Hail Measurement Techniques for Evaluating Suppression Projects

STANLEY A. CHANGNON, JR.
Illinois State Water Survey, Urbana

(Manuscript received 18 April 1969, in revised form 12 May 1969)

ABSTRACT

Collection of hail data that will provide meaningful measures of the results of hail suppression projects varies according to five factors, including the geographical-climatic site, the statistical design, and the goal of the project. Eight possible techniques of collecting hail data are evaluated with respect to their use in different areas, availability of historical data, and with different project designs. Each technique provides data that have distinct limitations. However, the two data collection techniques rated best for projects having a continuous seeding (on all hail days) design are networks of passive hailpads and raingages, and crop-hail damage records. The best technique for use in projects utilizing a single-storm seeding design or a random daily seeding (single area) design is a network of recording hailgages.

1. Introduction

One of the important problems for all hail suppression projects is the collection of surface hail data that will allow a meaningful, practical evaluation of the modification effort in a minimum amount of time. An evaluation of the major types of data and means of measuring surface hail that are either being employed in various projects or are being considered for future projects is the purpose of this study.

A major research effort of our organization in recent years has been the detailed study of hail, including its climatology and mesoscale distribution at the surface. Certain of our findings considered pertinent to the evaluation of hail data for verification of modification experiments are presented. Eight different techniques for hail measurements are evaluated and recommendations for future projects are offered.

These evaluations are based on a belief that the application of hail modification will not be accepted and supported by the scientific community and the general public until actual mesoscale measurements provide results clearly demonstrating economic gains. Obviously, this cannot be achieved until the alleviation of hail damage at the surface can be defined quantitatively, and this is chosen as the project goal for evaluating each technique. Thus, indirect means of evaluating hail modification, such as chemical analyses of hailstones for the presence of seeding agents, are not considered in this paper.

The proper selection of a particular technique for collecting data depends upon five variables inherent in any hail suppression project. These variables include: 1) the goal of the modification project; 2) the specific geographical-climatic area; 3) the type of statistical design; 4) the duration of the project; and 5) the areal extent of project area. Decisions regarding these variables largely determine both the type of data to be collected during the project, and the type of unmodified data (historical or otherwise) required to delineate the natural spatial-temporal variability of the hail event in the proposed project area.

These techniques also were evaluated with respect to certain basic operational-statistical designs for seeding, including 1) the single-paired cloud design, 2) the random daily seeding of all storms in a single area design, and 3) a design of continuous seeding (on all potential hail days) in a single area. The crossover design between areas is not considered because of the poor correlation between hail in adjacent areas (Changnon and Schickedanz, 1969) and its unlikely use. Research utilizing Illinois hail data has shown that the continuous seeding design would provide a statistically significant measure of hail reductions sooner than any other design, but the continuous seeding design requires a historical data series in the area of experimentation (Schickedanz *et al.*, 1969). Evaluation of all the factors involved in choosing the optimum statistical design for a hail suppression project in Illinois indicated that seeding 80% (randomly chosen) of the forecasted hail days was the optimum design (Changnon, 1969). Essentially, this design approaches the continuous-seed design with its major advantage of treating almost all occurrences of a relatively rare event (hail), and yet retaining some randomness (no-seed hail days) to check for trends during the seeding period.

The types of hail data collected by the eight possible techniques include: 1) the daily occurrences of hail from a network of volunteer cooperative observers and U. S. Weather Bureau observers; 2) the amount-extent of crop-hail damages from crop insurance records; 3) the

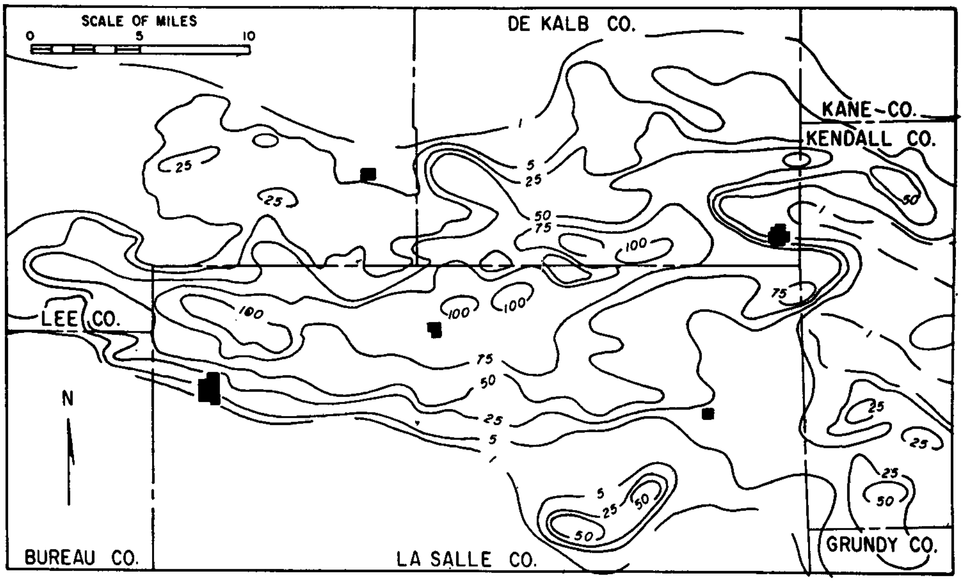

FIG. 1. Isopercentile loss pattern, based on per cent loss to corn yields, produced by hailstorms on 19 June 1964, in northern Illinois.

frequency and areal extent of hailstorms defined by radar; 4) the areal extent of hailfall areas delineated by mobile field survey teams; 5) hailfall energies estimated from passive hailpads in a dense network; 6) the areal extent of hailfalls and damage areas ascertained by areal photography; 7) the areal extent of hailfall areas established from airborne infrared sensors; and 8) the areal extent-intensity of hail measured by a dense network of recording hailgages.

2. Examples of hail measurements

Any evaluation of hail suppression efforts intended to be realistic and practical will require extensive surface measurements of the areal extent, and intensity or damage production of hail. Hail over an area exhibits a great amount of spatial variability for any given minute, storm, day or season. Not surprisingly, the areal variability also is considerable for quite long periods of years.

Figs. 1–4 illustrate many of the spatial variations in

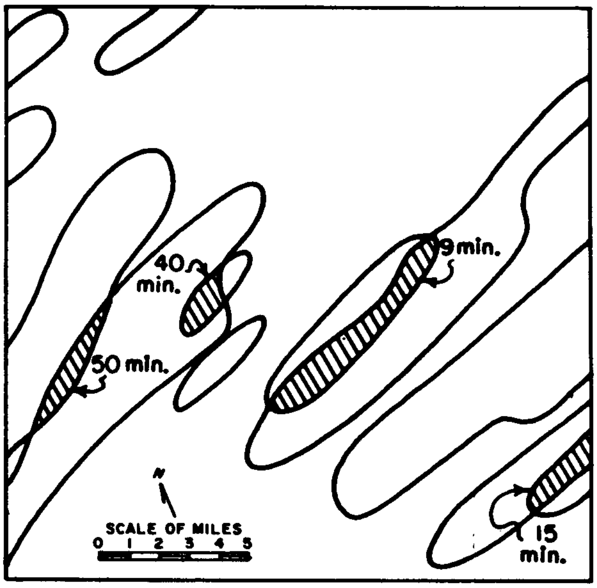

FIG. 2. Hailstreak outlines in a 400-mi² area during a 75-min period showing overlapping hail areas and time differences between overlapping.

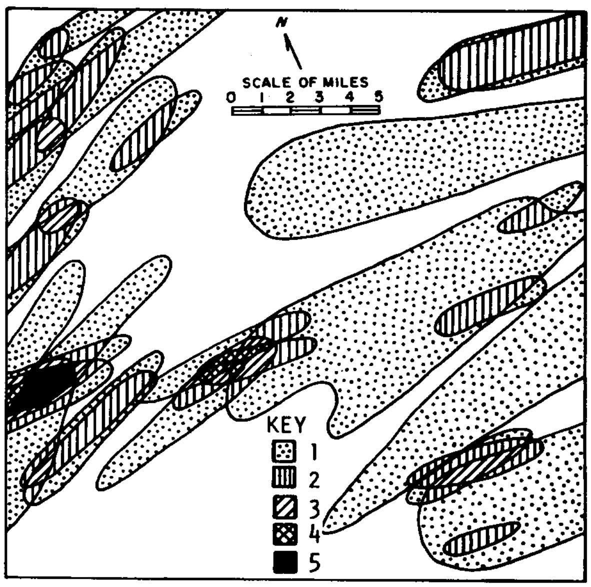

FIG. 3. Pattern of hail occurrences in 400-mi² area during five consecutive days in June 1967.

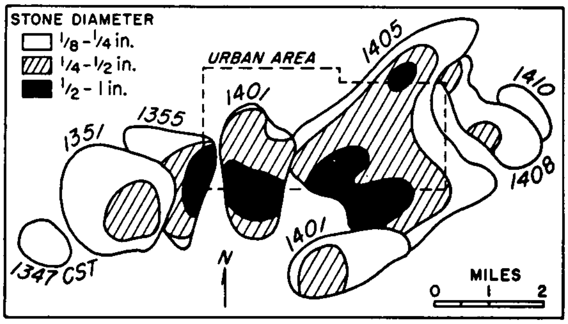

FIG. 4. Selected 1-min hailfall areas for two hailstreaks on 17 May 1962.

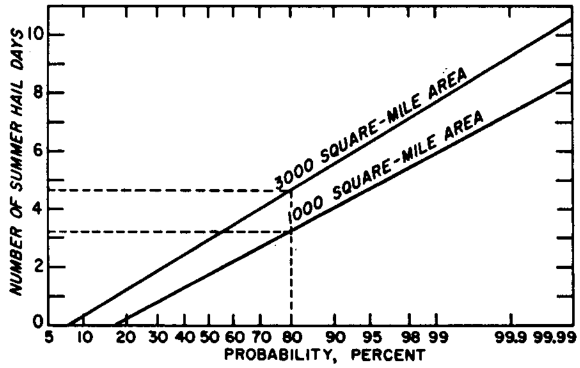

FIG. 6. Probability curves for summer hail days in two Illinois areas.

hailstorms occurring within a few minutes, hours or days. These time-space variations, common in many midwestern hailstorm situations, present critical requirements on the collection of data for modification evaluation. Fig. 1 presents a crop-loss pattern for a complex of hailstorms occurring in a 5-hr period (Changnon, 1966). Eighteen different hailstorms occurred in this area between 1400 and 1900 CST, and the 100% loss areas each were a result of at least three separate storm passages. Fig. 2 shows a series of 12 hailstreaks (areas of continuous hail) during a 1.3-hr period in a 400-mi² network area (Changnon *et al.*, 1967). Four areas of overlapping hail occurred, and hailfalls in one area were separated by only 9 min. Fig. 3 shows a composite of 34 hailstreaks in a 5-day period, with at least one hailstreak occurring on each date of the period. Fig. 4 shows a series of instantaneous areas of hailfall for two intersecting storms during a 24-min period. The size, shape and stone distributions of the hailfall areas all exhibit rapid changes during the short periods between portrayals.

Such illustrations reveal the necessity of highly accurate time-space data for field experiments involving either 1) seeding of individual clouds, or 2) seeding based on a random daily design. Spatial overlapping of hailstreaks also was found in all of the five major case study days in Project Hailswath, indicating that this condition also is common during hailstorm days on the Great Plains (Schleusener, 1966).

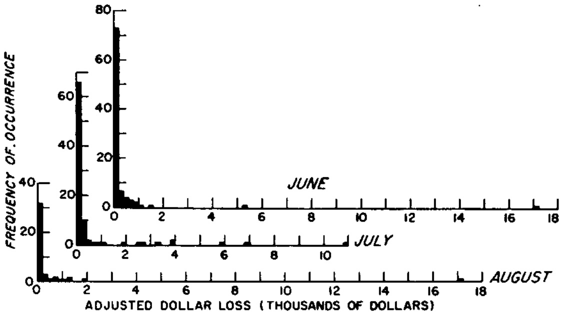

FIG. 5. Frequency distribution of daily dollar losses in 1500-mi² area in central Illinois (1948–66) with dollar values adjusted to a common base index.

One of the important considerations in the choice of design of any hail modification experiment is the severe, widespread, and complex storm day, as illustrated in Fig. 1 for a 1964 storm which caused $10 million in crop losses in Illinois. In an average year, 48 days with damaging hail occur in Illinois. However, the severe complex storms normally occur on only three of these days (6%), and yet they produce 65% of the total annual hail damage in Illinois. One of the problems they present for an experiment using crop-loss data for verification is illustrated in Fig. 5. These monthly histograms, which are based on daily dollar loss data from a 1500-mi² area for a 19-yr period, show that 7 days produced more than $5000 in losses, and that 171 days had losses <$200. Such a skewed distribution is a considerable statistical problem for verifying seeding results. These few widespread, severe mesoscale hail systems also must be recognizable and eventually susceptible to modification if hail suppression is to be successful in the agriculturally rich Midwest.

The areal variations in damaging hailstorms during longer periods are reflected in Figs. 6 and 7. Fig. 6 shows probability curves for the number of summer hail days in two different areas, based on U. S. Weather Bureau 30-yr records. Eighty per cent of the time there will be three hail days or less in the 1000-mi² area and less than five hail days in the 3000-mi² area. Fig. 7 shows the annual dollar losses for two adjacent 1500-mi² areas during a 19-yr period; exceptional variability is evident. Although the year-to-year fluctuations are generally harmonious, certain disagreements are in evidence. Two of the diverging fluctuations in these natural data are compared with changes noted by Sulakvelidze (1966) in adjacent Russian areas that were claimed to result from seeding.

A long-term average hail-day pattern in a four-state area is depicted in Fig. 8. Several rather sharp areal variations are evident across short distances, and these become important considerations in the selection of specific seeding locations.

3. Assessments of techniques and types of data

Inspection of the examples in Figs. 1–7 and research into areal sampling requirements for hail (Changnon, 1968) reveal that the measurement of hail in areas subject to modification efforts will require areal sampling with a density of at least one observation per 2 mi^2. Eight techniques for gathering hail data appear to exist, and these are evaluated by describing their known or probable advantages and disadvantages.

a. Cooperative observer network

Advantages. A network of volunteer observers including those at U. S. Weather Bureau substations can provide at little cost a good measure of hail occurrences. It can be developed in most areas of hail interest except those with a very sparse rural population. It is a source easy to maintain, and can provide inexpensive data in all seasons and over long periods of operation. Available historical hail-day records at the U. S. Weather Bureau stations are one of the three hail data sources of sufficient length to provide adequate measures of natural variability of hail (Fig. 6), and thus allows meaningful evaluations of modification efforts through various statistical techniques (Changnon and Schickedanz, 1969).

Disadvantages. The primary disadvantage is that hail-day data are not necessarily a direct measure of hail damage, and can be used only in testing a project designed to reduce hail-day frequencies. Unless a very dense grid of observers is developed, the data will not allow accurate areal mapping of hail occurrences. Since hourly occurrence data from such networks are often inaccurate or missing, these data are not useful in projects designed for single-paired storm seeding. Experience has shown that volunteer hail observers often do not observe small hail or any hail at night. Since 24% of all damaging hail in Illinois occurs between 2300 and 0600 CST, such omissions would seriously affect the hail-day sample (Huff and Changnon, 1959).

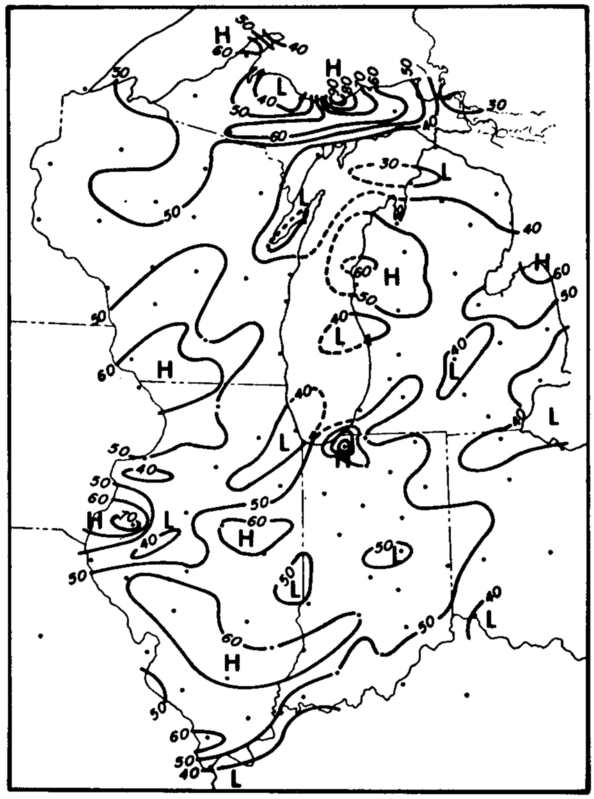

Fig. 8. Number of hail days in an average 20-year period.

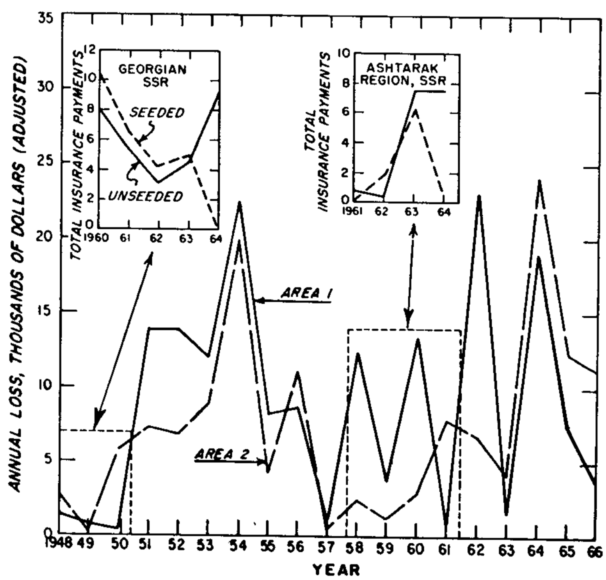

Fig. 7. Curves of annual dollar losses in two nearby 1500-mi^2 Illinois areas and similar data for two Russian hail modification sites.

b. Crop-hail insurance records

Advantages. The primary advantage of these records is that they are a direct measure of hail damage, and thus for the general public they are the most meaningful quantitative data for use in evaluating suppression efforts. Because these data are being routinely collected by insurance companies, they can be obtained at extremely low cost. In other words, the data collection system is already in existence. Of further importance is the fact that in many states relatively long-term records of loss are now available, making these data one of three types with sufficient length to furnish statistical measures of their natural time-space variability (Fig. 7). In areas of dense liability (>60% insured), these data will accurately measure the areal

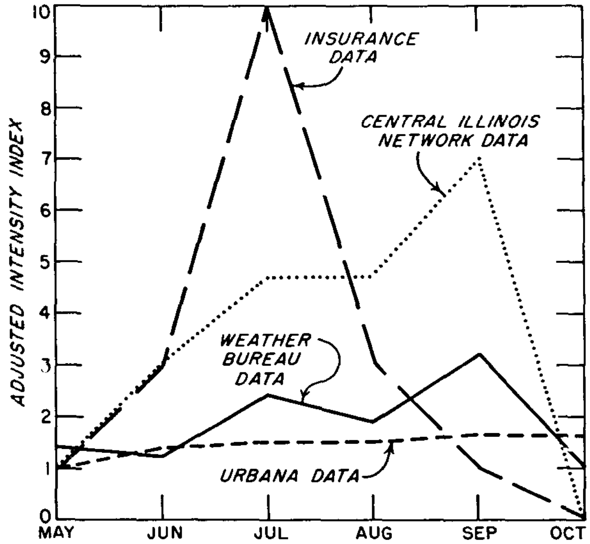

FIG. 9. Seasonal variations in hail intensity exhibited by different indices developed for various types of Illinois hail data.

extent of hail for a daily or continuous-seed experimental design.

DISADVANTAGES. These data are available only for the crop growth season, which is normally four months for most hail-threatened crops, and no data are available in all other months. Furthermore, during the growing season the susceptibility of most crops to hail damage changes and does not reflect the actual intensity or damage capability of a given storm (Fig. 9). These corn-loss insurance data for Illinois show that the average storm in July has an index of intensity (loss) of 10, whereas that of the average storm in September is 1, and yet the three more direct measures of average storm intensity show the September storms to be the most intense (Changnon, 1967). Therefore, insurance loss data in one month are hard to compare with those in another, and thus are somewhat difficult to analyze for a random seeding design based on daily units. The lack of precise timing in the data, other than to the date of occurrence, eliminates the use of insurance data for designs involving single storm modification. Unfortunately, crop-hail insurance coverage is not sufficiently dense or extensive in several potential suppression project areas of the Great Plains.

c. Radar data

ADVANTAGES. Radar investigations have shown that most surface hail was associated with echoes having high reflectivities in the 10,000–20,000 ft level (Donaldson, 1958; Wilk, 1961), and Russian scientists have used radar to detect hail aloft to select storms for seeding (Sulakvelidze, 1966). If radar can identify all storms producing surface hail, it might possibly provide information for mapping the areal extent of hail. It would become a single-instrument technique for collecting hail occurrence data 1) over various sized areas, 2) in any geographical location, 3) in any or all seasons, and 4) over long periods of time. Since radar will likely be an essential part of a hail modification experiment to direct seeding activities, its cost as a data collection source could be considered negligible.

DISADVANTAGES. The ability of radar to accurately detect all storms producing surface hail or to map the areal extent of hail has yet to be established, although Rinehart and Staggs (1968) have investigated it. Their preliminary results indicate that 3-cm radar will not provide reasonably accurate measures of the areal extent of hail nor of the number of hailstorms. In either case, the radar data would not be quantitative measures of the hail intensity or damage. Analysis of radar data will be an expensive undertaking, and there are no historical data available for statistical evaluation of the natural variability.

d. Mobile field surveys

ADVANTAGES. Personnel moving in vehicles after a storm passage can inspect damage and interview persons to gather data on the hailstorm's areal extent, time of occurrence, and stone types. This type of data can be collected in all seasons and does not necessitate the presence of crops.

DISADVANTAGES. This approach at gathering data is extremely demanding (expensive) in relatively skilled personnel, especially if pursued for a very lengthy period of operation. There are no historical data to evaluate the natural variability of the data, and at best the data gathered are only semi-quantitative measures of loss (Changnon and Stout, 1964). This approach is also limited to areas with good rural road networks and relatively dense rural population (Schleusener, 1966).

e. Passive hailpad networks

ADVANTAGES. Such networks have been employed in Oregon (Decker and Calvin, 1961), Colorado (Schleusener, 1962), Illinois (Changnon *et. al.*, 1967), and several other states to measure ice volume, energy, and stone sizes of hailfalls occurring between times of pad servicing. They can furnish estimated hail intensity data for designs based on continuous seeding and on daily (random) seeding units if serviced daily. If installed with recording raingages, the time of measured hail energies can be determined except in cases of overlapping hail (Figs. 1–3), and the amount of rain with hail can be ascertained. The hailpads are inexpensive to build, install and operate, and they can be installed in large numbers to adequately measure the areal extent of hail. They also furnish data in all months, and there have been sufficient data collected in some potential seed areas to provide an adequate historical description of the natural variability of the pad-measured hail parameters.

DISADVANTAGES. Inability to separate the pad energy (nonrecorded) data from repeated hailfalls in a matter of minutes, hours, and/or even a few days (Figs. 1–3) eliminates their use in experimental designs based on single-paired storm seeding, and limits their usefulness in designs involving daily seeding units. The energy data are only semi-quantitative (estimated) and can be serious underestimated when either heavy or light hailfalls occur.

f. Aerial photography

ADVANTAGES. This technique of collecting surface hail data is generally unproven, but might provide from a single instrument a detailed measure of the areal extent of damaging hail with quantitative measures of damage. The use of standard black and white (infrared) film to delineate surface hail loss has been explored and found lacking, but some data resulting from exploratory crop-disease research using infrared, camouflage-detection film appears promising (Manzer and Cooper, 1967).

DISADVANTAGES. An oblique infrared aerial photograph taken 1000 ft above each of three different crops (Fig. 10), each with its surface adjusted hail loss, was carefully analyzed by crop adjustors, and they were unable to even approximate the degrees of loss. These results and other research on photographic resolution by photogrammetrists indicate that the use of panchromatic or infrared black-white films to detect hail damage will require flight missions at <500 ft. This becomes infeasible due to the expense of data collection ($50,000 to photograph a 1000-mi² area) and subsequent analytical interpretation unless used for a few single cloud experiments. However, a major problem that cannot be solved by any film type is the inability to separate overlapping hailstreaks as illustrated in Figs. 1 and 2. This occurs because of the necessity for proper photographic weather (no turbulence and no clouds), which may not exist for many hours or days after the hailstorms. This source is further restricted to data collection only during the growing season, which does not sample much of the total hail season in the Midwest. There is no historical data to refer to in evaluating the results of seeding using aerial photo data. Crop-hail losses need to be photographed using the promising camouflage-detection film and then studied. However, the processing and analysis of this film type also promise to be very difficult and expensive.

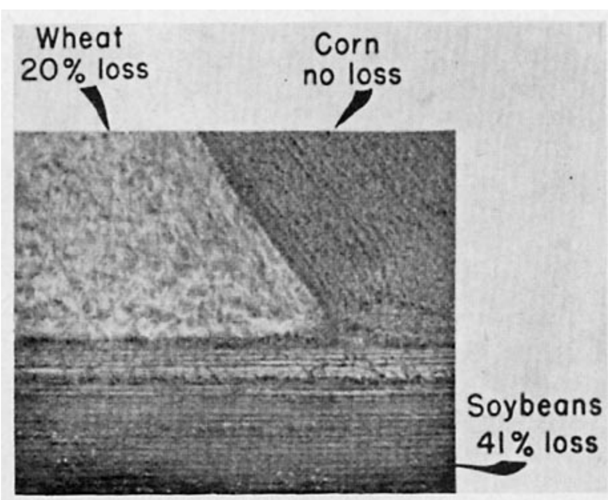

FIG. 10. Infrared oblique photograph taken 1000 ft above hail-damaged crops showing per cent crop loss values as adjusted at surface.

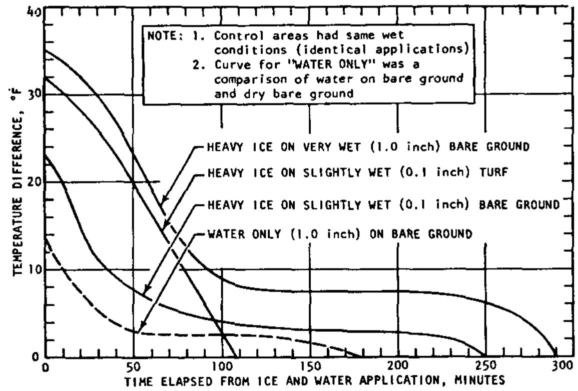

FIG. 11. Temperature differences between area of heavy ice (1 to 2 inches deep) and no-ice control areas as a function of time with obscured sun.

g. Infrared temperature sensing

ADVANTAGES. The use of airborne infrared radiometers to sense surface temperature differences between hail and no-hail areas is another potential data-gathering technique employing a single instrument to rapidly measure the areal extent of hail. Weickmann (1969) used a scanning radiometer to define the boundaries of a 1968 hailstorm in Colorado.

DISADVANTAGES. Experiments in Illinois using a radiometer on a 40-ft tower were performed to sense various hail conditions created with crushed ice on bare ground (silt-loam) and turf. The curves in Fig. 11 for "1-inch water only" and for "1-inch water plus very heavy ice application" reveal that they have discernible temperature differences from each other and from the control (no water or ice application) areas. Unfortunately, the maximum ice-water curve, which represents a very severe hailstorm, shows the "hail" temperature difference disappeared 290 min after the application (hypothetical storm), and the more reasonable Illinois hail storm conditions (Fig. 12) show a disappearance of the hail effect within 105 min after application. This rapid decay of the effect indicates that 1) the approximate area of the hailstreak would have to be known quickly after its occurrence, and 2) the infrared sensing of hail

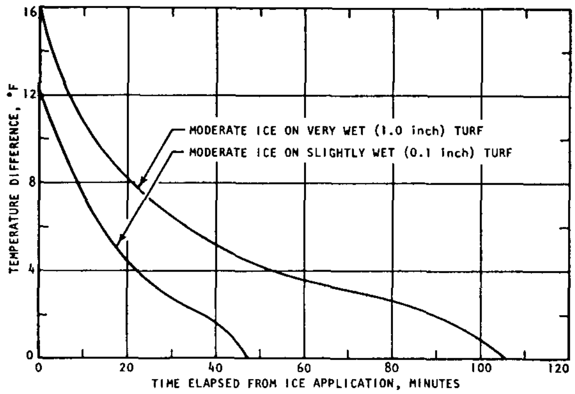

FIG. 12. Temperature differences between areas of moderate ice (60–70 hailstones ft^{-2}) and no-ice control areas as a function of time with obscured sun.

areas would have to be performed very rapidly after a storm, tasks extremely difficult to accomplish in many hailstorm conditions. Again, the problem of overlapping hailstreaks during a short period (Figs. 1 and 2) limits the capability of this data source on single-paired storm seeding projects. An even greater disadvantage is the apparent inability to get data which will quantify the intensity or damage unless the volume of ice, and thus a temperature difference, is directly related to damage as indicated by Schleusener (1963). Also, there are no historical natural data upon which to base statistical evaluation of the results; thus, because of areal referencing problems, analysis will be difficult.

h. Recording hailgages

ADVANTAGES. Another technique which holds promise would be a network of devices which will precisely record the time of the hail and its intensity (energy or momentum). Such instruments have been developed (Mueller and Changnon, 1968; Fremstad, 1968) and are being field tested. If sufficiently inexpensive to allow dense networks, these instruments can provide the quantitative data needed in any type of experimental design ranging from single-paired storm seeding to continuous daily seeding. They can be operated continuously, do not have crop season limitations, and could be installed in any geographic area.

DISADVANTAGES. These instruments are generally in the unproven stage although two gages appear to have considerable promise. Whether such instruments can provide quantitative hailfall data that are relatable to damage is yet uncertain, and the instrument must be relatively inexpensive to allow dense installations in study areas. Obviously, there are no historical records of natural hail data from such instruments, but if the data correlate with the degree of crop loss, this disadvantage can be eliminated by using the historical crop-loss insurance data.

4. Summary and recommendations

All of the listed techniques for gathering hail data have significant advantages as well as disadvantages. To allow assessment and comparison of the various

TABLE 1. Assessment of eight hail data sources according to three seeding designs and locations in the Great Plains (GP) and Midwest (MW).

Data source	Single storm seeding GP	Single storm seeding MW	Random daily seeding GP	Random daily seeding MW	Continuous seeding GP	Continuous seeding MW
Observers	NS	NS	NS	NS	PS (i,L,q)	PS (i,q)
Insurance records	NS	NS	PS (a,L,t)	PS (a,t)	PS (t,L)	PS (t)
Radar	PS	PS (a, h, q, and u apply to all three designs and areas)	PS	PS	PS	PS
Field surveys	PS (c,h,i,L,q)	PS (c,h,i,q)	NS	NS	NS	NS
Hailpads	NS	NS	PS (o)	PS (o)	S	S
Aerial photos	NS	NS	NS	NS	PS (a,c,h,L,t,u)	PS
Infrared sensors	PS (a,h,i,q,u)	PS	NS	NS	NS	NS
Recording gages	S	S	S	S	PS (h)	PS (h)

Key

a analysis difficult and expensive
c costly in equipment or personnel
h no historical record
i incomplete areal sampling
L limited to certain geographical locations
NS not suitable
PS partially suitable
o other equipment-data essential
q not quantitative measures
S suitable
t time of sampling limited to certain seasons
u unproven technique

data sources in relation to 1) the three basic types of experimental designs, and 2) two potential geographical areas of experiments (Midwest and Great Plains), each source was evaluated as being suitable, partially suitable, or not suitable (Table 1). If the source was considered to be partially suitable (PS), the primary reasons (disadvantages) were indicated by the subscript letters shown in Table 1.

One suitable and five partially suitable data sources are available for projects based on the continuous seed design, and the selection of data source will likely depend on geographical and cost limitations. For daily (random) seeding projects in a single area, the hailpad networks, radar, and insurance data are considered partially suitable sources, but recording hailgage networks are considered to be the only suitable source. There are three partially suitable sources for experiments involving single-paired storm seeding, but none provide quantitative data nor have historical data; again, a network of recording hailgages appears to be the only suitable data source. The only limiting feature of the recording hailage is a lack of historical record, but if on-going research proves its data is correlated with the degree of crop loss, the historical insurance loss experience could be substituted. Only the U. S. Weather Bureau hail-days data, crop-insurance loss data, and passive hailpad data have sufficient historical records to allow an adequate description of their natural variability and hence employment in statistical evaluation tests.

The longer hail season, extending beyond the crop-growing season, and frequent occurrence of nocturnal hailstorms in the Midwest are limiting factors in the choice of data sources in that area, whereas nonuniform and low densities of crops, roads, rural populations, and crop insurance are limiting factors on data choices for the Great Plains. The hail data provided by four data sources, the volunteer observers, radar, field surveys, and infrared sensors, are not objective or quantitative measures of intensity or damage.

The results of this evaluation of hail data sources for suppression projects in both areas suggest that a network of recording hailgages would be the best data source for projects involving either single-paired storms or random daily seeding designs. The best data for monitoring continuous seeding designs are those from hailpad networks. The insurance records also have considerable merit for this design with the added virtues of meaningful information inexpensively collected.

Acknowledgments. Much of this research was supported by the Atmospheric Sciences Section, National Science Foundation, under Grant GA-482. Useful data have been supplied by the Crop-Hail Insurance Actuarial Association. This work has been done under the supervision of Glenn E. Stout, Head of the Atmospheric Sciences Section of the Illinois State Water Survey. The advice of William Block of Chicago Aerial Surveys and the assistance of John Hornaday are greatly appreciated. The infrared experiments were performed with a radiometer loaned by the Atmospheric Science Laboratory, USAECOM, Ft. Monmouth, N. J.

REFERENCES

Changnon, S. A., 1966: Disastrous hailstorms on June 19–20, 1964, in Illinois. Crop-Hail Insurance Actuarial Assoc., Chicago, Res. Rept. 31, 37 pp.

——, 1967: Areal-temporal variations of hail intensity in Illinois. *J. Appl. Meteor.*, **6**, 536–541.

——, 1968: Effect of sampling density on areal extent of damaging hail. *J. Appl. Meteor.*, **7**, 518–521.

——, 1969: Hail evaluation techniques. Part 1, Final Rept., NSF GA-482, Illinois State Water Survey, Urbana, 88 pp.

——, and P. T. Schickedanz, 1969: Utilization of hail-day data in designing and evaluating hail suppression projects. *Mon. Wea. Rev.*, **97**, 95–102.

——, P. T. Schickedanz and H. Q. Danford, 1967: Hail patterns in Illinois and South Dakota. *Proc. Fifth Conf. Severe Local Storms*, St. Louis, 325–335.

——, and G. E. Stout, 1964: A detailed investigation of an Illinois hailstorm on August 8, 1963. Crop-Hail Insurance Actuarial Assoc., Chicago, Res. Rept. 18, 33 pp.

Decker, F. W., and L. D. Calvin, 1961: Hailfall of 10 September 1959, near Medford, Oregon. *Bull. Amer. Meteor. Soc.*, **42**, 475–480.

Donaldson, R. J., 1958: Analysis of severe convective storms observed by radar. *J. Meteor.*, **15**, 44–50.

Fremstad, P. G., 1968: Transducer for measuring hailstone momentum. Rept. 68-4, South Dakota School of Mines and Technology, Rapid City, 47 pp.

Huff, F. A., and S. A. Changnon, 1959: Hail climatology of Illinois. Illinois State Water Survey, Urbana, Rept. of Investigation 38, 46 pp.

Manzer, F. E., and G. R. Cooper, 1967: Aerial photographic methods of potato disease detection. Univ. of Maine Bull. 646, 14 pp.

Mueller, E. A., and S. A. Changnon, 1968: A recording hailgage for use in hail modification projects. *Proc. First Natl. Conf. Wea. Modification*, Albany, N. Y., 494–502.

Rinehart, R. E., and D. W. Staggs, 1968: Use of radar to delineate surface hail areas in weather modification experiments. *Proc. First Natl. Conf. Wea. Modification*, Albany, N. Y., 464–473.

Schickedanz, P. T., S. A. Changnon and C. Lonnquist, 1969: A statistical methodology for the planning and evaluation of hail suppression experiments in Illinois. Part 2, Final Rept., NSF GA-482, Illinois State Water Survey, Urbana, 140 pp.

Schleusener, R. A., 1962: The 1959 hail suppression effort in Colorado and evidence of its effectiveness. *Nubila*, **1**, 31–59.

——, 1963: Hailstorm characterization and the crystal structure of hail. *Meteor. Monogr.*, **5**, No. 29, 173–176.

——, 1966: Project Hailswath: Final Report. Vols. 1–2, Inst. Atmos. Sci., South Dakota School of Mines and Technology, Rapid City.

Sulakvelidze, G. K., 1966: Results of the Caucasus anti-hail expedition of 1965. *Vysokogornyi geofiz. Inst. Tr.*, **7**, 1–61.

Weickmann, H. K., 1969: ESSA-1968-Colorado hail research. *Proc. Sixth Conf. Severe Local Storms*, Chicago, 385–391.

Wilk, K. E., 1961: Radar investigations of Illinois hailstorms. Sci. Rept. 1, Contract AF19(604)-4940, Illinois State Water Survey, Urbana, 42 pp.