central Kansas on this date, giving widespread precipitation and hail damage in northeastern Colorado. Winds at 500 mb were from WSW at about 40 knots in advance of a trough in western Montana, Idaho and northern Nevada.

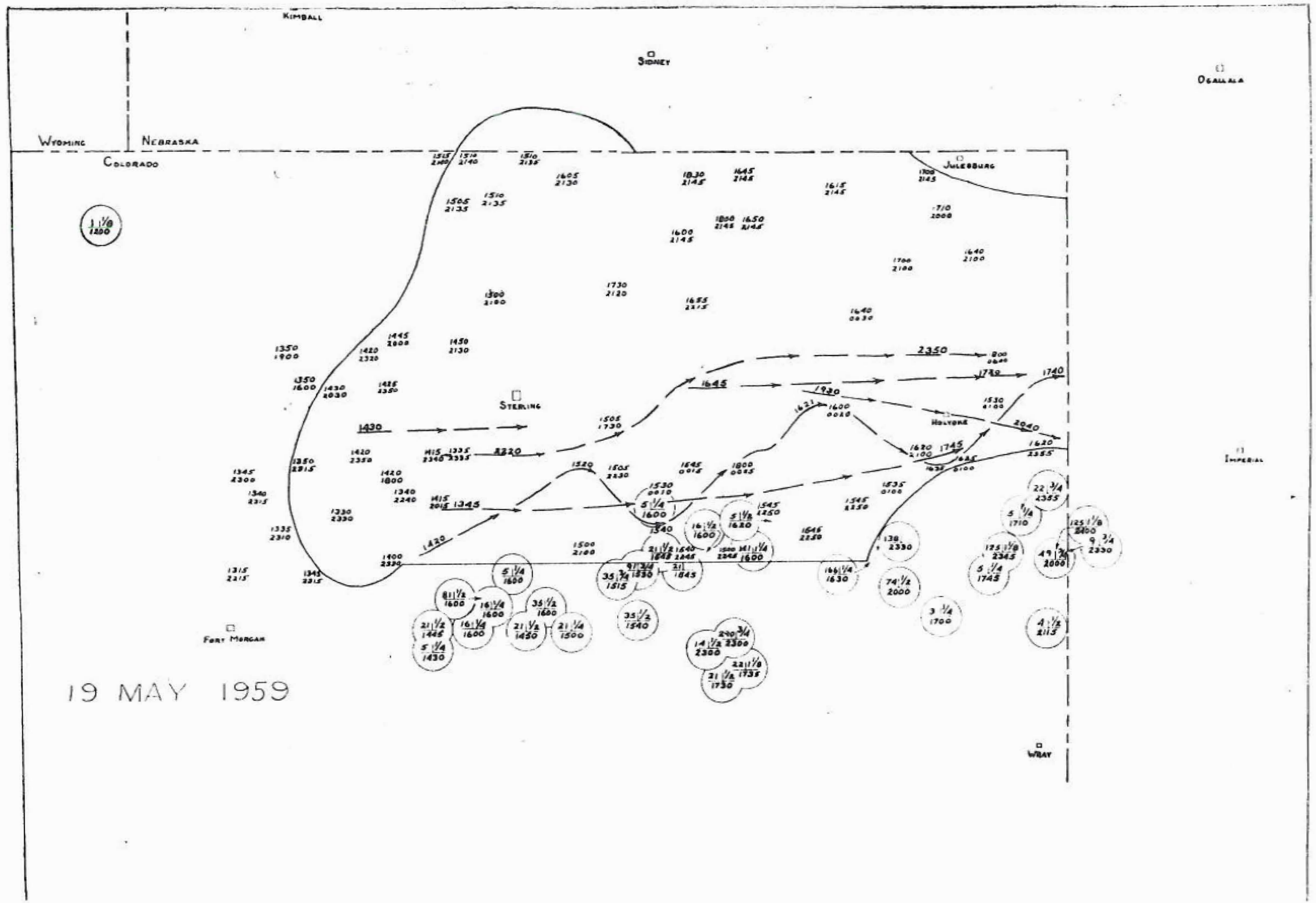

Figure 17 - Case history of 19 May 1959. Circles show location of hail reports and include the time of hail occurrence (MST), the estimated hail impact energy in ft-lbs per sq. ft, and the diameter of the maximum hailstome reported. Uncircled figures indicate locations and times of ground generator operation. Arrows show the general routes and times of cloud seeding by aircraft.

Areas of hail damage reports: Fig. 19 shows that hail fell in much of northeastern Colorado. The most severe damage path began near Fort Morgan and moved eastward to the Colorado-Nebraska border (The last half of this damage path is not shown on Fig. 19).

Special observations: Reconnaissance of the area along the western border of the target area showed a region where hail intensity and areal extent decreased concurrently with the beginning of

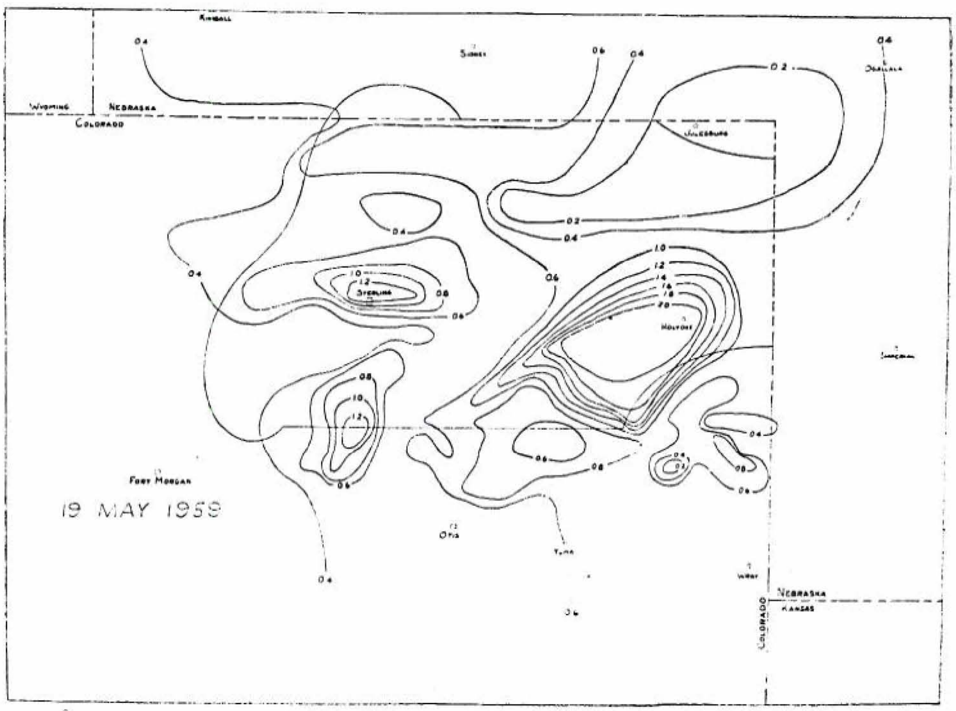

Figure 18 **- Case History of 19 May 1959. Iso-Lines show the amount of precipitation received (in inches).**

seeding. However, as the storms moved eastward, hail increased in the vicinity of Sterling, then again decreased to zero as the storms moved toward Holyoke. In contrast, the storm that began near Fort Morgan continued eastward without significant change in intensity until it reached the vicinity of the Colorado-Nebraska border.

Comparisons: On this day, both types of comparisons can be made. A comparison on the basis of before and after seeding an individual storm can be made on the storm that moved through Sterling. A comparison between seeded and unseeded storms can be made for the storm paths that passed through Fort Morgan and Sterling.

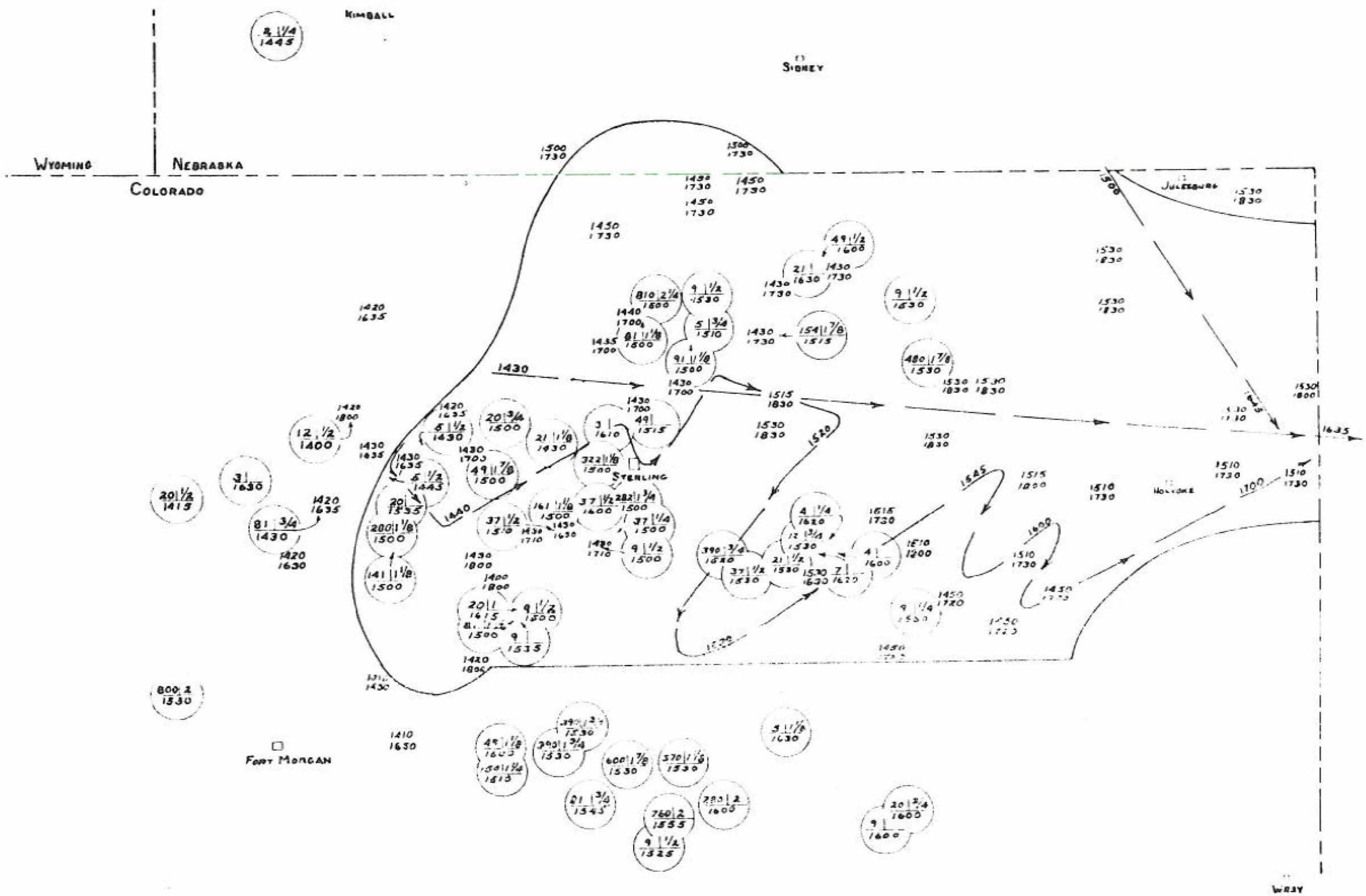

Figure 19 - Case History of 30 May 1959. Symbols are the same as for Fig. 17.

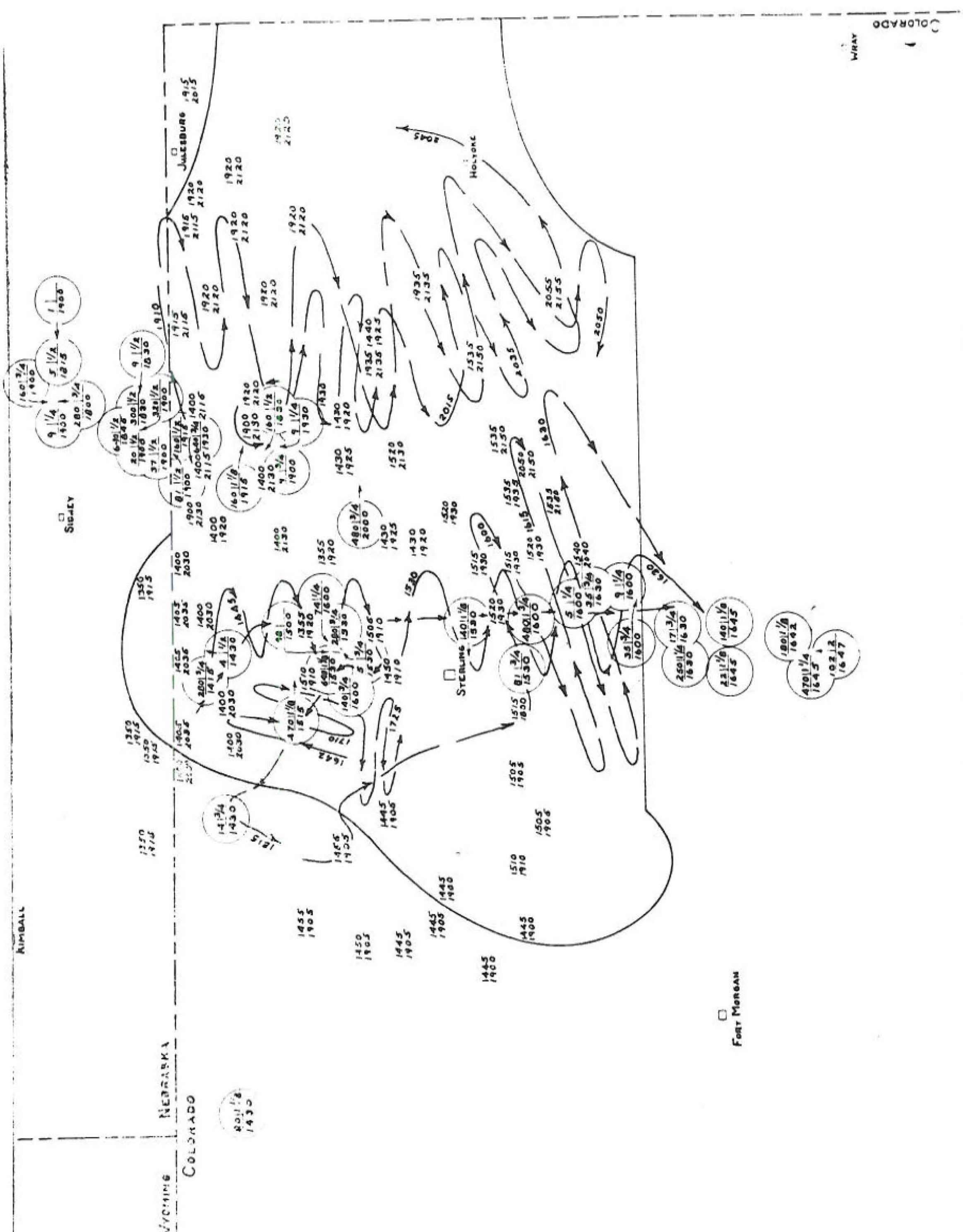

Figure 20 - Case History of 12 July 1959. Symbols are the same as for Fig. 17.

On this date, maximum precipitation and maximum hail coincided.

Conclusion: This case history gives conflicting evidence, since west of Sterling, seeding was concurrent with an increase in hail intensity. The most striking feature of this case history is the contrast between the continuous hail damage path from Fort Morgan to Wray and the hail damage path that diminished between Sterling and Holyoke.

Storm of 12 July 1959

Synoptic situation: No fronts affected the target area on this date as a weak high pressure cell moved from eastern Nebraska into southern Illinois. Strong southerly winds at the surface combined with 500 mb winds of 30 knots from the northwest brought increasing instability to northeastern Colorado. Individual thunderstorm cells of great severity moved from north to south.

Areas of hail damage reports: Fig. 20 shows that the most severe damage came from a cell which developed west of Sidney, Nebraska and moved through the entire target area to more than 50 miles south of the southern border of the target area. A second system developed later in the day east of Sidney, Nebraska, but did not produce hail beyond the center of the target area.

Special observations: Hail damage decreased after seeding began as the first cell moved into the target area. However, the cell intensified again north of Sterling. Hail damage was lighter from south of Sterling to the southern border of the target, then became severe following termination of seeding; and continued to give severe damage for at least 50 additional miles. Inside the target area, areas of precipitation and hail damage coincided.

Comparisons: Comparisons could be made before and after seeding individual storms.

Conclusion: Evidence from this case history suggest that hail had decreased following treatment, and increased following termination of seeding. However, this case is listed as giving conflicting evidence, since some intensification of hail took place north of Sterling concurrent with seeding.

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